POWER GENERATED BY **TOSHIBA** MOTOR CONVERSION

LATHE TEST DATA

Toshi was performance tested under battery charging load on 25 January, 2009. The lathe provided input power to the shaft at variable speeds, while the case was restrained by a torque beam assembly. Rotor speed and the corresponding Input and Output power data was collected.

Test data from the 48V Parallel Star Connection

ω_{T_n} :=	P_OUT_n :=	P_IN_n :=	EF_n :=
165·RPM	2·W	25·W	10·%
176·RPM	133·W	187·W	71·%
234·RPM	537·W	797·W	67·%
312·RPM	935·W	2259·W	41·%
413·RPM	1112·W	4376·W	25·%
539·RPM	1358·W	6715·W	20·%

The data is fit to smooth curve functions to be used below.

$$P_{out}(\omega) := \text{linfit}\left(\frac{\omega_T}{RPM}, \frac{P\_OUT}{W}, F\right) \cdot F\left(\frac{\omega}{RPM}\right) \cdot (\text{watt})$$

Output Power
(fit to data with an inverse logarithm function)

$$P_{in}(\omega) := \text{linfit}\left(\frac{\omega_T}{RPM}, \frac{P\_IN}{W}, G\right) \cdot G\left(\frac{\omega}{RPM}\right) \cdot (\text{watt})$$

Input Power
(fit to data with a 4th order function)

$$\text{Eff}(\omega) := \frac{P_{out}(\omega)}{P_{in}(\omega)}$$

Efficiency of conversion on Input Power into Output Power.

The original test speeds are input into the curve fit functions to see how close they are.

$\frac{\omega_{T_n}}{RPM}$ =	$\frac{P_{out}(\omega_{T_n})}{W}$ =	$\frac{P_{in}(\omega_{T_n})}{W}$ =	$\frac{\text{Eff}(\omega_{T_n})}{\%}$ =
165	4	62	7
176	121	136	89
234	567	819	69
312	900	2248	40
413	1130	4379	26
539	1355	6715	20

