Performance analysis and improvement of a small locally produced wind turbine for developing countries

Msc thesis presentation Nienke Hosman

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STICHTING Energy Solutions For Humanity

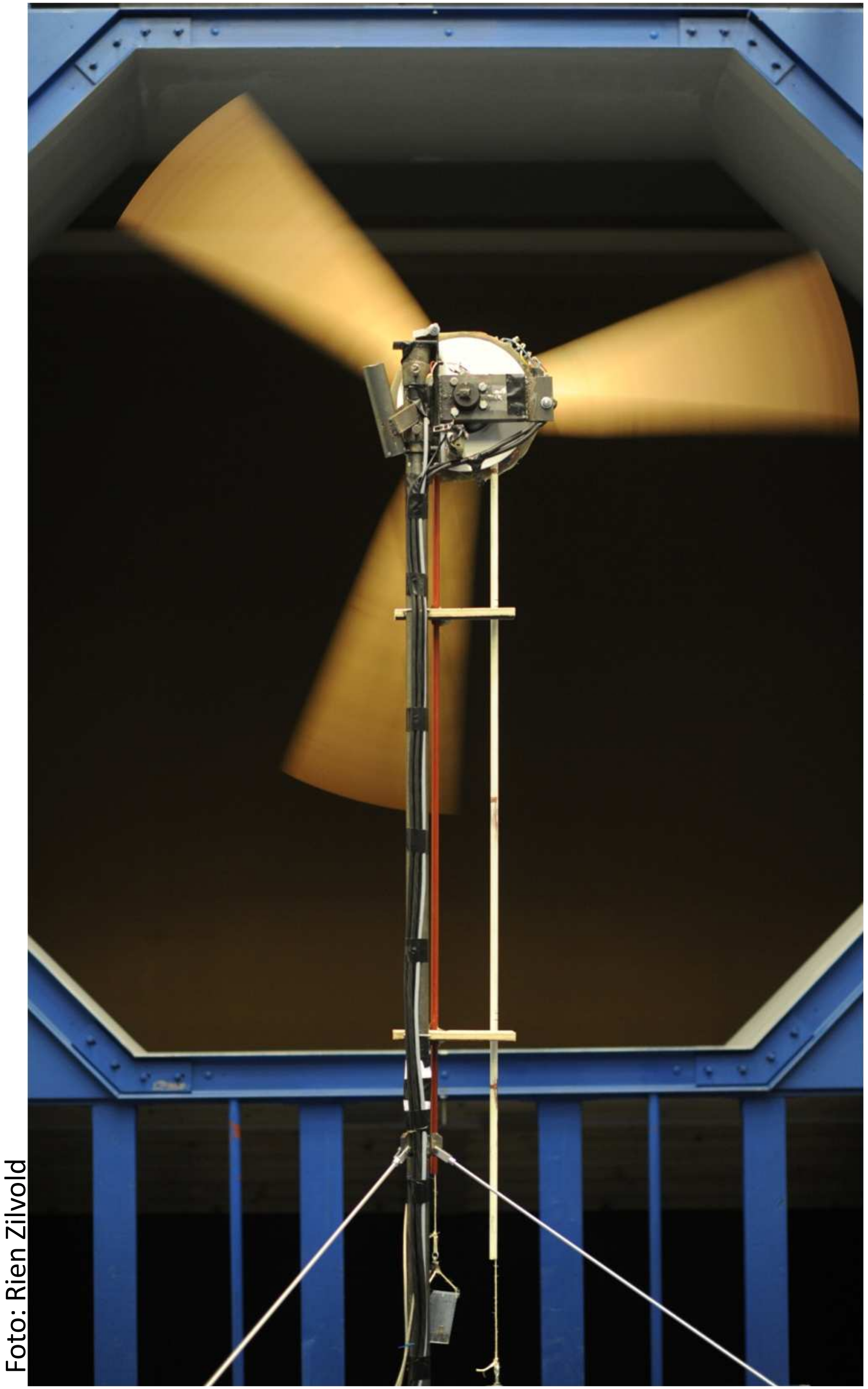


Foto: Rien Zilvold

Mali

- For 95% of the population there is no access to the electricity grid

- In rural areas:
  - People depend on batteries for electricity supply
  - Gasoline generators are used to charge the batteries
    → Electricity price high!

- Energy Solutions for Humanity
- i-love-windpower movement
  - Provide training of local people on building small wind turbines using local materials

STICHTING Energy Solutions For Humanity

Hugh Piggott wind turbines

- Do-It-Yourself wind turbine manual
  'A Wind Turbine Recipe Book'
  - Easy production
  - Turbine sizes: 1.2 m to 4.2 m diameter
  - Maximum power: 200 W to 1500 W
  - Costs: 900 - 2000 euro

- Design is used by many organizations worldwide

- Performance measurements are required for further improvement

Organizations of the Wind Empowerment association

Research objective

1. Identify the performance of the Hugh Piggott wind turbine
2. Design a new wind turbine that has improvements in one or more aspects

Contents

- Introduction
- Identification of the Hugh Piggott wind turbine - What needs to be improved?
  - Evaluation of production process → field experience
  - Performance calculations
  - Wind tunnel experiment 1
- Design of an improved wind turbine - How can it be improved?
  - Design and performance calculations
  - Production
- Evaluation of the improvement - Is the improvement successful?
  - Wind tunnel experiment 2
- Conclusions

Identification

What needs to be improved?

- Evaluation criteria
- Overview of the turbine
- Production
- Performance calculations
- Performance measurements

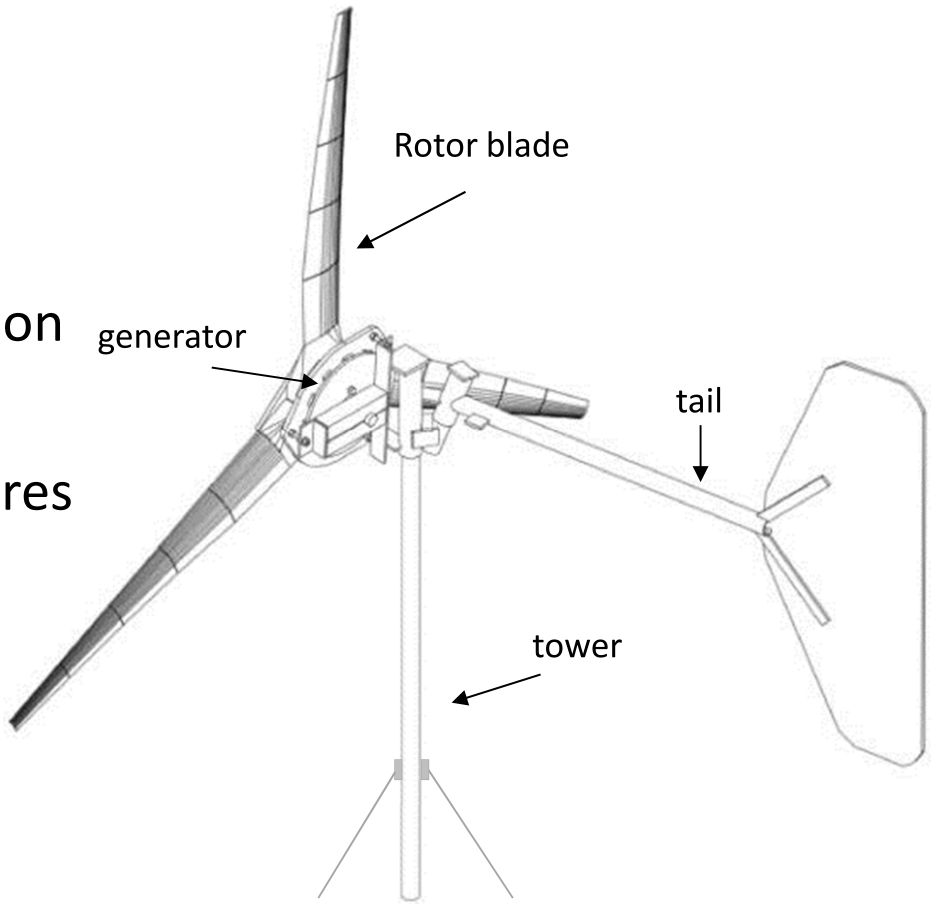
Evaluation criteria for small wind turbines in developing countries

