Commercialization of a Diffuser Augmented Wind Turbine for Distributed Generation

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Abstract. Small-scale distributed wind generation faces challenges in being cost competitive due to recent advances in solar photovoltaic and battery storage technology. Reductions in levelized cost of energy (LCOE) can be achieved by improvements in aerodynamic efficiency, generator controller design, or reducing cost of manufacture. In this paper we present a case study detailing the commercialization of a novel 200 W high-efficiency diffuser augmented wind turbine (DAWT). Results include increased rotor efficiency, bespoke controller design, and the novel use of manufacturing processes. Findings and conclusions are of direct interest to small wind turbine designers as they seek to reduce LCOE.

1. Introduction
Small wind turbines are defined as having a rotor area less than 200 m² and power output less than 50 kW [1]. Turbines in this class are less technologically mature than utility scale wind turbine technology. They have been documented to suffer from poor realized power output, structural failures, and a higher LCOE [2, 3]. More recently, the significant reduction in cost of solar photovoltaic (PV) modules and battery storage systems has driven the need to reduce LCOE of small wind energy [4]. Small wind turbines typically need feed in tariffs (FIT) to become cost competitive [5]. Despite these challenges, small wind turbines still have a part to play in increasing the renewable penetration and reducing system cost of hybrid microgrids [6].

Aside from the use of FIT’s, one obvious way of reducing small wind turbine LCOE is by improving the system efficiency. This efficiency has a theoretical upper limit of 59.3%, also known as the Betz limit. Its derivation is covered in significant detail in [7]. Diffuser augmented wind turbines (DAWT) hold potential to increase power output and have been the subject of previous investigation [8]. In this embodiment, the performance of the turbine is augmented by the use of a cylindrical diffuser or shroud that surrounds the rotor plane of a horizontal axis wind turbine as per Figure 1. This cylindrical shroud usually has an airfoil shaped cross-section. The lift generated by the shroud increases the mass flow rate across the rotor plane and hence power coefficient. A DAWT with a given exit area can therefore generate more energy than an equivalent sized HAWT rotor.
Studies have revealed other advantages of DAWT’s including improved performance in turbulent conditions and lower susceptibility to a reduction in power output due to yaw-errors [9]. They are often quieter due to the diffuser’s suppression of the blade tip vortices and physical inhibition of sound wave propagation [8], and are safer as the blades are encapsulated in the event of failure or when placed in proximity to human interaction.

There has been renewed interest in the application of diffuser augmented wind turbines [10-12]. Recent focus has consisted of improving the design of the rotors with respect to the inlet wind profile at the rotor, optimizing the location of the rotor in the throat of the diffuser, and the interaction of the actuator disk within the DAWT. There exist published methods for optimizing the rotor design, where this usually involves the use of computational fluid dynamics (CFD). The need to reduce small wind turbine LCOE and the simultaneous reduction in cost of computing power has undoubtedly driven the renewed academic and commercial pursuit of DAWT’s.

Despite these performance gains, many designers have claimed to have exceeded the Betz limit. Often these claims are misleading as the rotor area of a DAWT is erroneously used in calculations that show an “exceedance of the Betz limit”, when in reality the larger exit area of the diffuser is the more correct metric. Commercial failures of DAWT’s such as the Vortec7 and Donqui most likely contribute to their bad public perception. Despite these failures, it is encouraging to see commercialization efforts undertaken by Ducted Turbine International and Wind Lens in developing their technological readiness level (TRL) towards a commercially viable product.

The study documented in this paper is aimed at reducing the LCOE of small wind generation by the use of an aerodynamically shaped diffuser to improve HAWT performance. A case study detailing the commercialization process will be presented and discussed. Commercialization of technology in any field is a challenging endeavor. The aim of this paper is to present a case study and add to the literature of shared experiences and “lessons learnt”. The authors’ intend that this manuscript would contribute to the commercialization effort of small wind technology, and thereby realize reductions in LCOE for small wind or hybrid distributed energy systems.
2. Methodology

2.1. Turbine design

The initial stage of turbine development is deciding on the rotor design and hence power output. Once these critical details are “locked in”, engineering effort can be applied to designing and developing the balance of the system, including; component sizing, material selection, and manufacturing techniques. This step is known as design for manufacture or DFM. Once DFM is complete, a bill of materials (BOM) can be produced which forms the basis of vendor selection for manufacturing said components.