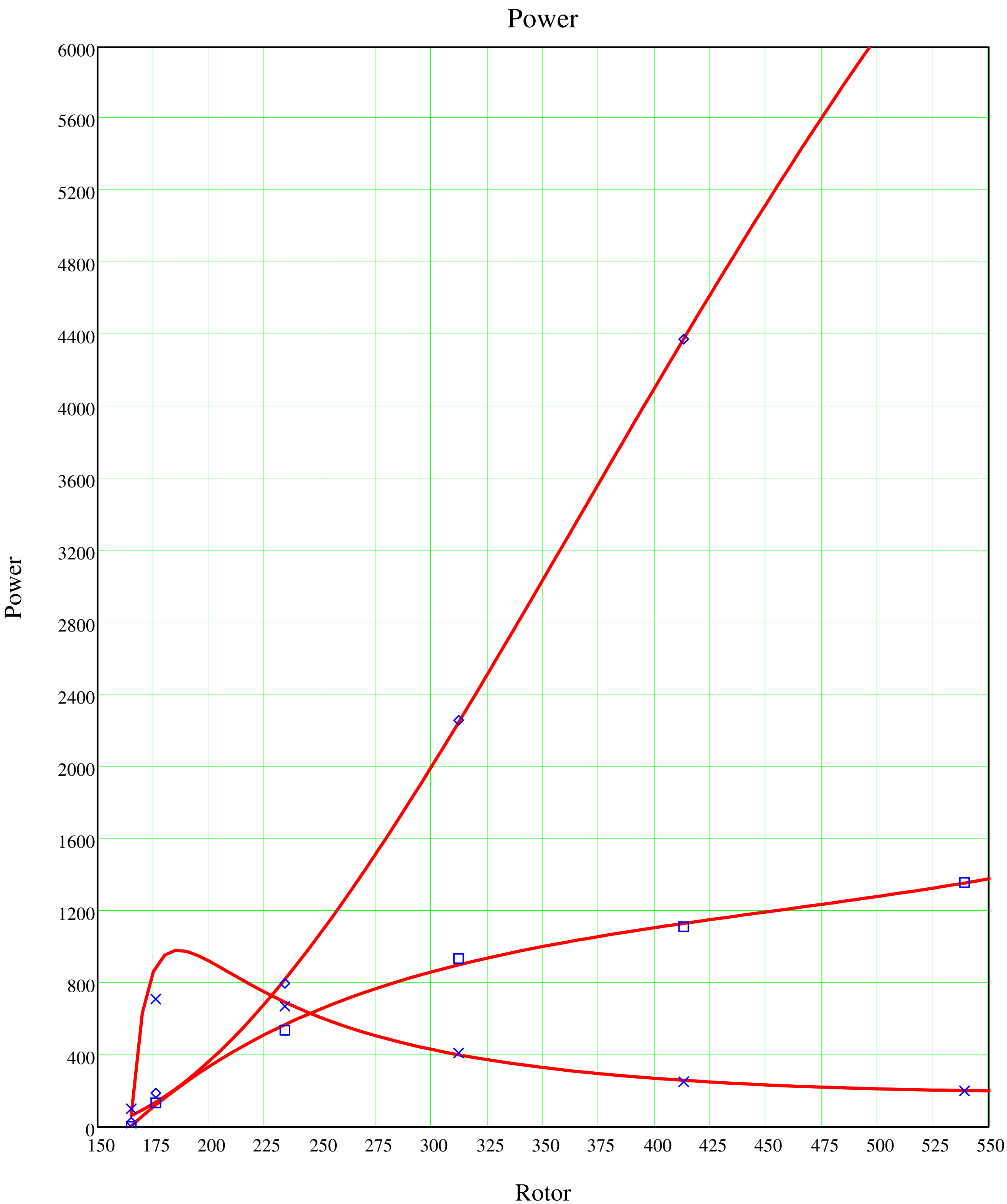
Or, an arbitrary test speed can be selected: $\omega_i := 200 \cdot RPM$

...and the corresponding value of output power can be estimated: $P_{out}(\omega_i) = 335\,W$

...and the Input Power: $P_{in}(\omega_i) = 364\,W$

...and the Efficiency: $\text{Eff}(\omega_i) = 92\,\%$

The data also demonstrate the cutin speed. $\omega_{CUTIN} := 165 \cdot RPM$



Power
6000
5600
5200
4800
4400
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
Power
150
175
200
225
250
275
300
325
350
375
400
425
450
475
500
525
550
Rotor

MATCHING PROPELLER TO THE POWER DATA.

In the wind turbine, it is the propeller blades that supply the Input Power to the generator. Using the input power required to turn the generator from the tests, various sizes and parameters of propeller can be compared to find a combination that fits.

$R \equiv 5.0 \cdot ft$ — Rotor Blade Radius.

$X_o := 5$ — Rotor's design Tip Speed Ratio (varies with load)

$X = \frac{\omega \cdot R}{V_w}$ — Definition of Tip Speed Ratio

$V_w(\omega, X) := \frac{\omega \cdot R}{X}$ — Expression of wind speed as a factor of both RPM and actual TSR. This is useful because now the appropriate wind speed can be found for any given RPM and assumed TSR.

Eg. if: $\omega_i = 200\,RPM$

and: $X := 9$

then: $V_w(\omega_i, X) = 3.5\,\frac{m}{sec}$ $\quad V_w(\omega_{CUTIN}, X_o) = 5.3\,\frac{m}{sec}$

$cutin := 3.5 \cdot \frac{m}{s}$ — Target Cut-In speed (wind speed where the mill starts producing power).

$(cutin) = 13\,kph$

$furl := 15 \cdot \frac{m}{s}$ — Target Furling speed (wind speed where the tail folds to protect the mill).

