Scooturbine: A Recycled Wind Generator Testing Report

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I. Introduction

Previous Scooterbine reports have presented a process for designing effective blades, and detailed the process of designing a nacelle, tower, gearing system, and electrical components.

Along with design work, a number of testing objectives were outlined. These objectives were not entirely achievable within this ENGR440 project, as there were some unexpected barriers to getting the system generating energy. This report discusses the issues faced with rotor cut-in speed and the approaches taken to improve startup torque generated by the rotor. A number of modified testing goals are presented, focussing on analysis of cut-in speed and the impact of gear configuration, analysis of the three phase rectifier, and finally the development of power curves for varying output loads.

II. Preliminary Testing & New Testing Goals

A. Original Testing Goals

Previous work has laid out the following testing goals:

- Test a range of gear ratios, and determine optimal gear ratio for acceptable cut in speed and high operational generator RPM.
- Generate a power curve for two different blade profiles (A18 and SD7032).
- Characterise the behaviour of the developed three phase rectifier.
- Analyse how load on the rectifier output impacts the power curve of the turbine.

B. Rescoping

Preliminary testing of the SD7032 rotor has indicated the rotor is capable of reaching 700RPM in relatively low wind speeds. However, with the generator connected to the rotor the system does not cut-in until 4.5m/s.

This is non ideal, as it results in a significant amount of unusable wind energy in the chosen location. Figure 1 makes this clear, with one quarter of the wind received in the desired location at or below 4.5m/s. This distribution indicates that if a cut-in speed of between 2m/s and 3m/s could be obtained, approximately 85% of the available wind would be harnessed by the turbine.

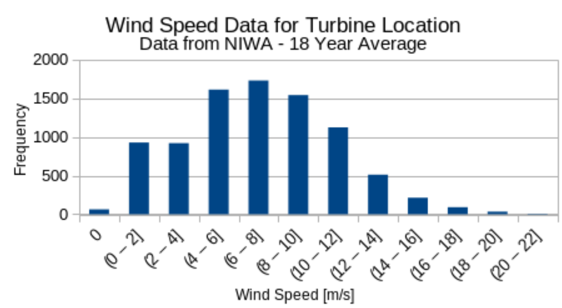


Fig. 1: Windspeed distribution curve, from 18 year NIWA data [1]. Figure reproduced from Blade Design report.

If the rotor is started manually in lower windspeeds (around 3m/s), then it is capable of reaching full operational speed with the generator attached. Therefore the biggest issue in the system is the torque required to start the generator, once the rotor overcomes this it can reach the designed tip speed ratio.

Literature discussing the startup behaviour of small wind turbines suggests that widening the root section of the blades provides higher torque when starting the rotor [2].

It was decided that testing would pivot to focus on the impact of blade design on rotor cut-in speed. This is due to the fact that the original testing plans could not be properly executed without manually starting the turbine, which could lead to inaccurate data.

C. Modified Testing Goals

With testing now based around the implementation of a new rotor design, a new set of goals was developed. These goals are as follows:

- Analyse the cut in speed for a new rotor design, compare this cut-in speed to the original rotor design. Perform this analysis for a range of gear ratios, to determine an optimal sprocket combination for turbine operation.
- Provide some characterisation of the generator. Ideally this would be done by connection to an external motor, however time does not permit this, and alternative methods will be designed.
- Analyse the developed three phase rectifier. Determine how clean the output is while the turbine is operational.
- For an optimal gear ratio, determine the impact of load on power output of the turbine. This will involve developing a power curve for two different loads.

III. Blade Iteration

In order to ensure that the turbine cuts in for reasonably low windspeeds, a new rotor was developed to provide more startup torque. It was identified that the root section is responsible for the starting torque for the rotor, and therefore methods of increasing torque from this section of the rotor were analysed [2].

Firstly, it has been identified that a reduction in tip speed ratio (TSR) will result in a wider blade. During the blade design process, rotor solidity was identified as an important aspect of a rotor. As TSR is reduced, required solidity increases. Therefore, a lower TSR necessitates wider blades.

Identifying an ideal TSR is difficult, and there does not seem to be consensus on an ideal value. Most sources propose that a TSR between 6 and 9 is ideal for three bladed turbines [3]. However, other sources provide equations suggesting that a TSR of 4.2 is ideal for three bladed rotors [4].