Complicating the design further, there is also no specific guidance for shrouded or diffuser augmented wind turbines as per the small wind turbine design standard IEC 61400.2. This standard is exclusively limited to open bladed horizontal axis wind turbines. Despite this, a deft designer could appropriate this standard for initial determination of design loads. This lack of a relevant standard may lead to the bad market perception of small scale wind, extensive customer interviews by the authors’ revealing that noise, safety concerns (either real or perceived), and cost were major barriers to adoption.

In previous studies, a small 35 W DAWT ($U = 10.5 \text{ m/s}$) was designed using a CFD methodology. This wind turbine had a diameter of 430 mm, and was printed from PETG material. This 3D printed wind turbine then underwent aerodynamic testing in a wind tunnel at the University of Newcastle, Australia. The CFD design methodology was validated using data obtained from the wind tunnel measurements [13]. Sufficient confidence in the design methodology and diffuser augmentation has been developed by the authors to allow for scale to a larger design. Larger designs usually result in an increase in coefficient of performance due to the reduced effects of hub losses, etc. with respect to the total rotor area.

A 200 W DAWT ($C_p = 0.42, U = 10.5 \text{ m/s}$) has been developed as per previous work by the authors in [13]. This represents an appreciable improvement compared to existing market products such as the Rutland 914i (0.26), Superwind SW1250 (0.30), and the Leading Edge LE-300 (0.35). Despite the promising theoretical design, there is a significant gap between research and commercial application. This commercialization process is rarely discussed in the open literature. In Australia this landscape is changing with the creation of programs such as the CSIRO ON Program. This is Australia’s National Science and Technology Accelerator and is focused on driving and supporting the commercialization of publically funded research. The commercialization journey is extensive for any piece of technology and it is envisaged that this manuscript would serve as a case study with learnings applicable to others within academic organizations who wish to commercialize their research.

2.2. Manufacturing techniques and materials

Small wind turbines are constructed from a myriad of different materials and manufacturing techniques. Common materials include; fibreglass, carbon fibre, timber, sheet metal, and injection moulded polymers [14, 15]. All have various trade-offs in terms of stiffness, cost, and manufacturability. One other challenge is that lower production run of units is undertaken, which reduces the possibility of savings for high volume orders. This means that the amortisation of expensive capital items such as moulds are less favourable, thus increasing the overall LCOE.

The nature of the wind turbine blades and diffuser makes them challenging to produce. For example, both have a varying continuously smooth surface that tapers to a trailing edge. This surface is critical to the aerodynamic operation and therefore must be machined to a very high geometrical tolerance. The mass (and hence inertia) of the blades and diffuser are required to be kept to a minimum as the net mass has ramifications to the support structures, while a high rotor inertia has negative effects on starting performance and gyroscopic loadings. The blades are also subject to fatigue loading during operation, especially in turbulent wind resources [16-18]. They are known to be fatigue critical by design, experiencing up to $10^7$ cyclical loads during an expected life of 20 years; an order of magnitude more cycles than experienced by large scale wind turbines [19]. In summary, the blades and diffuser
have three main manufacturing requirements; high stiffness to mass ratio, accurate geometrical construction, and high resistance to fatigue loading.

The choice of material affects the manufacturing technique, and vice versa, so it is necessary to consider both the material choice and manufacturing method in parallel. While a model was 3D printed using a PETG material for testing, it was never intended as a material for manufacture in large quantities. The obvious starting point for the manufacture of the 400 mm long blades is the application of fibre reinforced polymer composites such as carbon fibre and fibreglass, as these are widely used in the construction of large wind turbine blades. Multiple vendors were approached both domestically and internationally, with the resulting quotation and unit costing being prohibitively expensive. CNC milling of hoop pine timber was also investigated due to its easy machining and fatigue resistance properties. While the initial stock was cheaper, the material wastage and mill cycle time is high. Milling fine geometric details such as the blade tip and trailing edge would also be challenging and prone to suffering from the effects of tool chatter.

The use of injection moulding was decided upon for the production of the blades as it satisfied the stiffness to mass ratio requirements, while being cost effective even at lower volume production runs. A mould was made in two halves by CNC milling incorporating the design of the sprue, runner, and ejector pins. The blade was constructed from a proprietary nylon/carbon fibre fill material, which is injectable for our dimensions in question. Post-injection, only a small amount of finishing work is required to remove the sprue and flashing from the parting lines (Figure 2). Due to the homogeneous nature of the material and tight geometric tolerance derived from this method, the blades require little to no effort for balancing.