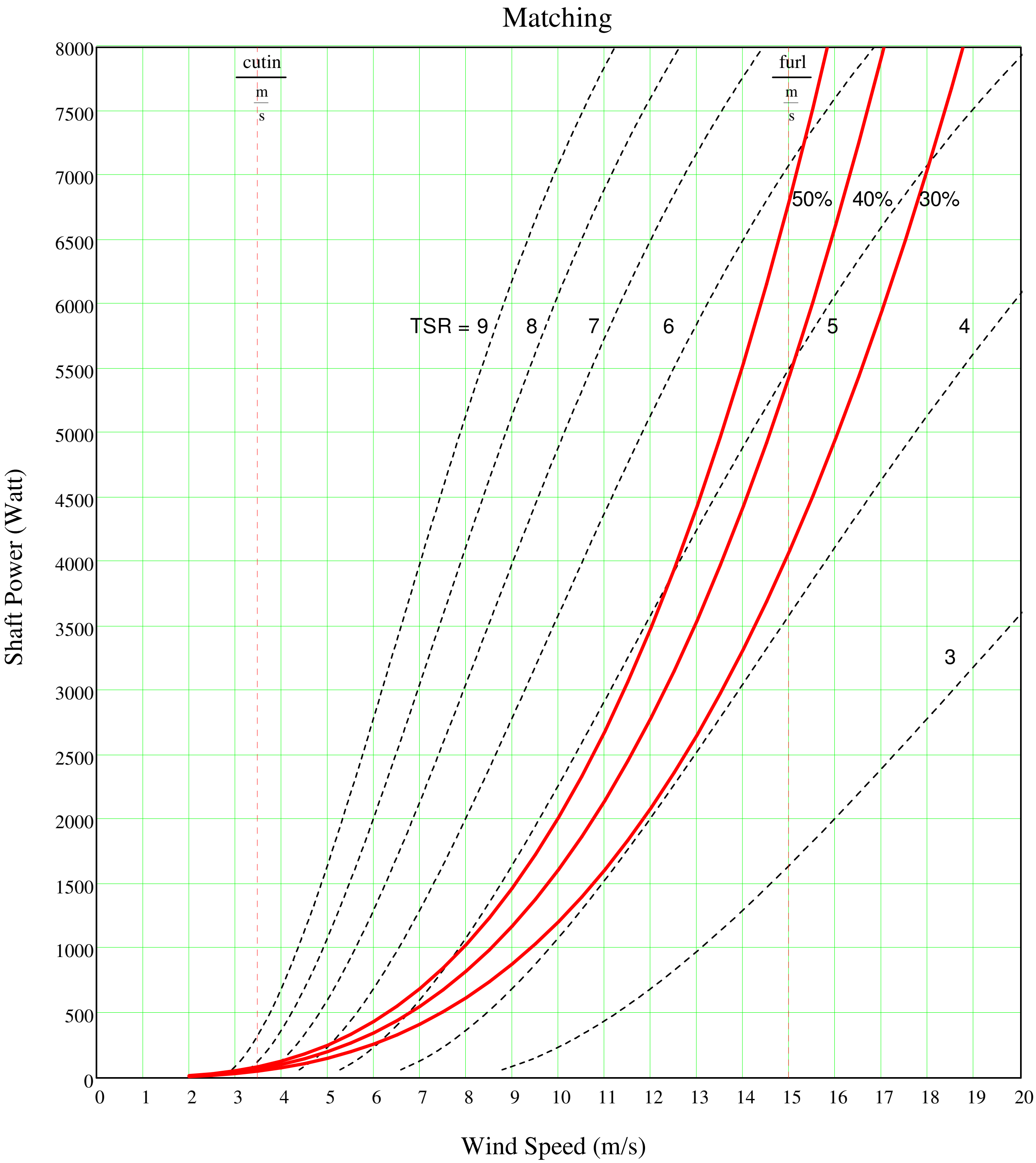
$(furl) = 54\,kph$

$C_p := 50 \cdot \%$ — Target Power Coefficient (usually only achieved at design speed)