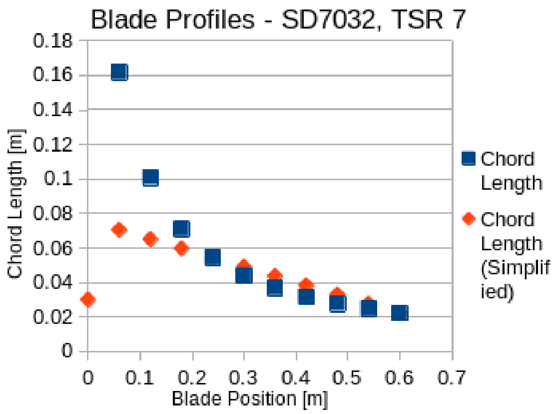
This TSR was used to develop a blade profile via the method outlined in the blade design report. Simulations were run in QBlade to determine an approximate Reynolds number. With this, the developed blade generation spreadsheet was given the optimal lift coefficient, optimal angle of attack, and the new TSR. This spreadsheet indicated that a TSR of 4.2 would produce a blade that is too wide and bulky. Simulations and calculations were then performed for a TSR of 5, which provided a blade that did not use too much material while still providing a significantly larger root section. It is also worth noting that reduction of the TSR to this value is not likely to have an impact on the maximum power coefficient, reducing it from 0.58 to 0.57 [5].

Alongside the TSR reduction, the chord profile was reconsidered. previously a linear simplification of the blade shape was utilised, in order to reduce material usage. However, this simplification is linear, and shifts a lot of material from the root section to the middle of the blade, which ultimately reduces the startup torque generated.

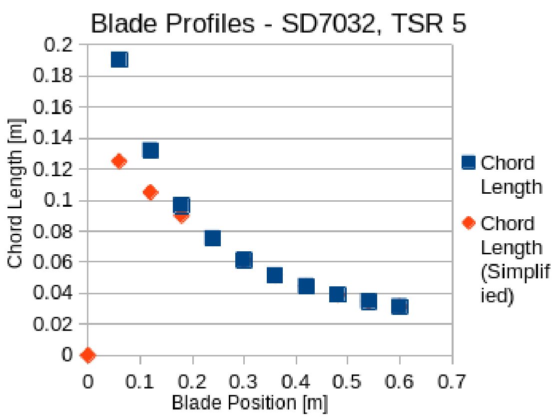
This is highlighted in Figure 3. Figure 2a shows the SD7032 profile that was generated for the initial rotor. The simplification here linearised the profile equation, and it is clear that beyond the 0.2m point the simplification has wider chord length than required, while below this point the chord length is significantly smaller than desirable.

Figure 2b shows the new blade profile. In the mid-section and tip of the blade the profile equation is adhered to. This results in narrow chord widths for most of the blade, reducing material usage. In the root section the chord lengths given by the equation are too large to realistically fabricate, and therefore have been simplified. However, this simplification ensures that the root section remains wide, and follows the general trend of the rest of the blade. This cuts down material usage while ensuring the root section is large enough to provide significant torque while starting up.

This new rotor was modelled in OnShape, and compared to the previous design. Figure 3 compares these two rotors. Figure 3a shows the original rotor, with very narrow linear blades. Figure 3b shows the new rotor design, with a much more pronounced root



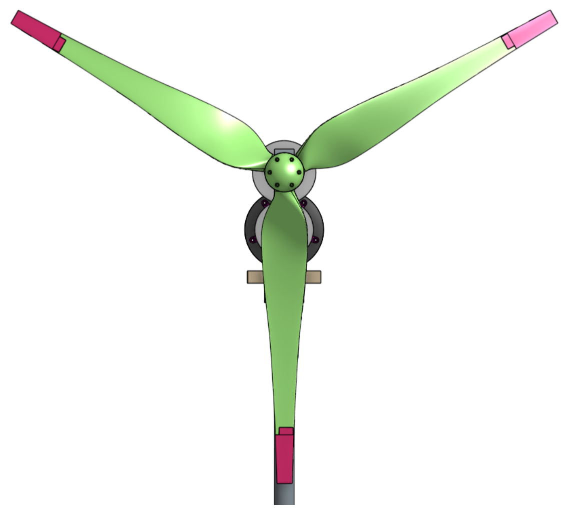
(a) Original SD7032 blade profile, with TSR = 7 and heavy profile simplification.