- Performance
  - Powercurve: power vs. wind speed
  - Performance at the Malian average wind speed of 4 m/s
  - Start-up wind speed: should be below cut-in wind speed
- Ease of production process
  - Production time
  - Tools required for production
  - Tolerance in the production process→ uniformity
- Availability of good quality (local) materials
- Material costs

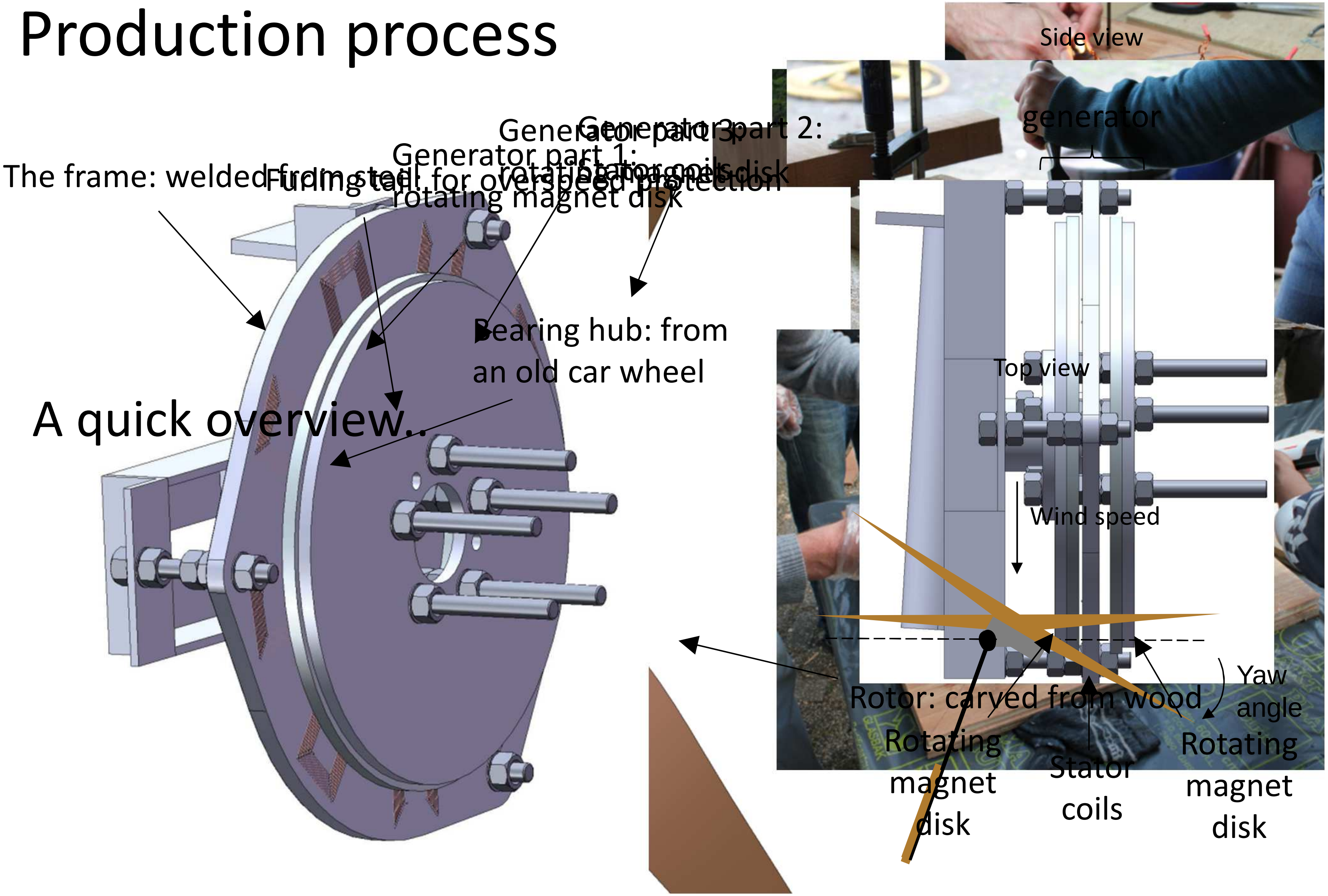
Overview of the HP turbine

- 3-bladed rotor, with twisted and tapered wooden blades
- Permanent magnet generator
- Furling tail for overspeed protection
- Single tower supported by guy wires

Test turbine = 1.8 m diameter



Production process



Wind turbine costs and production time

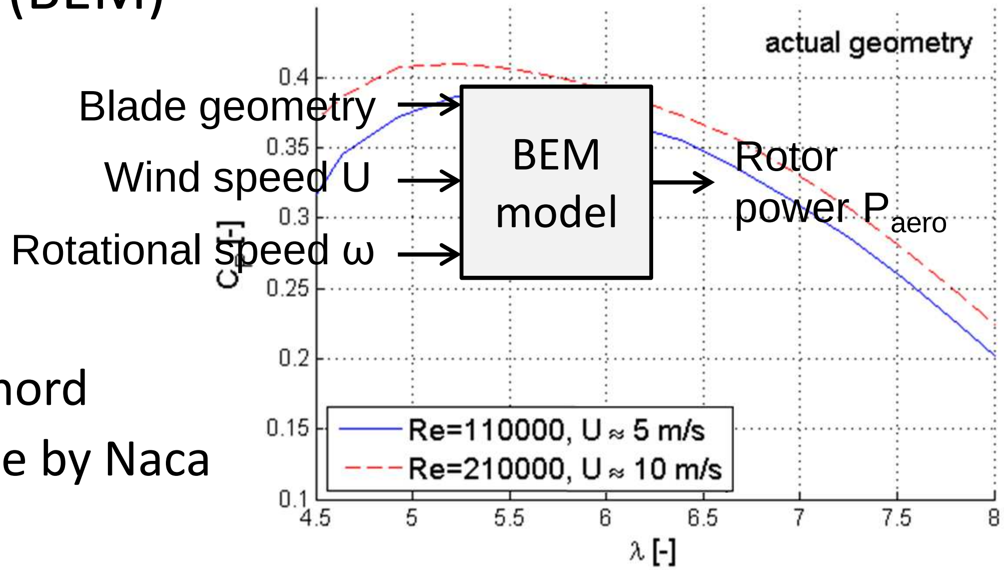
Estimations for the 1.8 m turbine, for the case of Mali

Component	Material costs [€] *	Production time [man hours]	Production time [%]
Wind turbine components			
Rotor	80	50	36
Tail	40	10	7
Generator	170	40	29
Frame	40	20	14
Assembly	-	20	14
Total wind turbine	330	140	100
Supporting components			
Charge controller (off-the-shelf)	150	Design in progress	
Electrics (cables, diodes)	50		
Tower (12m) and guy wires	250		
Batteries	300		
Total system	1080		

*costs are estimations of Malian prices

Performance calculations

- Blade Element Momentum (BEM) model



- Blade geometry:
  - Measured blade angle and chord
  - Approximation of blade shape by Naca 4412 and Naca 4415 airfoils