$P_w(V_w) := \frac{\rho_{calgary}}{2} \cdot (V_w^{\,3}) \cdot (\pi \cdot R^2)$ — Power available in the wind (without including factor for power capture or the Betz limit). This function multiplied by different factors for the power captured by the prop gives curves that can be plotted below and compared to the generator's curve.

where $\rho_{calgary} = 1.11\,\frac{kg}{m^3}$

Three curves are plotted for Cp = 50%
40%
30%


Matching
Shaft Power (Watt)
Wind Speed (m/s)
cutin
m/s
furl
m/s
TSR = 9
8
7
6
5
4
3
50%
40%
30%
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20

The cut-in wind speed target is $cutin = 3.5\frac{m}{s}$ For this to work, the input energy must be available at that wind speed, to create both the required torque and RPM to match the load that the generator requires. In Parallel-Star, the cut-in speed was approximately 160 RPM. For this speed, in a wind of $cutin = 3.5\frac{m}{s}$, then we can quickly show that the cut-in TSR is:

$\omega_{CUTIN} = 165\,RPM$ The data also demonstrate the cutin speed.

$x_{cut\_in} := \frac{\omega_{CUTIN} \cdot R}{cutin}$ The TSR at cut-in is greater than the design TSR, showing that the blade will not start "in stall". $x_{cut\_in} = 7.5$

Show that the input and output energy can balance out at cutin speed and varying conditions. Applying several assumed values of Cp, we can show that the prop is able to start the generator no matter what conditions prevail (smooth air or rough, ice build-up or clean surfaces) that affect the Cp.

$P_w(cutin)\cdot(50\cdot\%) = 87\,W$ $P_{in}(\omega_{CUTIN}) = 62\,W$ $X_{cutin} := \frac{\omega_{CUTIN} \cdot R}{cutin}$ $X_{cutin} = 7.5$

$P_w(cutin)\cdot(30\cdot\%) = 52\,W$ $P_{in}(\omega_{CUTIN}) = 62\,W$ $X_{cutin} := \frac{\omega_{CUTIN} \cdot R}{cutin}$ $X_{cutin} = 7.5$

Each of the cases considered shows that the cut-in wind speed will provide more rotor speed than necessary to start generating electricity in the generator. One last check of the raw torque required under these conditions:

$\frac{P_w(cutin)\cdot(50\cdot\%)}{\omega_{CUTIN}} = 44\,in\cdot Lb$ $\frac{P_{in}(\omega_{CUTIN})}{\omega_{CUTIN}} = 32\,in\cdot Lb$

By comparing this required torque value with the values measured during the tests, this checks out correctly, and is confirmed to be enough torque at the prop to start the generator.

