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Exploring technology options for future wind energy converters

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Abstract. This analysis aims to identify appropriate technology options for wind energy converters across all sizes by matching the sizes of the primary mover and the time scales of the extraction and conversion processes to the wind conditions as quantified by mean winds and turbulence intensity. The approach was to set out the options in a process tree and then group technology options according to common characteristics which can be used to estimate productivity in wind scenarios characterised by the wind speed, wind direction and turbulence statistics.

Key words. Wind Turbine, Technology Options, Technology Futures

1. Introduction

Much research explores challenges faced by the significant scaling-up of turbine sizes for offshore wind farms at one end of the scale and energy scavenging options at the micro-turbine scale. The main direction of research for offshore wind farms focusses on material challenges for ever larger turbine blades [1] as well as the complexities encountered by floating wind turbines [2]. However, one alternative explored is the multi-rotor concept whereby many rotors are mounted on a common frame, effectively covering the same swept area as a single large rotor but filling that area with many smaller and independently operating wind energy converters [3]. The scale of a unit device, be that a single rotor or a frame with many rotors, is on the scale of many *megawatt*.

At the other end, research explores energy extraction utilising conversion technologies on, for example the electrostatic [4], piezoelectric [5] [6], dielectric [7] or triboelectric [8] principles as well as hybrid of the above [9] or the standard rotor [10]. These are usually driven by aerodynamic pressure fluctuations, such as vortex shedding from a cylinder or flutter caused by turbulent fluctuations [11] or by pressure changes induces such as in a Venturi channel [12]. Devices typically target power output in the *milliwatt* range.

The intermediate range is almost entirely occupied by the three main wind turbine types. One of these is the downscaling of the main horizontal-axis wind turbine (HAWT) [13]. The other two are vertical-axis wind turbines (VAWT), either lift-operated, such as the Darrieus or H-rotor, or drag-operated VAWT, such as the Savonius rotor [14]. Of these, the HAWT has the potential to be the most efficient under suitable conditions but the fact that they need to be yawed into the wind in an environment where the wind direction varies much more significantly at short time scales than higher up in the atmosphere causes the rotor to be frequently not in design conditions. The advantage of VAWT rotors is that they are not sensitive to the wind direction and might therefore be more productive than equivalent HAWT rotors despite their inherent lower aerodynamic efficiency. Despite those challenges, the urban wind resource has been identified as an important potential contribution on the path to net zero [15] [16]. One can reduce the complexity of the urban wind resource to the intricately linked pair of mean wind and turbulence intensity where the turbulence intensity is the key to accessing the resource [17]. Alternative technology approaches have been based on the principle of radial-flow machines similar to Francis turbines or fans [18] [19], oscillating blades [20].

A fairly recent technology review and forecasting study [21] has focussed entirely on the large turbine sector and its evolution and challenges. Looking across all scales of turbines, a recent review of developments in wind turbine technology [22] has covered the three main technology types based on lift forces from aerofoils in HAWT and lift-driven VAWT and on drag forces for the Savonius-type rotor. However, they have not covered in detail alternative technology options.

The aim of this paper is to present a systematic review of physical process and conversion technologies, and to discuss these in the context of linking converter size with the inherent length- and timescales in the wind.

2. Methodology

The methodology consists of four steps, starting with identifying physical process and corresponding conversion approaches in a structured format. The resulting technology typologies are then analysed and classified according to their intrinsic length and time scales. The third step combines the resource characteristics with corresponding technology characteristics.

A. Conversion Typology

Following the standard approach of creating a hierarchy of technology options but including all possible conversion approaches identified in section 1 will be drawn up according to the fluid mechanics, extraction physics, and conversion options. The format for this analysis uses the framework of a Morphological Analysis [23] [24].

B. Technology Option Classification

Each of the technology options, from initial fluid process to final energy output, will be analysed according to their time scales intrinsic in the conversion change, be that a fixed time scale or a scaling function of size of the device, measured in the two key parameters of primary mover size (e.g., rotor diameter or inlet cross-sectional area) and power output. Using specific criteria and thresholds (or a formal cluster analysis), the options will be allocated to one of a set of groups.