- Limited accuracy of calculation because of incertainty in geometry input

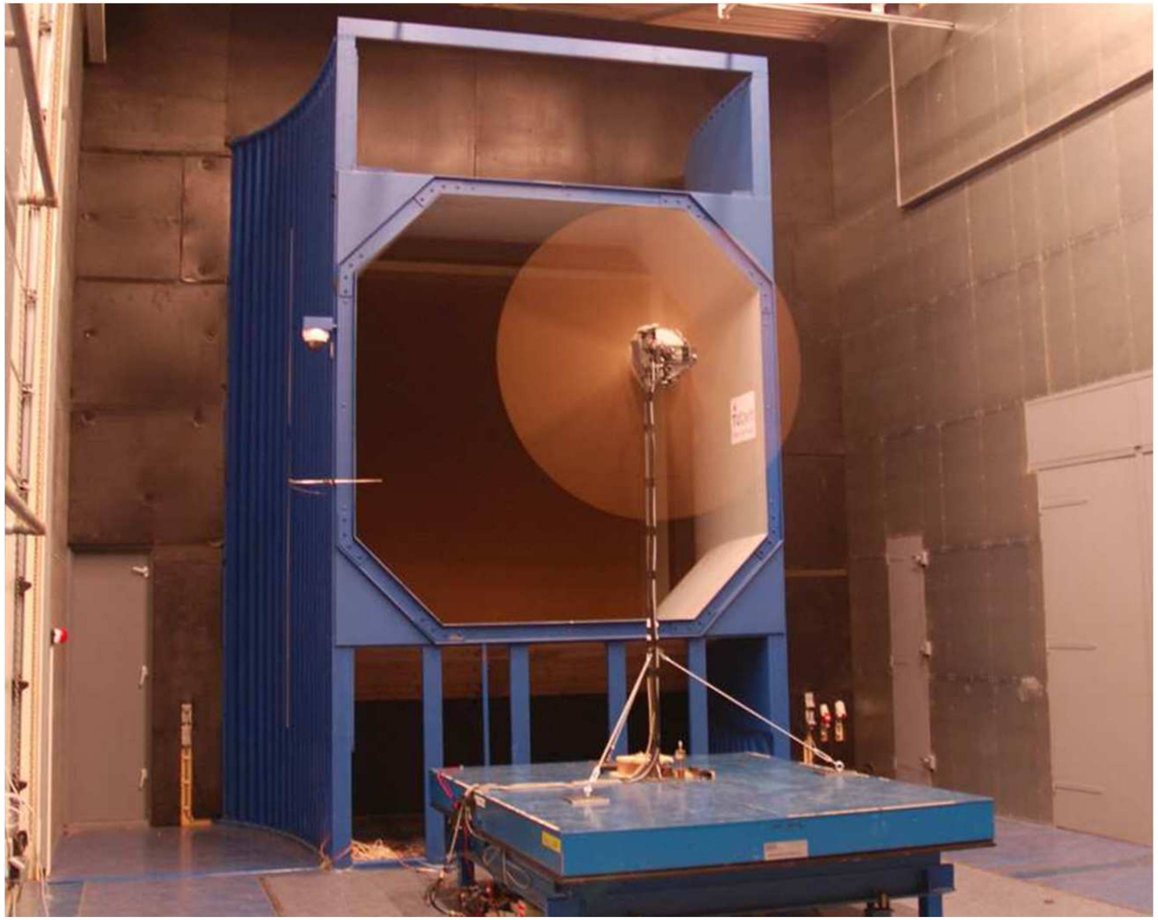
C_P = power coefficient

$$\text{Tip speed ratio } \lambda = \frac{\omega \cdot R}{\text{wind speed}}$$

Wind tunnel experiment 1

Experimental set-up in the Open Jet Facility (OJF) windtunnel

OJF characteristics	
Type	Closed circuit
Tunnel exit (w x h)	285 x 285 cm
Maximum wind speed	35 m/s



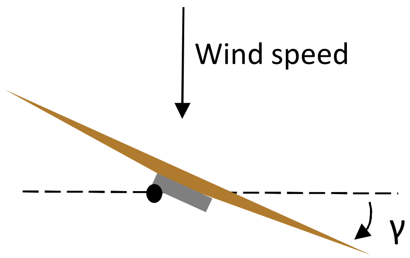
Overview of tests

Rotor performance — generator is in open circuit (decoupled from rotor)

Total performance — generator is connected to external circuit

- Generator efficiency
- Furling behaviour

Test matrix



	load	tail	Yaw angle γ	Result
Rotor performance	Prony brake	-	0°,20°,40°,60°	Aerodynamic power curves
Generator efficiency	Dummy load	-	0°	Total power curve at 0°
Furling behaviour	Dummy load	yes	Free yawing	Total power curve

Prony brake

Technique to measure rotor torque

P_{aero} = Torque · ω

Generator in open circuit!

Dummy load

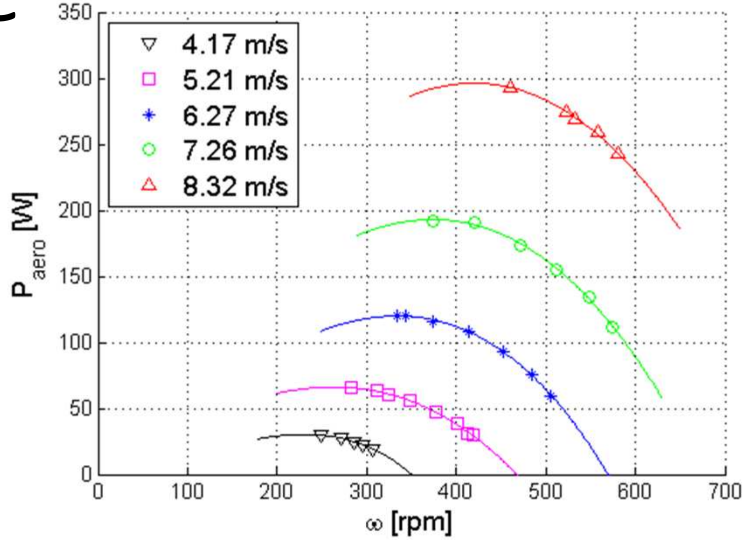
Resembles battery operation

$P_{wt} = V_{wt} \cdot I$ wt = wind turbine

Generator coupled to external circuit and variable resistance

Results: Rotor performance

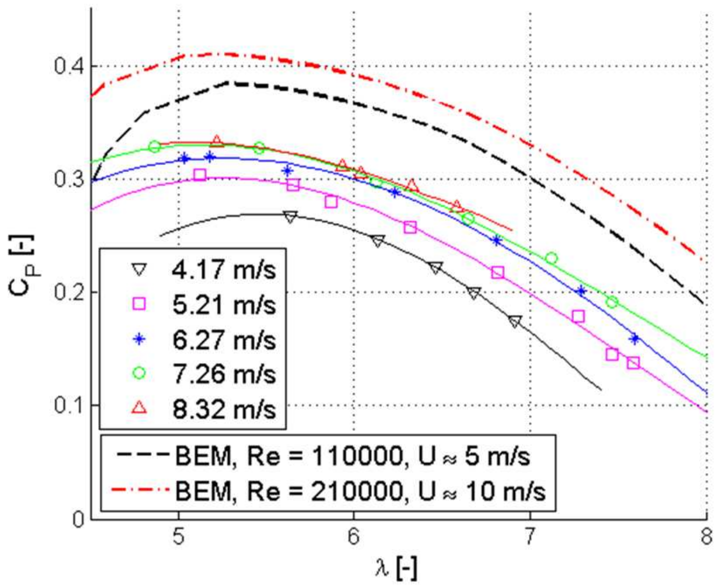
At 0° yaw



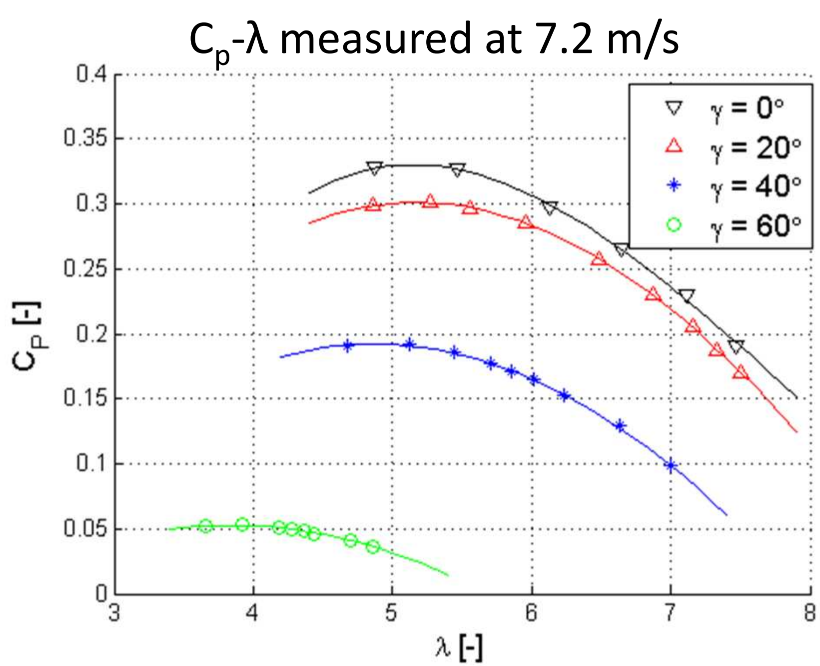
- At higher wind speeds higher performance power coefficients are measured, caused by higher Reynolds numbers