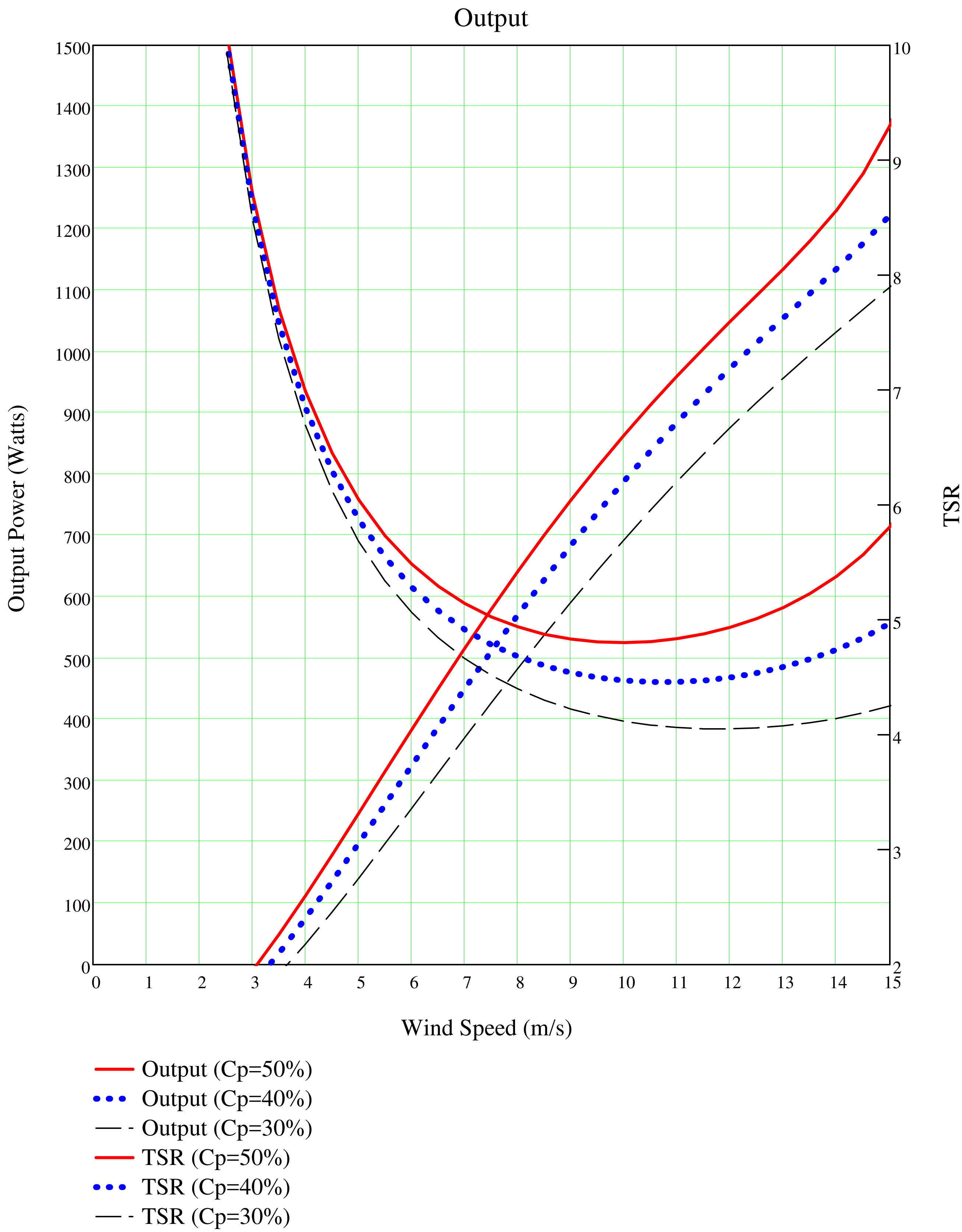
This round-about process has shown that, when connected in Parallel-Star to a 48 Volt battery system, a rotor with the following dimensions will start Toshi in a $cutin = 3.5\frac{m}{s}$ wind.

Unfortunately, the curve-fits being used are VERY INACCURATE below 200 RPM, so this is only approximate!

The output power can be summarized in one equation: $Power(v, Cp) := P_{out}(root(P_{in}(r) - P_w(v)\cdot Cp, r))$

The Tip Speed Ratio can also be summarized: $X(v, Cp) := \frac{(root(P_{in}(r) - P_w(v)\cdot Cp, r))\cdot R}{v}$

Both of these are plotted on the graph below, but the Cp that will be met in practice is still unknown. Each is plotted for a range of Cp and later testing and data logging will show the result.


Output
Output Power (Watts)
TSR
Wind Speed (m/s)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
2
3
4
5
6
7
8
9
10
Output (Cp=50%)
Output (Cp=40%)
Output (Cp=30%)
TSR (Cp=50%)
TSR (Cp=40%)
TSR (Cp=30%)