![Figure 2. The completed mould (left), and resulting blade (right).](image)

The use of reinforced composite polymers for the diffuser was quickly abandoned due to the high cost. It is important that the cost of the diffuser does not offset the monetary gains of the increased
efficiency over a bare wind turbine. One factor that worked in our favor is that the diffuser was never designed nor intended to be a structural component (unlike the blades). These structural loads due to wind actions are supported by the cross members and centrebody of the wind turbine, they are then transmitted through the central yaw bearing and into the tower. After much investigation, the only viable manufacturing technique was rotational molding where a HDPE blend (in solid granular form) is placed into a cavity mold. This is then heated in an oven to melt the polymer stock and rotated on two axes to ensure an even and regular coating. Upon cooling, this is then released from the mold. Final finishing is then undertaken to remove any excess flashing (Figure 3).

![Figure 3. The diffuser mold (left), and the unfinished diffuser part (right).](image)

Compared to the blades and the diffuser, the other mechanical components such as the center body, cross supports, and yaw mechanism are trivial to design and manufacture. These were conducted at a local steel fabricators workshop from readily available stainless steel and aluminum stock. As such, these details will not be presented here and in any matter are likely to be of little interest to the reader.

### 2.3. Electrical and controller design

Creating an efficient electrical system complimentary to the turbine output is a difficult task that has plagued small wind manufacturers. Poor historical generator electrical controller design has had negative impact on small wind [6]. Permanent magnet generators (PMGs) are commonplace amongst most small-scale wind systems, due to recent reductions in cost and physical size but off-the-shelf components often don’t match turbine performance. For controlling the power output, in many cases, a simple solar PV module maximum power point tracking (MPPT) controller is used, instead of a wind turbine specific controller.

Despite the fact that an aerodynamically ideal rotor may be designed, the need for a suitably idealised generator and controller system is necessary to translate the aerodynamic efficiency gains into electrical power for the end user. This end-user can operate a wide array of power systems.

Small wind turbines typically do not have the means to measure the incoming wind speed, such as via ultrasonic anemometers or lidar systems. This would significantly increase the overall system cost, and adds an additional challenge to the control scheme. MPPT control methodology as it applies to small wind turbines is detailed in many references such as [20].

Small wind turbines often operate at lower voltages with comparatively higher currents which must be carefully considered in the electrical system design to avoid significant losses. Something as trivial as cable selection can have a significant impact on system performance. The effort required to
achieve a 5% gain in rotor performance can be immense, and is easily negated through improper selection, as shown in Figure 4.

![Figure 4](image_url)

**Figure 4.** Cable losses calculated for 200 W DAWT for a 25 m length.

### 2.4. Market applications

Currently small wind turbines face challenges in being cost competitive with incumbent sources of centralised energy generation (i.e. coal, gas, oil, and utility scale renewables). Designing a grid connected small wind turbine provides extra challenges both in the electrical control system and certification. While rotor optimisation is the topic of interest of most studies, designing and manufacturing a complete small wind system includes a number of components beyond the rotor design. Due engineering effort has to be undertaken in the design and manufacture of the tower, nacelle and yaw system, generator selection, electrical control, and grid connection. These sub-components can be expensive, for example the breakdown of a 5 kW HAWT and 200 W DAWT is given by:

| Component                  | 5 kW HAWT [19] | 200 W DAWT |
|----------------------------|----------------|------------|
| Blades                     | 7%             | 9%         |
| Diffuser                   | N/A            | 11%        |
| Platform, tail fin         | 5%             | 29%        |
| Gearbox, generator, brake  | 6%             | 11%        |
| Nose cone and cover        | 3%             | 3%         |
| Controller/inverter        | 18%            | 12%        |
| Tower                      | 32%            | N/A        |
| Installation and grid connection | 29%        | 34%        |
It can be seen from Table 1 that the two most expensive components of the 5 kW small wind system are the tower, installation, and grid connection. When considering the 200 W DAWT, the diffuser accounts for only 9% of the installed system cost. The nacelle platform and yaw mechanism is the highest percentage of the system, and is likely due to the high cost of “one-off” machining. Higher volumes would see this reduce in absolute terms. The lack of a tail fin also represents a cost saving.