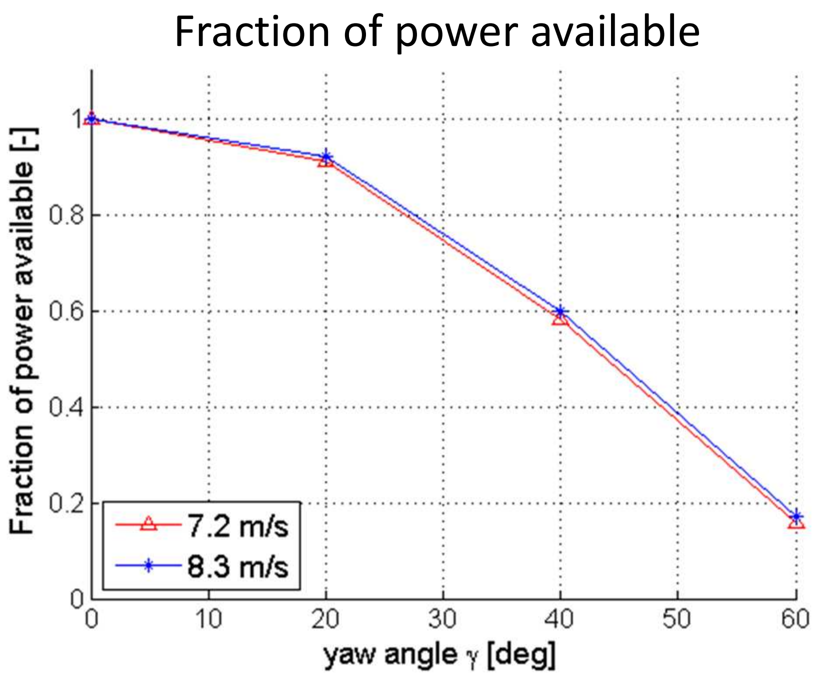
→ Larger diameter turbine would also increase Reynolds numbers

- Difference between theory and practice is caused by:
  - Deviations in geometry: actual airfoils are not perfect Naca airfoils
  - Friction in the bearing hub
  - Inaccuracy of the BEM model

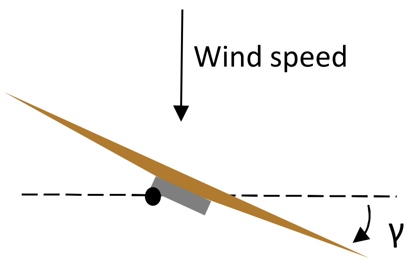


Rotor performance at yawed flow



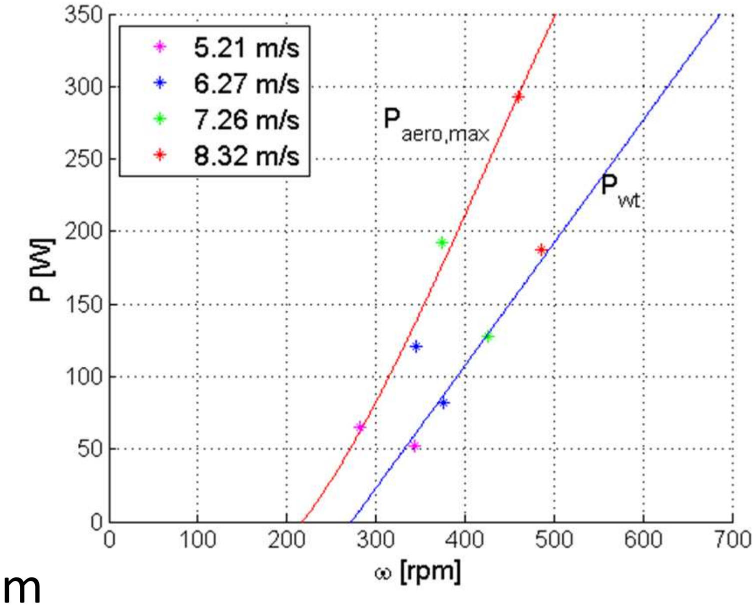


- Power decreases with increasing yaw angle



Results: Total performance

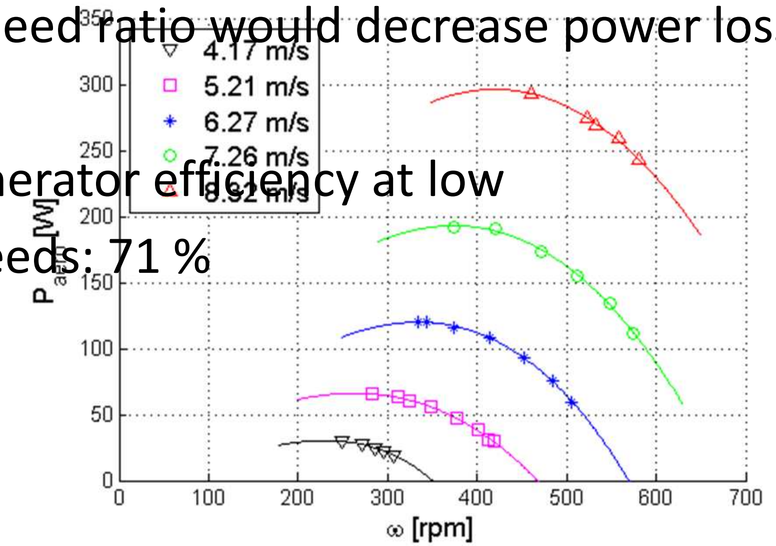
at 0° yaw

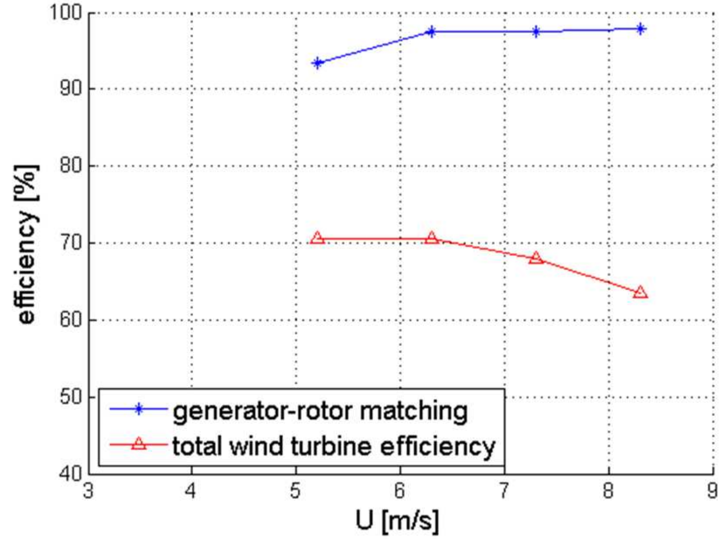


- The turbine operates at variable rotational speed ω and tip speed ratio λ
  → Generator rotor matching!