C. Matching device to the resource

Using the widely accepted power spectrum of the wind resource, a scaling is developed to quantify the part of the turbulence accessible by quantifying the additional available power by accessing the low-pass part of the turbulent kinetic energy spectrum.

Linking the accessible frequency range to lengths scales of the velocity fluctuations and corresponding device conversion length scales, then allows to quantify the accessible wind energy to different device sizes. This can then be used to provide guidelines to matching the response times of power conversion principle or control, or for most appropriate device choices for a particular installation site.

3. Results

A. Conversion Typology

The typology is developed by starting from the ultimate wind energy resource, and then following through various stages in the conversion process to useful energy. The attributes identified to draw up the typology shown in Figure 1 are:

1) Wind resource
2) Capture conditioning
3) Energy supply
4) Energy acceptance
5) Power conversion
6) Power conditioning

While the morphological analysis attempts to be fully inclusive to potential options, the structure of an attribute and the values for each attribute are a first version based on the literature covered represented by examples in Section 1, and might need expansion or modification in future work. At this stage, the control options are explicitly excluded as they form a second layer of device deployment once a device is constructed on the basis of the chain laid out in Figure 1.

The wind resource is described by the fundamental energy forms present in airflow. Given that the kinetic energy is provided by the 3-dimensional velocity field, wind direction is as important as wind speed. Hence, the first step in the conversion is termed capture condition, where the incident energy flux is modified before the actual conversion from wind energy to another form is started. These options are essentially means to convert the air’s energy into another form of the air’s energy – be that change in relative direction of the air’s velocity to the capture device, or a transfer between kinetic and pressure energy. In terms of aligning the kinetic energy with the capture device, one option is to change the air’s flow direction, e.g., by using a duct, or to change the device, e.g., by yawing the device into the wind. For completeness, the option of not using capture conditioning is included. At this stage, it is instructive to note that some items in the list of options within a stage are mutually exclusive, while others can be combined in a single device. As an example, ‘none’ cannot be used in combination with any of the other choices, but ‘Device Yaw’ can be combined with a ‘Duct’.

The next two stages split the energy transfer into the ‘supply’ and the ‘acceptance’ sides. The supply side resides within the air, either completely, as described by aerodynamics, or partly but crucially, as described by aeroelasticity. Matching that is the acceptance side which describes the response of the device to convert the fluid energy into a form which the power generation technology can access. Apart from heating, all acceptance forms are mechanical motion. That motion is then used by the various power conversion principles to convert that energy into useful power, mostly electrical power but it is also possible to use the motion to create heat directly, for example by friction.