(b) New SD7032 blade profile, with TSR = 5 and less blade profile simplification.

Fig. 2: Comparison of old and new blade profile designs.

(a) Old SD7032 rotor design. Note the narrow root section.



(b) New SD7032 rotor design. TSR reduced to 5, and root section widened.

Fig. 3: Comparison of old and new rotor designs.

section, and a less linear shape.

Finally, it is worth noting that a lower TSR will reduce the operational rotor velocity. Provided the generator can still be operated at an RPM high enough to have a high efficiency, this is desirable as it makes the unit less prone to stress related failure.

Testing will identify the cut in speed of this rotor with the same low gear ratio that was implemented on the previous iteration of the rotor. This will allow an insight into how effectively the new rotor improves the startup torque.

IV. Cut-in Speed Analysis

With a new rotor printed, it was important to determine whether these new blades resulted in an acceptable cut in speed. This parameter is critical, as it effectively determines the minimum windspeed that the turbine will harness energy from. This analysis had the following objectives:

- Determine cut-in speed with a sprocket ratio of 0.44 (15T/34T), and compare this to the cut-in speed of the original rotor with the same ratio.

This will quantify whether this rotor provides better performance.
- Determine an optimal sprocket combination for use during turbine operation. This combination will cut in between 2m/s and 3m/s, harnessing approximately 85% of the available wind.

A. Method

Due to the need to make a custom length of chain for each sprocket combination, only three combinations were analysed. The first combination was the 15T/34T giving a ratio of 0.44. This is the combination that was utilised with the original SD7032 rotor, giving a best case cut in speed of 4.5m/s.

It was also desirable to analyse a lower gear ratio, and an 11 tooth sprocket was obtained. With this, the second combination analysed was 11T/34T. This gave a ratio of 0.32, which was designed to give the lowest cut in speed possible.

Finally, previous design work has presented 500RPM as an approximation of the ideal velocity for the generator. The final sprocket combination analysed was designed to result in this velocity. In order to do this, equations from the previous report were utilised to determine the nominal operational speed of the new rotor, with a TSR of 5. This process indicated a rotor speed of 520 RPM.

In order to reduce 520 RPM to 500 RPM, a gear ratio of $500/520 = 0.96$ was required. Referring to the gear table in Figure 4, the closest available ratio is 0.91, with a sprocket combination of 21T/23T.

Therefore, chains were made for the following sprocket combinations:

- 11T/34T (0.32 ratio)
- 15T/34T (0.44 ratio)
- 21T/23T (0.91 ratio)

Testing was performed by configuring the turbine with a sprocket set, and installing the nacelle to the tower. Windspeed was measured as the rotor cut-in, and then the rotor was stalled. Measurement of the windspeed required to start the rotor from a stationary position was noted five times for each sprocket combination. This provided an estimate of the average cut-in speed for each combination.

		Driven Gear Teeth [n_g]								
		11	15	17	19	21	23	25	30	34
Drive Gear Teeth [n_d]	11		0.73	0.65	0.58	0.52	0.48	0.44	0.37	0.32
	15	1.36		0.88	0.79	0.71	0.65	0.60	0.50	0.44
	17	1.55	1.13		0.89	0.81	0.74	0.68	0.57	0.50
	19	1.73	1.27	1.12		0.90	0.83	0.76	0.63	0.56
	21	1.91	1.40	1.24	1.11		0.91	0.84	0.70	0.62
	23	2.09	1.53	1.35	1.21	1.10		0.92	0.77	0.68
	25	2.27	1.67	1.47	1.32	1.19	1.09		0.83	0.74
	30	2.73	2.00	1.76	1.58	1.43	1.30	1.20		0.88
	34	3.09	2.27	2.00	1.79	1.62	1.48	1.36	1.13	

Fig. 4: Gear combination grid. Shows gear ratio n_d/n_g for each possible sprocket combination. This is an updated version of the table presented in the previous report.