→ For low wind speeds (4 m/s) a higher optimum tip speed ratio would decrease power losses

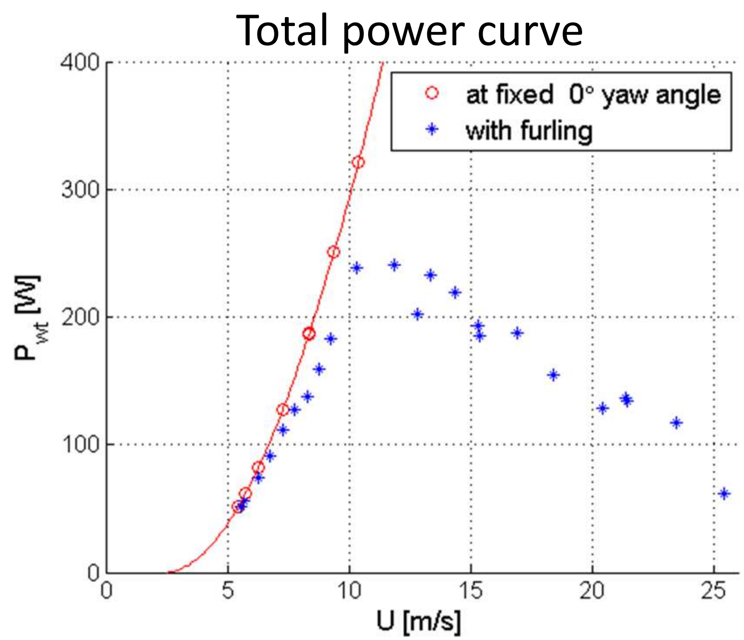
Total generator efficiency at low wind speeds: 71 %





Results: Furling behaviour

Turbine is free to yaw

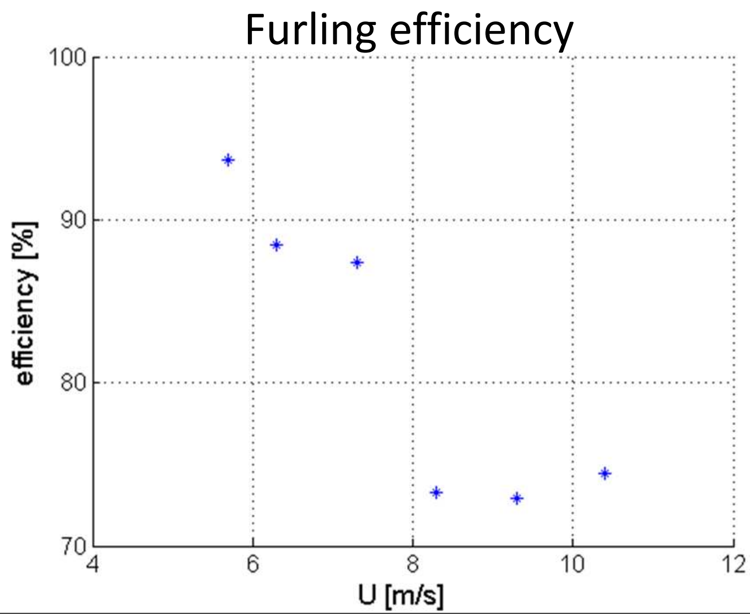


- Maximum power: 240 W at 12 m/s
- Power at 4 m/s only 15 W

- Tail provides good overspeed protection

But:

- Furling at low wind speeds is unnecessary, because overloading is not a danger



- Furling losses below 6 m/s are < 10%

Start-up wind speed

- Start-up wind speed – turbine starts rotating
  = 3.0 m/s

- Cut-in wind speed – turbine starts producing power
  = 3.2 m/s

Conclusion on HP 1.8m identification

- Improvements can be obtained in all tested parts: rotor, generator and furling system

Most interesting:

- Improve efficiency at low wind speed
- Decrease the tolerance in the production process and improve uniformity

→ Concentrate on improvement of rotor design

  - Most difficult production
  - Efficiency at low wind speeds can be increased → better generator matching

Design

How can it be improved?

- Design
- Performance calculation
- Production

Design of a new rotor

Main design goal

- Easier production → higher uniformity
- Higher design tip speed ratio → better generator-rotor matching

→ Find optimum between ease of production & performance

Straight bladed rotor! → Lower performance but easier production

- Three-bladed rotor → structurally most simple
- Wood as a blade material
- Untapered and untwisted blades
- Naca 4412 airfoil
- $\lambda_{optimum}$= 5.8
- Optimum geometry determined with BEM: 8 cm chord and 7°pitch angle

Performance calculation

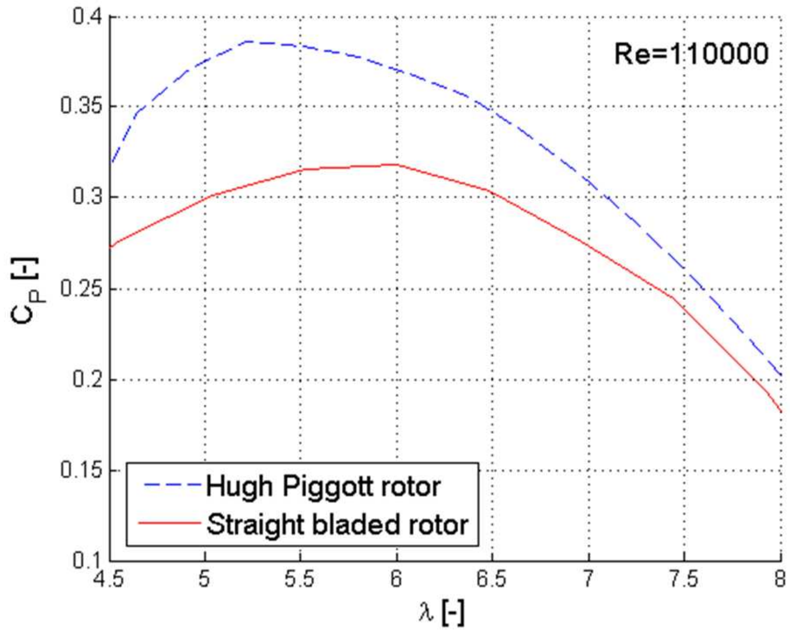
Theory: performance decreased

But:

- New geometry makes use of templates possible

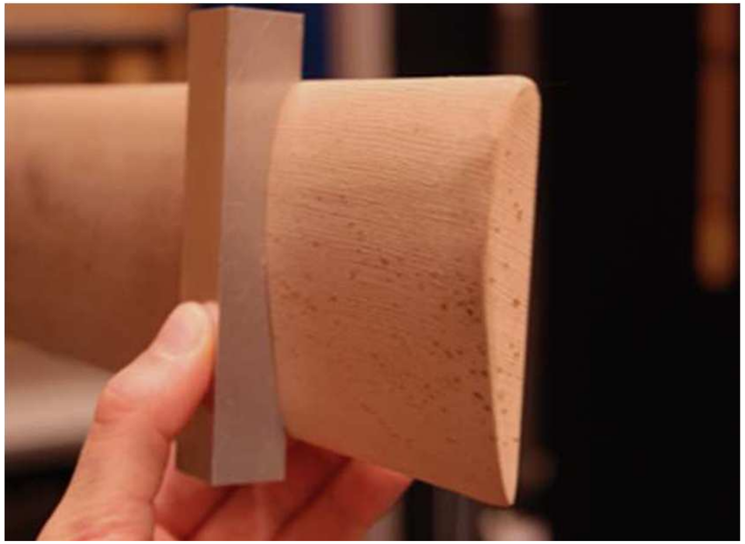
→ Power losses due to production errors are expected to be lower