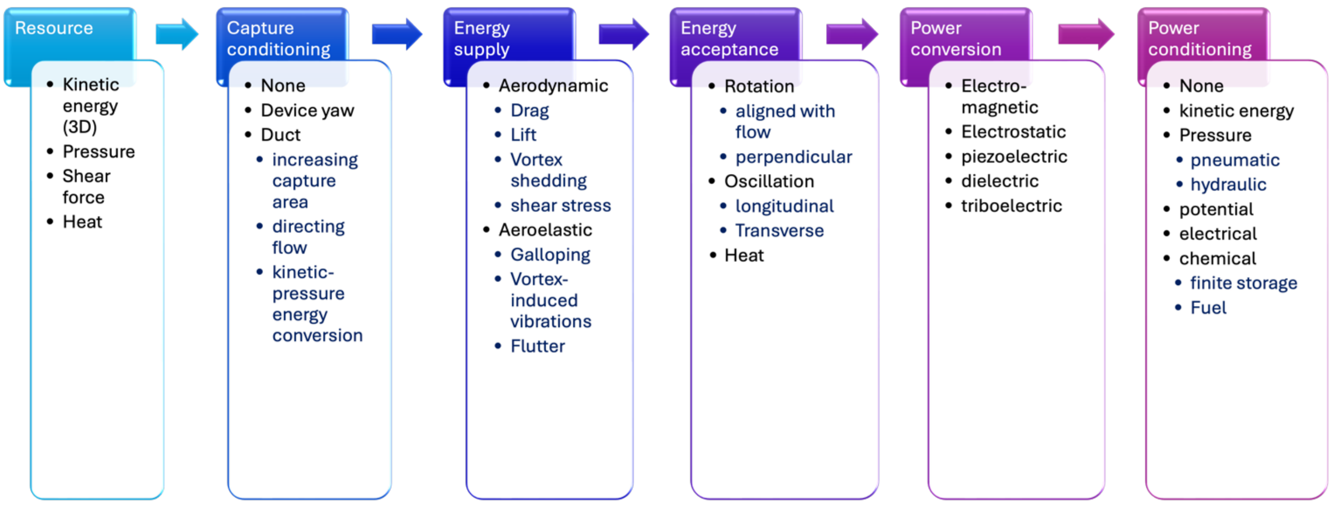

Figure 1. Attributes of wind energy converters.

The final power conditioning stage is an optional stage. Depending on the requirement, this could be actions to maintain power quality, such as the embedded kinetic energy in a synchronous machine providing grid inertia, or it could be for energy storage purposes to provide power at a later stage when requested.

This morphological analysis of wind energy conversion options now allows to create arbitrary device types by selecting one or more from each of the stages. As an example, a basic standard HAWT will exploit the kinetic energy by conditioning the capture area (rotor) through yaw which allows the dominant lift force (together with the inevitable drag force) to induce a rotation around an axis aligned with the flow to drive an electromagnetic generator without additional power conditioning if it is a typical variable-speed machine using a rectifier-inverter.

Another example might be a device using a venturi duct to induce flutter on a receptor in the through undergoing transverse oscillation which could then be converted by piezoelectric or triboelectric processes.

A third example could be employ a duct which can be yawed, with airfoils responding to lift and drag to induce transverse oscillations of the airfoils, using hydraulic accumulators to condition the power before driving an electromagnetic generator feeding a fuel cell. The two key points of this example is that it uses more than one value in some of the attributes, and also that the suggested 'left-to-right' order is just a suggestion, since one of the power conditioning elements is prior to the power conversion, and the second after. Similarly, there are numerous examples combining two energy supply values, such as hybrid Savonius-Darrieus VAWT [25] or hybrid piezo-dielectric [9] or triboelectric-electromagnetic [26] devices.

B. Wind and technology time scales

Given the vast range of sizes, from millimetre to 100 m or the capture area, and the vast range of device dynamics, it appears natural that matching a choice to a particular resource will include consideration of the length and time scales at which the device is to operate.

The resource itself shows a broad range in variability. The earliest detailed analysis identified two major variability time scales, one at a period of about 1 minute and the second at a period of about 4 days, together with a clear spectral gap of low variability in the range from about 10 minutes to one hour [27]. More recent observations show also clear periods at one day and one year [28]. However, all devices capture the wind energy at much shorter time scales. At time scales shorter than 1 minute, the frequency spectrum appeared close to isotropic 3D turbulence, with the frequency-weighted spectrum decaying with $\sim f^{-2/3}$ [29] .

To estimate the fraction of the energy spectrum accessible by the device, the concept of resolved energy variations slower than a device-intrinsic time scale, and unresolved time scales faster than the response time of the device is useful. As a result, the time resolution of the power output is given by the that device response time and equally the relevant wind resource is that averaged over the response time. Given that the power in the wind is a cubic function of the velocity, the power from the averaged wind speed is lower than the averaged power from the wind speed.

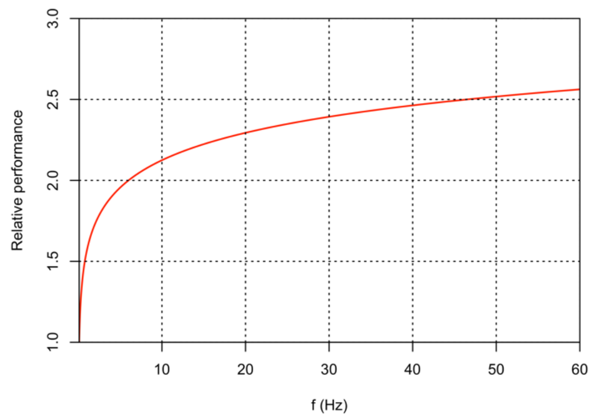

Figure 2. Potential enhancement from additional turbulent energy captured over large HAWT.