Cut-In Speed [m/s]	Gear Ratio		
	0.33	0.44	0.91
Trial 1	2.4	2.8	3.6
Trial 2	2.4	2.4	3.5
Trial 3	1.8	2.7	3.4
Trial 4	1.9	2.8	3.5
Trial 5	2	2.5	3.5
Average	2.1	2.64	3.5

Fig. 5: Results of gear ratio cut-in testing.

B. Results & Discussion

Figure 5 shows the results of these tests. As expected, a higher gear ratio results in a higher cut-in speed. Both the 0.33 and 0.44 sprocket ratios had an average cut-in speed below 3m/s, and the 0.91 ratio had a cut in speed above 3m/s.

On of the most interesting points that this data highlights is the fact that the new rotor provides much more desirable behaviour. For the previous rotor, a ratio of 0.71 was utilised in order to achieve 500RPM on the motor when the rotor has reached its operational speed. With this new rotor, the same calculations have shown that a ratio of 0.91 provides the same functionality, operating the motor at 500RPM. Cut-in speed for the previous rotor with a 0.71 ratio was found to be 4.5m/s. With the new rotor and a 0.91 ratio, average cut-in speed for the same operational generator speed is reduced to 3.5m/s. This is positive, and suggests that the new blade design has substantially increased the startup torque.

In terms of selecting a suitable sprocket combination for the turbine during operation, it comes down to local wind behaviour. If the data from NIWA is to be utilised, then either a 0.33 or 0.44 ratio is likely ideal. At these ratios, cut-in speed is below the specified 3m/s maximum. This ensures that the turbine harnesses 85% of the available wind.

However, at these lower ratios the generator is operating at a lower speed. Generator output is almost certainly lower than the potential maximum while operating at such a low RPM [6, 7]. Utilising a higher sprocket ratio results in a higher operational generator RPM, which is likely to harness wind energy more efficiently.

For the remainder of the system testing procedures, the 0.33 ratio will be utilised. Weather forecasts for the available testing period indicated low winds, and therefore it was important that the system cut in at the lowest speed it possibly could. Without this, testing may have required standing outside under the turbine for hours waiting for gusts large enough to start the generator.

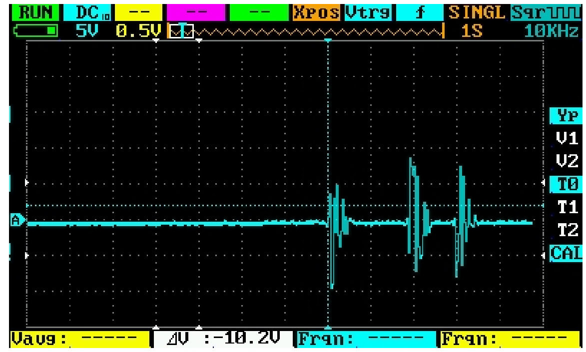
V. Generator & Three Phase Rectifier Testing

Before attempting to generate power curves for the turbine, it was important to ensure that the generator would output an acceptable voltage level and the rectifier would reliably convert this to a DC output. With these two aspects of the system functional, the rectifier output can be placed across a known load and voltage can be used to determine power output.

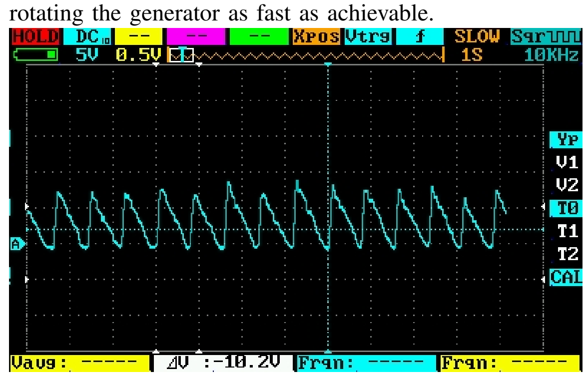
A. Method

In order to test the generator output levels a reading was taken of line voltage while the rotor was manually spun up. This was expected to lead to a short voltage pulse, which can be used to determine an approximate voltage level to expect while operating.

The three phase output was then connected to the rectifier unit, and the same manual cranking mechanism was utilised to generate voltage pulses into the rectifier. This testing was not expected to give any indication on output power capacity, and merely intended to produce an initial idea of what can be expected from the generator.



(a) Raw generator output. Pulses generated by manually rotating the generator as fast as achievable.