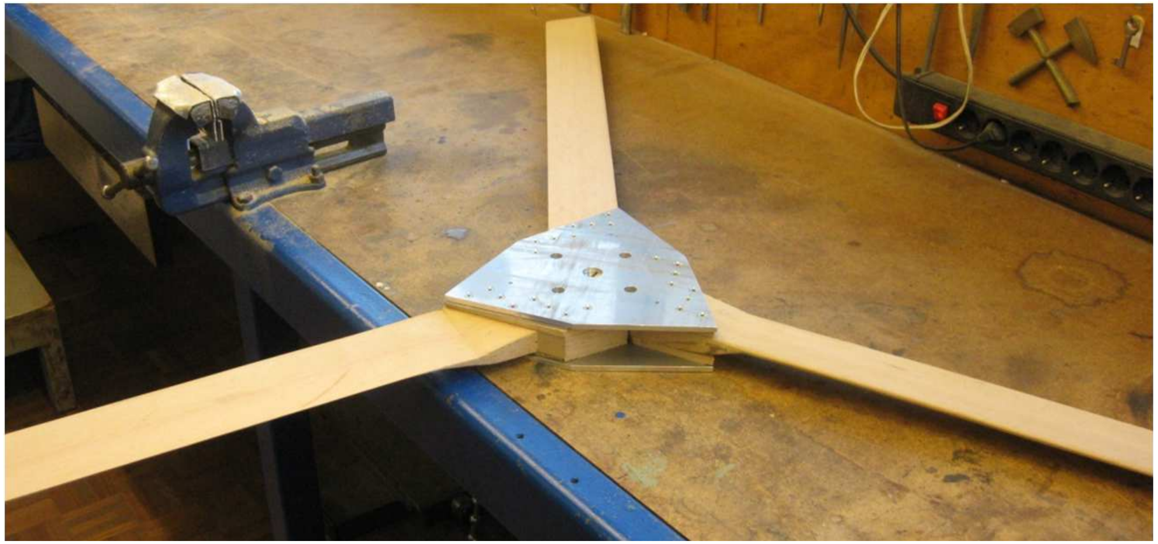
Practice: difference could be much smaller!



Production

- Use of an airfoil template
- Estimated decrease of production time: 20%
- Smaller wood size is required → increase of material availability!





Evaluation

Is the improvement successful?

- Wind tunnel experiment 2

Wind tunnel experiment 2

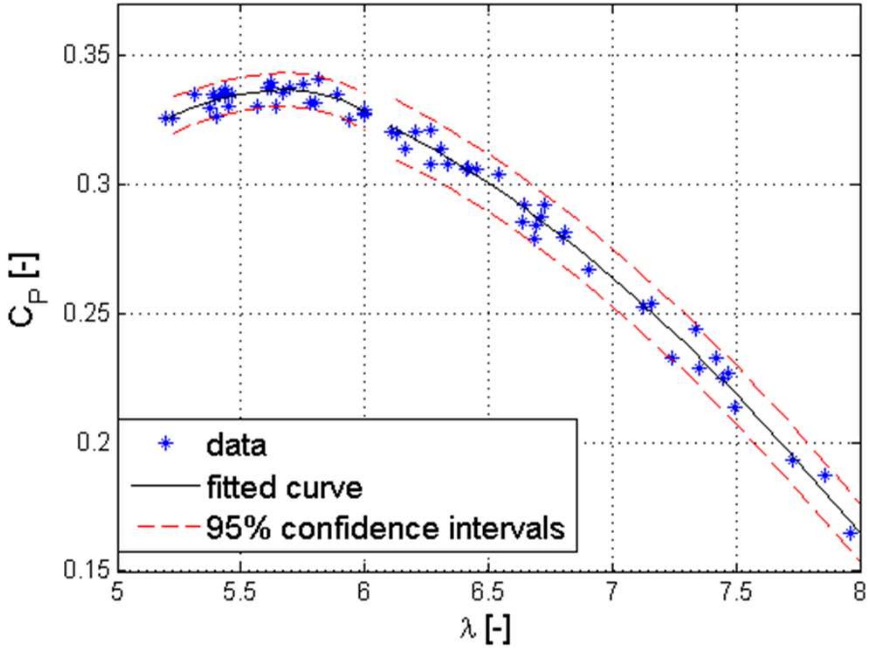
- Same experimental set-up as for experiment 1
- Only rotor performance measurements → prony brake
- Only tests at zero yaw angle

<u>Overview of tests</u>

• Hugh Piggot (HP) rotor	Sharp and round leading edge
• Straight bladed (SB) rotor	6, 7 and 8° pitch angle
• Measurement repeatability	

Measurement repeatability

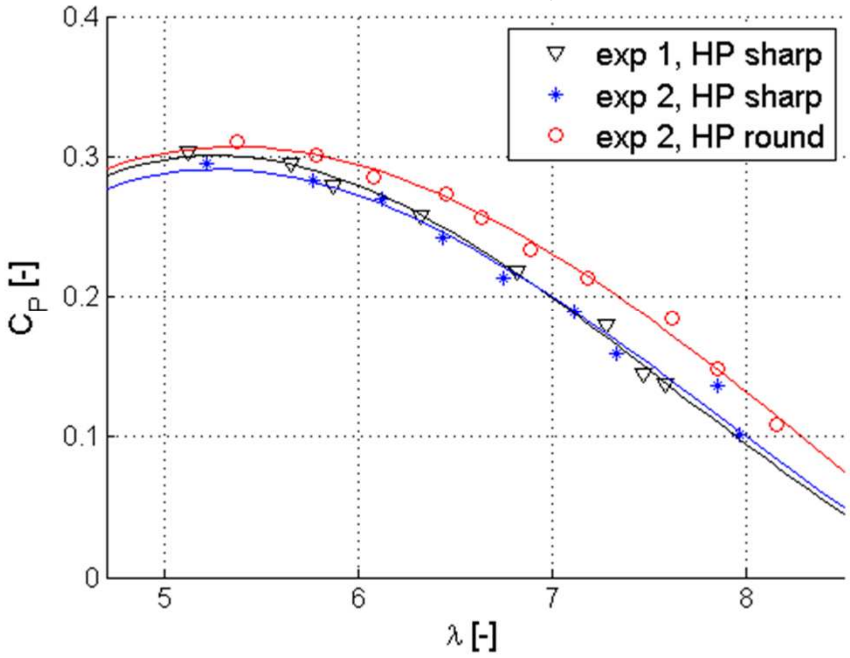
7 datasets of the straight bladed 7° rotor at U = 6.2 m/s



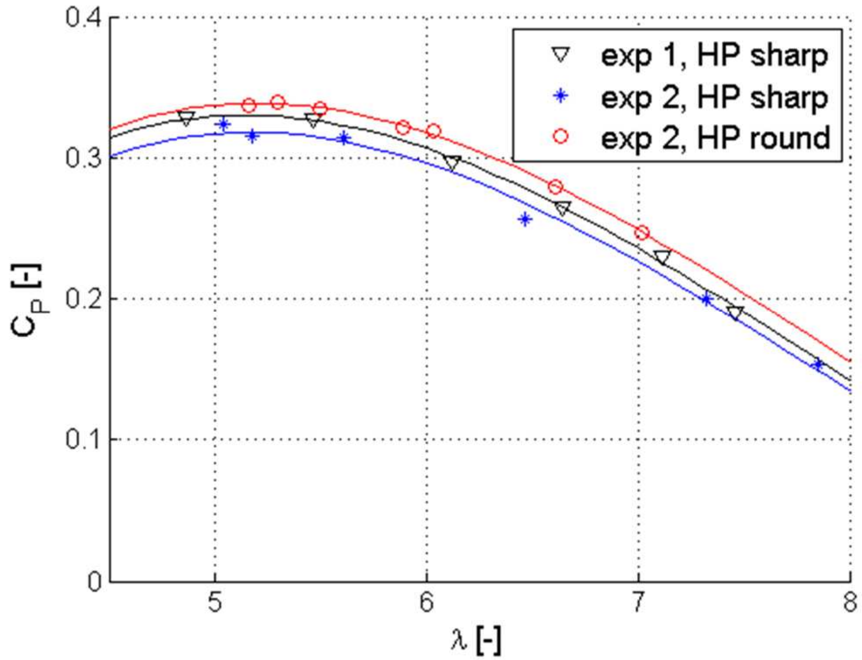
- Improvements less than 3.9% (for λ < 6.2) are not significant