The crucial device response time will be determined by the slowest process from the energy supply to the completion of the power conversion. In some cases, it will a time scale determined by an aerodynamic or aeroelastic process such as the frequency of vortex shedding. In another, it will be given by a time scale of the acceptance motion. For example, the rotation of a large horizontal-axis electro-magnetic wind energy converter (HAWT) averages over the area of the turbine over the rotation rate of the turbine.

The time scales involved in the energy conditioning stage are not believed to affect the device response time but can lead to losses due to a delay in conditioning. A prime example is the yaw of HAWTs. While losses due to delay in turning the rotor into the wind are only minor for large turbines, it is a major factor for poor productivity with small turbines for urban or building-integrated designs. There the high turbulence intensity of the wind renders the expectation for the wind direction to remain stable over the time the turbine yaws futile. This is one of the reasons that the market for 1 kW building-integrated wind turbines collapsed after high expectations in the first decade of this millennium.

Give that the standard method to quantify wind is by a mean wind speed and either a measure of the gusts or of turbulence intensity as the standard deviation of velocity in a 10-minute window, a first estimate of how the potentially available power changes with the device response scale, the energy spectrum from the reference cut-off used for the standard definition of turbulence intensity, namely 10 minutes down to the device response time is estimated by integrating the 3D-turbulence spectrum using 10 minutes (= 1/600 Hz) as the lower limit and the variable device response time down to an arbitrarily chosen 60 Hz as the upper limit, chosen to safely include observed flutter frequencies.

To compare the ability of other technology choices to extract different amounts of power from the spectrum, they are compared against the slowest, and therefore largest, realistic machines. The largest structures anticipated currently are multi-megawatt offshore wind turbines with a diameter in excess of 100 m and a rotation rate of around 0.1 Hz. Hence the part of the power contained in the part of the turbulent spectrum quantified by the standard turbulence intensity is calculated by the ratio of power from the 10-minute window to the device response time scale against that from the 10-minute window to the 0.1 Hz (or 10 second) window of an offshore HAWT rotor. This is shown in Figure 2. One has to remember, however, that this enhancement is only for the part of the turbulent spectrum faster than the standard reference 10-minute mean. Therefore, a device with a 1 Hz response rate can capture about 55% more of the turbulent wind than the slow HAWT, so that multiplier of 1.55 has to be applied to the turbulence intensity. In an offshore situation with a low turbulence intensity, typically around 5%, the additional energy capture would the 1.55*5% = 7.8%. The enhancement becomes more important for conditions with a lower wind speed but higher turbulence intensity. Closer to the ground or built structure, the turbulence intensity can easily exceed 30%.

C. Length scales

The two main relevant length scales are the size of the catchment area of the wind energy flux and the length scale of how the device responds to the air velocity fluctuations. The first of the two is for the standard HAWT the swept area of the rotor, $A = \frac{\pi}{4} D^2$.

The second is not as clearly defined but depends on the conversion process. In the case of a standard HAWT with a rigid turbine blade, it will be the rotor diameter as the productive torque is the sum over all turbine blades of the integral of the torque distribution along each blade. In the case of a H-type VAWT rotor, it can be argued that it is the larger of either the blade length or the rotor diameter. For a device operating on vortex-induced vibration through vortex shedding, it will be the diameter of the body from which the vortices are shed, since the vortex diameter is of a similar size as the body. The length scale for a device exploiting flutter will be given by the excited vibrational mode of the prime mover.

The relationship between the capture area, A, and the response length, L, can be expressed as a single reference length scale, L, and a geometric aspect ratio AR. This allows to extend the scaling explored for the time scales to a corresponding scaling for the size of the device given by in terms of the response length. This length can be linked to the time scales in the isotropic turbulence range using the eddy turnover length scale, $L_e = U/f$ and estimating the velocity fluctuations from the turbulent power spectrum. Applying this gives a guide to the highest frequency accessible by a device with a given response length. This is shown in Figure 3, where for example, a device with a response length of the order of 1 m would only be able to capture the part of the turbulent energy spectrum down to a frequency of the order of 1 Hz.