(b) Output from rectifier with the pulses generated with the same method as above.

Fig. 6: Generator output indicator tests.

B. Results & Discussion

Figure 6 shows the results of this testing. Figure 6a shows line voltage as the generator is manually rotated. Figure 6b shows the result of putting these pulses through the rectifier. It is clear from the rectifier output that these pulses are effectively converted to a DC output, and that an output of approximately 10V is obtained. Generator RPM was not measured

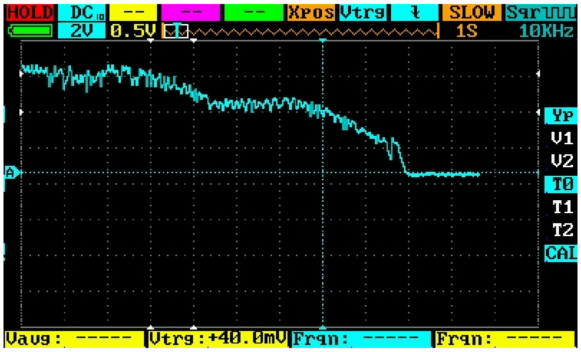


Fig. 7: Rectifier output with an active generator. Voltage reaches a maximum of 5.8V.

during this testing, and therefore there is no indication as to whether this voltage output is what should be expected during operation, or whether it is a low value.

Further testing on the rectifier was performed by looking at the output signal while the generator was operational. Figure 7 shows this output. The three phase signal has successfully been converted to a DC output, showing the generator capable of reaching a 5.8V output in high windspeeds.

VI. Load Impact Analysis

This testing aimed to determine the impact that output load has on generator power output. Currently the turbine utilises a fixed load on the output of the three phase rectifier. However future development on the system will aim to implement a maximum power point tracking (MPPT) device. This system will vary the load in order to achieve maximum power output for a given wind speed.

Analysis of how load impacts power output and potentially cut in speed is crucial for understanding how an MPPT charge controller should be implemented.

A. Method

Two loads were obtained, and the goal was to generate a power curve for each load. No automatic logging hardware was available for the project, and therefore the data had to be manually collected.

This was performed by attaching the load to the output of the three phase rectifier. DC voltage was measured across this load, and windspeed was collected with a handheld anemometer. Video was captured with these two devices visible while the turbine was operational. This video was then analysed, and a power vs windspeed curve was constructed based on these measurements. Two loads were utilised, a 10Ω and 100Ω load.

With data collected manually, these power curves were not expected to be incredibly accurate, or even necessarily represent a wide range of windspeeds. Standing in the wind is cold, and waiting for a period of high wind can be time consuming. Additionally, wind speeds were predicted to be relatively low during the testing period, which was likely to make collecting data at the higher end of the power curve difficult.

B. Results

Figure 8 shows power curves for two different loads. Windspeeds during the testing period did not exceed about 4m/s, and therefore this data only represents the low end of the power curve.

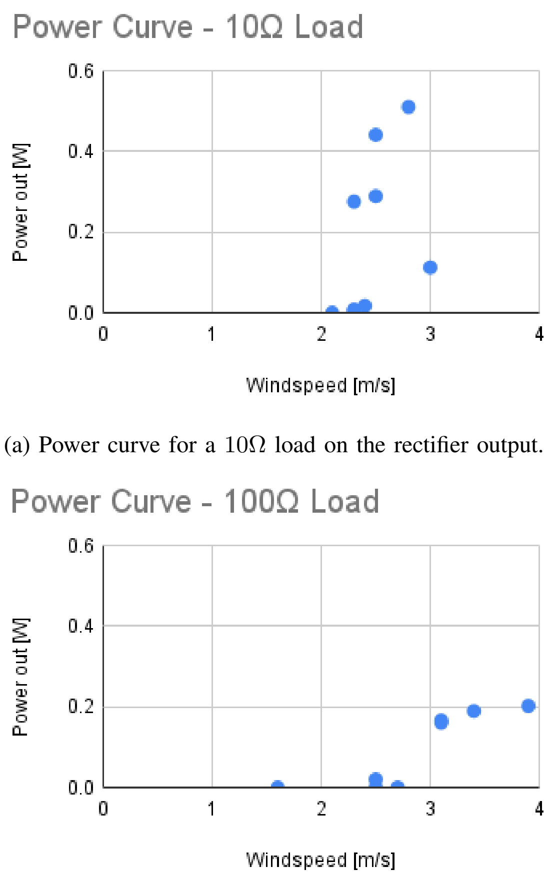
Figure 8a shows the behaviour with a 10Ω load on the rectifier. This data shows a cut in at around 2m/s, which was expected based on the previous testing on cut-in speeds. Power output is seen to reach 0.5 watts at approximately 3m/s.