Hugh Piggott (HP) rotor performance

U = 5.2 m/s



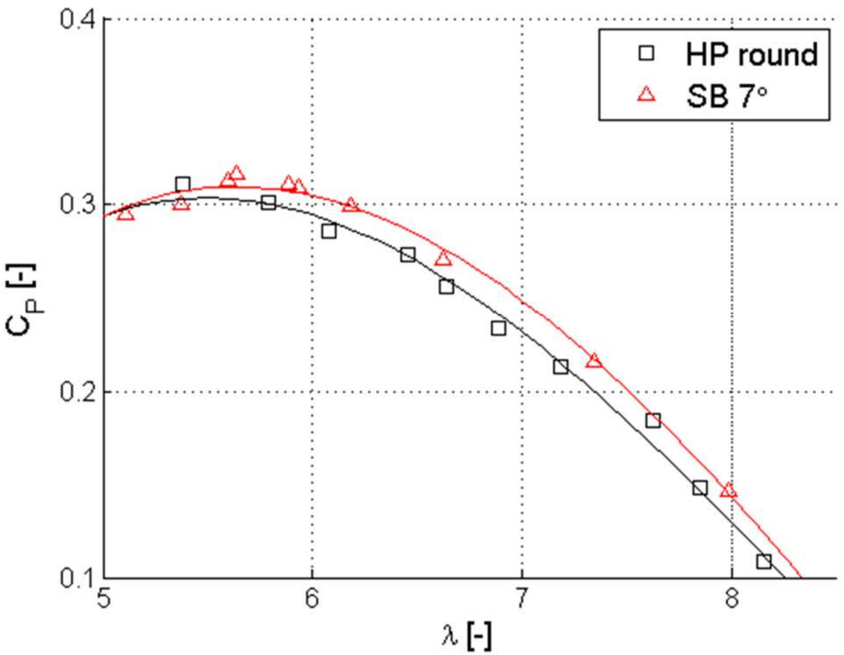
U = 7.3 m/s



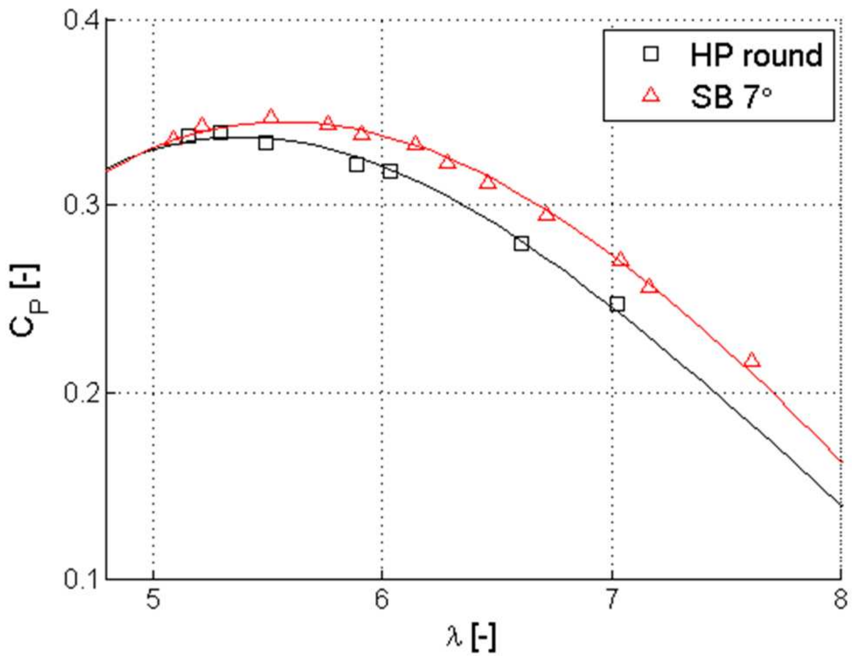
- Differences between results of experiment 1 and 2 are not significant
- HP-round rotor gives slightly higher performance (not significant for all wind speeds)

Straight bladed (SB) rotor performance

U = 5.2 m/s



U = 7.3 m/s

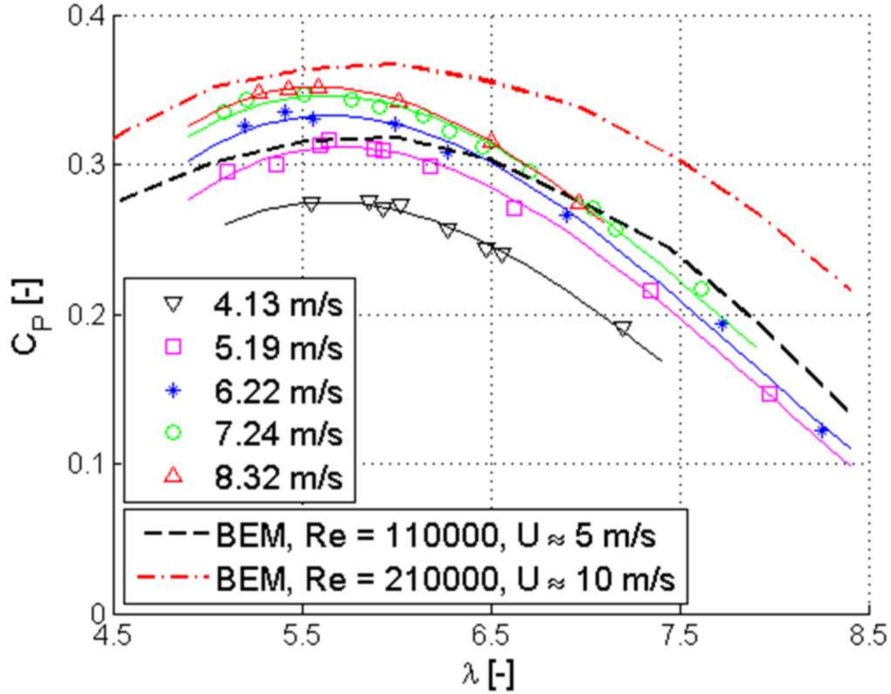


- SB 7° gives the best maximum performance
- SB 7° has a higher optimum tip speed ratio than HP
- For SB 7° start-up wind speed = 3.2 m/s → equal to cut-in!

Straight bladed (SB) rotor performance

Comparison between measurements and calculations of SB-7°

- Results are much more consistent than for the HP rotor



Main reason:

- Lower production tolerance, due to the use of an airfoil template

HP and SB rotor comparison

Comparison of optimum rotor performance
Results from experiment 2: SB 7° and HP-round

U [m/s]	$C_{P,max}$ [-] HP	$C_{P,max}$ [-] SB	**$C_{P,max}$ improvement [%]**	λ_{opt} [-] HP	λ_{opt} [-] SB	**λ_{opt} increase [-]**
4.2	0.261	0.275	5.4	5.6	5.7	0.1
5.2	0.307	0.312	1.6	5.4	5.7	0.3
6.2	0.331	0.333	0.6	5.3	5.7	0.4
7.3	0.338	0.346	2.4	5.2	5.6	0.4
8.3	0.348	0.352	1.1	5.3	5.6	0.3

Effect on total performance

Comparison of rotor performance at point of operation during normal battery operation

U [m/s]	ω [rpm]	λ [-]	C_p [-] HP	C_p [-] SB-7	**C_p improvement [%]**
4.2	307	7.0	0.186	0.207	11.3
5.2	337	6.1	0.290	0.305	5.2
6.2	376	5.7	0.325	0.333	2.5
7.3	425	5.5	0.336	0.345	2.7
8.3	483	5.5	0.347	0.351	1.2

experiment 1 (ω, λ, C_p HP) experiment 2 (C_p SB-7)

- New rotor operates closer to its optimum point at low wind speed
- If loading is unchanged, power increase at 4 m/s would be 11%!