D. Performance enhancement potential

Applying the size and response time scaling to the potential enhancement calculation for a selection of environments, allows an estimate of the potential performance enhancement for devices or different sizes deployed in those environments.

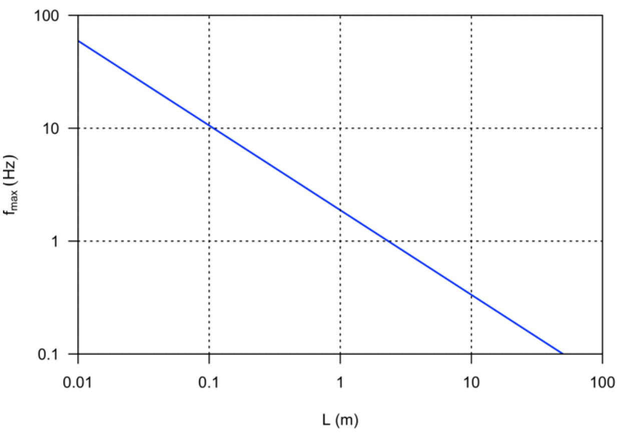

Figure 3. Maximum accessible fluctuation frequency for a given device response length.

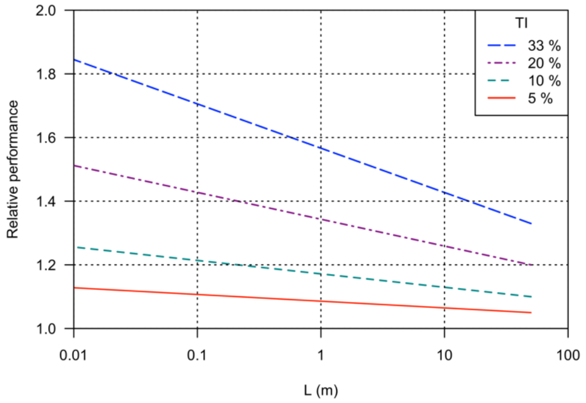

Figure 4. Performance enhancement potential against size for different turbulence intensities.

The environment is characterised by its typical turbulence intensity, where Figure 4 covers a typical offshore environment with a low turbulence intensity of around 5%, a typical turbulence intensity of around 10% commonly observed in locations suitable for large onshore wind farms, up to higher turbulence intensities of 20% and 33% observed in complex environments closer to the ground. Here, the enhancement is the possible AEP over and above that calculated by using the mean wind speed averaged over a 10-minute or hourly window.

The key message to be taken from Figure 4 is that there is little gain in trying to extract the additional turbulent energy in open sites with low turbulence intensities, where the available capture size is large to result in significant installed capacities. The argument holds that making turbines larger leads to economies of scale in both, financial terms and energy production. In highly turbulent environments, however, as in urban, sub-urban or industrial sites, the turbulence intensity however is significant and the energy lost from the mean wind to the turbulence could be accessible by devices of suitably small size coupled with a conversion technology and control system to capture the available turbulence spectrum commensurate with the size of the device.

4. Conclusion

This paper has presented a Morphological Analysis of the technology options to extract useful energy from the wind through the range of conversion technologies applied across the entire range of scales from energy harvesting micro devices to large offshore wind turbines. Combining knowledge of the power spectrum of the kinetic energy in the wind with scaling arguments for time scales and length scales of the associated velocity fluctuations and device responses, it has been possible to derive scaling estimates of the relative benefits of different device sizes for different environments. Associated with that, recommended device response times are found which can be used to tune the prime mover, limiting components in the conversion chain, or the control strategy of the device. Given that this analysis is based on physical principles as opposed to specific devices or device control methods, all the results have to be interpreted in this general framework but can, in further work, be refined to build a more complete model incorporating typical control mechanics.

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