Figure 8b shows power output with a 100Ω load. This curve appears to cut in at a slightly higher windspeed, however there is not enough data to make this claim conclusively. It is also apparent that the power output is lower for the larger load, only reaching 0.2 watts in a 4m/s wind.

This testing suggests that a larger load results in lower power output at the lower end of the power curve. In order to draw conclusions on the wider impacts of output load, testing would need to be performed across the entire range of potential windspeeds.

VII. Conclusions & Future Work

This report has detailed the process of initial testing on the Scooterbine wind generator. This testing is



(a) Power curve for a 10Ω load on the rectifier output.

(b) Power curve for a 100Ω load on the rectifier output.

Fig. 8: Power curves for two different loads on the rectifier output. 10Ω and 100Ω loads have been utilised.

the final stage of this ENGR440 project, however represents the first iteration of the Scooterbine. Initially testing was intended to analyse the impact of different blade profiles. However due to the original blade design not providing a high starting torque, the testing was re-scoped to focus on how TSR and blade profile impact the cut-in speed of the generator.

Rotor blades have been designed with a TSR of 5, a blade profile that puts emphasis on the root section of each blade, and an SD7032 profile. Testing has been performed on both the original SD7032 rotor with a TSR of 7 and the new design, analysing the cut-in speed when the power transmission is configured to operate the generator at 500RPM. This has identified that the revised design provides higher starting torque, and therefore a lower cut-in speed.

Testing was also performed to determine how varying loads impact the power output of the turbine. Windspeeds during this testing were low, and as a result the testing was really only indicative of behaviour at the low end of the power curve.

Power generated by the current prototype is very low, with testing not producing power greater than 1 watt. Output did tend to increase with higher gear ratios, however this also lead to a higher cut-in speed. It is likely that this low power output could be improved by operating the generator at a higher RPM, which is not very practically obtainable. Alternatively, a different generator could be utilised. This could be an alternative recycled motor, or the magnets and copper could be stripped from the Uber motors and a custom generator could be wound to generate optimally in the chosen location.

Ultimately, the developed turbine system acts as a proof of concept. The rotor that has been developed is incredibly effective, with blades effectively spinning the rotor up to desired speeds. However, the generator has posed a larger challenge than anticipated. Future work on this project will address the generator and investigate where the inefficiencies in the current set up lie.

Finally, it is worth noting the impact that lockdown during the trimester had on the project. Initially there were plans to characterise the generator by connecting it to a motor in the renewable energy lab on campus, and generate a power output vs RPM plot. This would have assisted in identifying an optimal gear ratio setup, and potentially indicated that the motor being used is not suitable for this purpose. Additionally, the lockdown had an impact on 3D printing material, prolonging blade fabrication processes.

A. Future Work

This testing concludes this ENGR440 project. However, this ENGR440 work is a small part of a larger project, and therefore lessons from this work will be critical in directing further work on the Scooterbine.

One of the most apparent issues that this testing highlights is how difficult it can be to develop a high resolution power curve. Testing presented in this report managed to collect some data on power output vs windspeed, however data collected did not exceed 4m/s windspeeds. As a result, the power curves presented barely represent the behaviour of the turbine.

Data collection was low resolution due to the time consuming nature of waiting for wind gusts large enough to provide the necessary data, which was exacerbated by the lack of high windspeeds during the testing period. This made it clear that manual data collection was not a suitable approach for obtaining insights into turbine behaviour. A better approach to testing turbine parameters would be to implement an automatic data collection system, and leave the system running over the course of a week. This automatic data logging unit would need to include an anemometer, a wind vane, and a method of measuring voltage across the output load.