The authors have taken a lean approach to hardware development, whereby superfluous system components are excluded from the design and manufacture phase. We have therefore solely targeted customers and applications that are not grid connected, and who already have an existing tower structure where the turbine could be mounted.

Market applications of small wind turbines in this instance would include: remote sites, monitoring stations, telecommunications, mining, agriculture, aquaculture, yachting, and off-grid dwellings. This DAWT is not intended for installation in residential sites in built-up urban areas.

2.5. Site installation

To field test our wind turbine in a commercial setting, we have undertaken a trial with an Australia-based remote telecommunications provider. Compounding the difficulties in the previously discussed controller and electrical system design, most telecommunication operators use 48 VDC systems for their towers. It is very difficult for a small wind generator to achieve the required voltages to charge the batteries in the system and a boost converter is therefore required. It has been challenging to source a suitable boost converter for this system, and may require a very significant further investment of time and money to develop one.

The authors’ note that due to the challenges of accessing remote locations, the control system should be as simple to install as possible. As access to the site is limited, installation should take place ideally as one body of work, without the need for additional visits. This field campaign is still ongoing, with future work to report a validated power curve.

An additional benefit of the diffuser is for safety and installation considerations - the diffuser provided a good lifting point for installation and provided an extra level of safety for the technicians who would have otherwise been working at heights in close proximity to exposed wind turbine blades (Figure 5). Conversely, the very rugged diffuser also protected the turbine blades from damage during the lifting and installation process.
2.6. Customer channels

The sale of utility scale wind turbines is classed as a complex or enterprise sale whereby many units are sold in a single high-value sales contract. These contracts may be negotiated over many months or years, as turbines of this scale are not sold by simple transactional sales. A small wind company faces the challenge of selling a product that is not usually purchased in bulk (i.e. a single unit is often sold), nor is it a simple transaction sale like smaller perishable or single use commodity items. Sales are often drawn-out if they involve wind resource siting. Most small wind sites are typically found by the “suck it and see” method in lieu of a detailed (and costly) wind resource assessment [21]. Small wind turbine purchasers may enter detailed discussion with the turbine supplier and a comparison can be made with competing small wind units by detailed system modelling, such as that offered by Homer Pro. This is indeed a time-consuming and costly process sales process, one which small wind manufacturers must take into due consideration.

Ideally a small wind turbine company would target higher value enterprise sales, whereby an order of many units could provide the capital to trigger a higher volume manufacturing order. Business to business (B2B) sales could eliminate the challenge of dealing directly with the customer, as retail customers often undertake extensive research on the purchase of even a single product. Nevertheless it is prudent for any small wind developer to have a well identified customer prior to the commencement of vendor selection.

3. Results and conclusions

There are several barriers to the adoption of small wind generation, including; poor historical performance, high LCOE, and safety and noise concerns. Diffuser augmented wind turbines hold potential in increasing power output and reducing LCOE. Several challenges have been identified in commercializing this technology:

**Figure 5.** Installation at a remote site.
Small wind turbines are a complex multidisciplinary system, involving: aerodynamics, electrical control, material science, manufacturing supply chains, and business operation knowledge.

Manufacturing supply chain issues due to high cost for low volume, exotic materials, and challenging manufacturing techniques.

Channels to market, including the balance between enterprise vs transactional sales, and the time-cost associated in making sales.

Niche market applications for small wind was identified in the following markets; remote monitoring sites, telecommunications, mining, and agriculture. A 200 W unit was designed, manufactured, installed and piloted at a customer’s remote telecommunications site.

4. Future work

Future work will be centered on performance assessment of the 200 W turbine in field conditions. Data logging is being undertaken on the site wind resource, turbine output power, and rotor rpm. These measurements are expected to form an experimentally validated power curve.

Ascertaining at what scale a DAWT is no longer commercially viable will provide future challenges. It is currently unknown at what rotor diameter (and hence power output) the physical structure of the diffuser would become untenable for field operation. The commercial failure of Vortec7 indicates that a 7 m DAWT is beyond the upper range of commercial viability. There is a trade-off between increased energy production and cost of materials, with this having an unknown impact on LCOE at larger scales.
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