This was considered in the very early stages of the Scooterbine, and development work was done on a solar powered anemometer capable of logging wind speed and direction measurements to a database over a network connection. This anemometer development was held up by component delays, and was not continued as part of this ENGR440 project. Expansion of this system to collect output power data would be incredibly valuable, and allow for high accuracy output power data to be collected over the span of weeks. Additionally, it would be ideal to integrate the generator encoder to this system. This would allow for analysis of the RPM that has actually been achieved by the generator while in operation.

Future work will develop this data collection unit further. With this, testing of each of the gear ratios and the output loads will be performed across an entire week, and data collated into a high resolution power curve.

Along with the low resolution power curves, the data used for windspeed is not incredibly accurate. It was collected from a NIWA database, and is a collation of data from a range of local weather stations [1]. With the Scooterbine installed against a north-facing wall of the house, it will not generate power for all winds in the are, especially not southerly winds.

Installation of a data collection unit will allow a very localised model of windspeeds to be developed, providing insights into average windspeed and wind direction. This data will allow for further optimisation of the turbine system. For example, if the model generated by this data logger shows a Weibull distribution with more right skew than the one from NIWA it will be important to minimise the cut-in speed of the turbine even further. As discussed in this report, this may necessitate a TSR or potentially even more than three blades. Implementing either of these adaptations would increase start up torque, and as a result reduce the cut-in speed.

Another major issue that has been identified by this testing is the low output power of the generator. Even with momentary strong winds, the generator was never observed to output more than 2 watts. Generator output increases with RPM, and as such it is proposed that operating the generator at a higher speed would improve the generation capacity of the system.

It is unknown what the optimal generator RPM is for these specific motors. There were plans to connect the scooter motor to an external motor and generate a power output vs RPM curve, however as discussed lockdown made this unachievable. This project has made it clear that having this model of generator behaviour is critical for optimising generator output, and future work will perform this testing to identify an optimal operational RPM.

It is likely that this analysis will identify that the generator is only suitable at an RPM higher than the 500RPM utilised in this initial design. Results in this report have shown that even operating the generator at 500RPM can be difficult, especially if low windspeed operation is required.

Combining this model of the generator with the environmental model developed by the data logging unit will provide strong insights into how effective these scooter motors are for the chosen location. There is a possible outcome where the generator is only suitable at high RPMs above 500RPM, while the local windspeeds tend to be lower than the NIWA model. If this is the case, then these motors are certainly not suitable for this application.

Based on this initial prototype, it appears likely that this will be the conclusion. With this in mind, there are a number of potential solutions. Firstly, the generator could be swapped with another recycled motor.

Since this project began, a number of recycled motors have been obtained. Given that a test rig is to be assembled for characterising the scooter motors it will be possible to characterise these alternative motors at the same time. These models could be combined with the environment model, hopefully identifying a more suitable generator unit.

Alternatively, copper wires and permanent magnets could be removed from the scooter motors and used to design a custom generator. This would require a significant amount of design work, however would provide a generator that is designed to operate most effectively at the natural RPM of the rotor, removing the need for a gear train entirely. Additionally, using a scooter motor as the generator means there is a large amount of excess metal on the rotor, as it needs to function as a wheel. Design and fabrication of a custom generator using recycled materials from the scooter motors would allow for a significantly lighter rotor, reducing required starting torque.

Additionally, further work is to be done on the electrical aspects of the system. Currently there is a very simple implementation, with a rectifier connected directly to a static load. In order to maximise turbine output most systems implement some form of maximum power point tracker, which acts to vary the load on the turbine to ensure it operates as efficiently as possible. It will also be important to develop a system for taking energy from the turbine and storing it in a battery system, as the wind can be very gusty in the installation location.

Finally, further work will look at the capacity factor and coefficient of power (C_p) for the overall system. Capacity factor of a turbine is represented as the ratio between average power output and rated power output, and is utilised as a quick measure of how much power a turbine tends to output over a given period of time. Coefficient of power is a measure of efficiency, representing what percentage of the available wind energy is converted to electrical energy by the device. This value will not be greater than 0.593, as specified by the Betz limit [5]. However, the value is likely to be much lower. This value is generally within a range of $0.46 - 0.48$ for good turbines [6]. These values will be obtained after all of the previously discussed work is implemented, and will be utilised as a benchmark of the effectiveness of the next prototype.

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