Conclusions and recommendations

Conclusions on performance identification

- Improvements can be gained in all tested aspects:
  rotor, generator and furling system

Most relevant:

- Improve uniformity by simplifying the production process
- Increase turbine efficiency at low wind speeds

→ Improve rotor design

Conclusion on new rotor design

Design: straight bladed rotor

Production

- Decrease in production time (estimated by 20%)
- Decrease in tolerance in production process → increase in uniformity
- Higher availability of wood

Performance

- Start-up wind speed equal to cut-in wind speed of 3.2 m/s
- Maximum rotor power coefficient $C_{P,max}$ is slightly better (2.2%)
- Better generator matching at low wind speeds
- Determined power increase at 4 m/s is 11%

Successful? → Yes!

Recommendations

<u>Additional testing</u>	Testing of ultimate loading and loading in yaw
	Testing of total performance
	Upscaling (3.0 m turbine) and field testing
<u>New design</u>	
Rotor	Design a two-bladed rotor
Furling system	Decrease the furling losses at low wind speeds
Support structure	Design an optimized lattice tower structure

Thank you for your attention

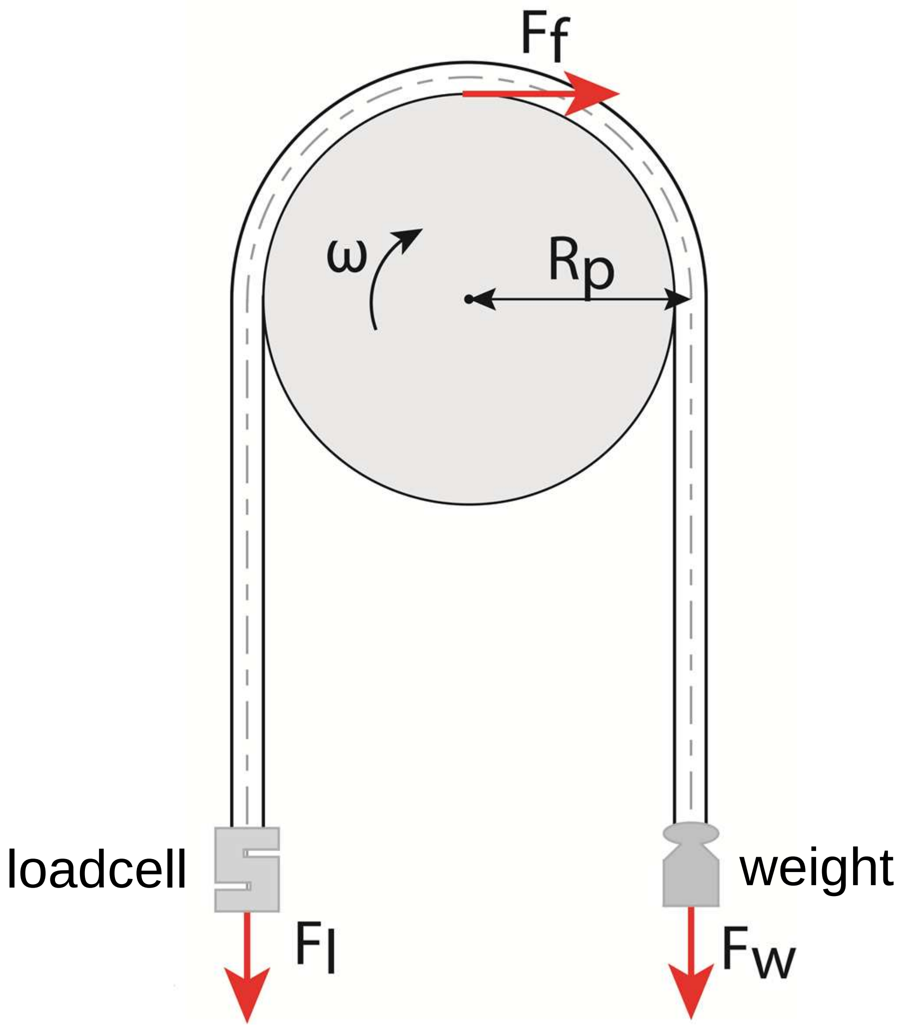
Results will become available on
www.windempowerment.org

Prony brake

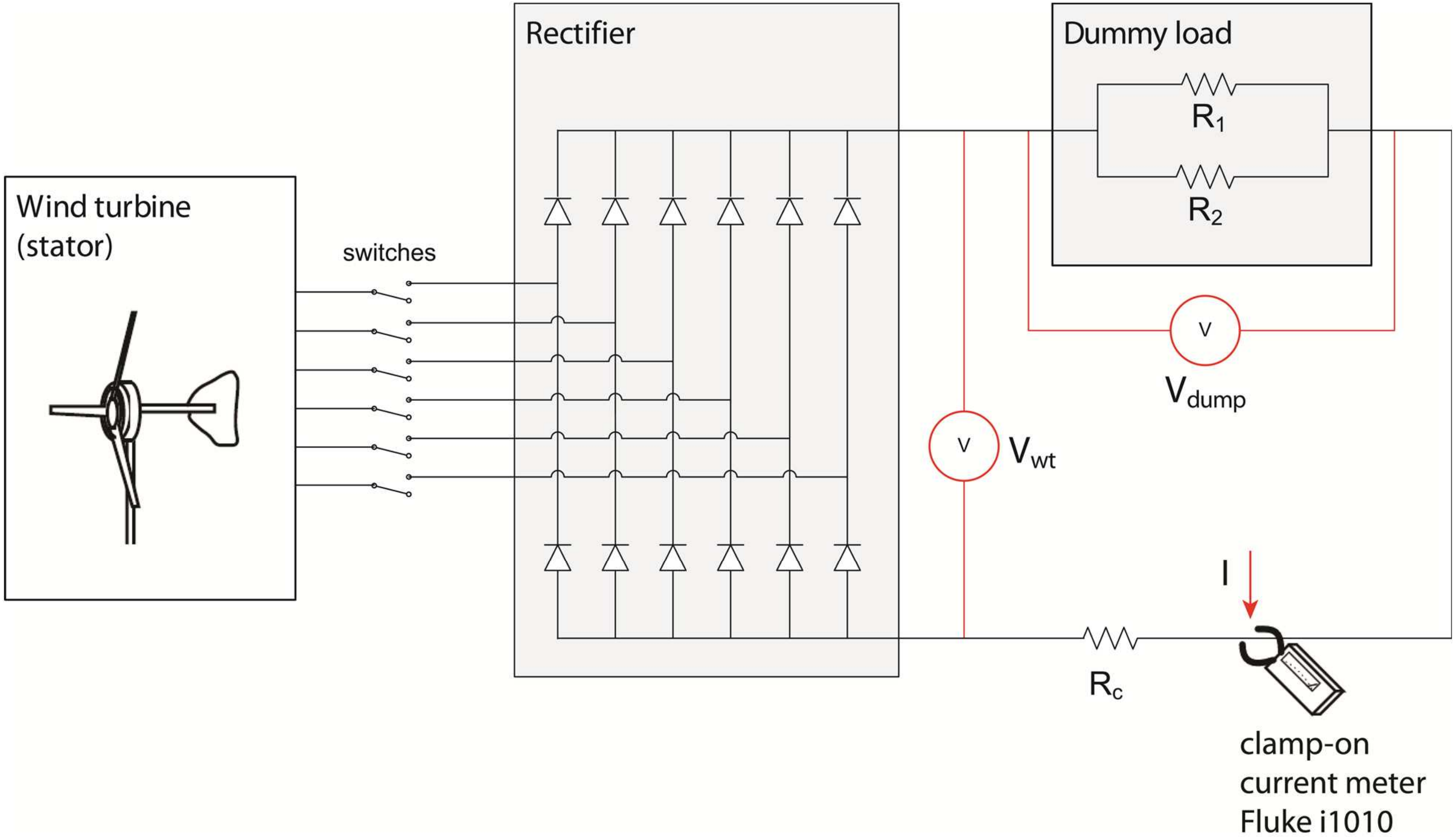
$$F_f = (F_l - F_w)$$

$$Q = F_f \cdot R_p$$
$$= (F_l - F_w) \cdot R_p$$

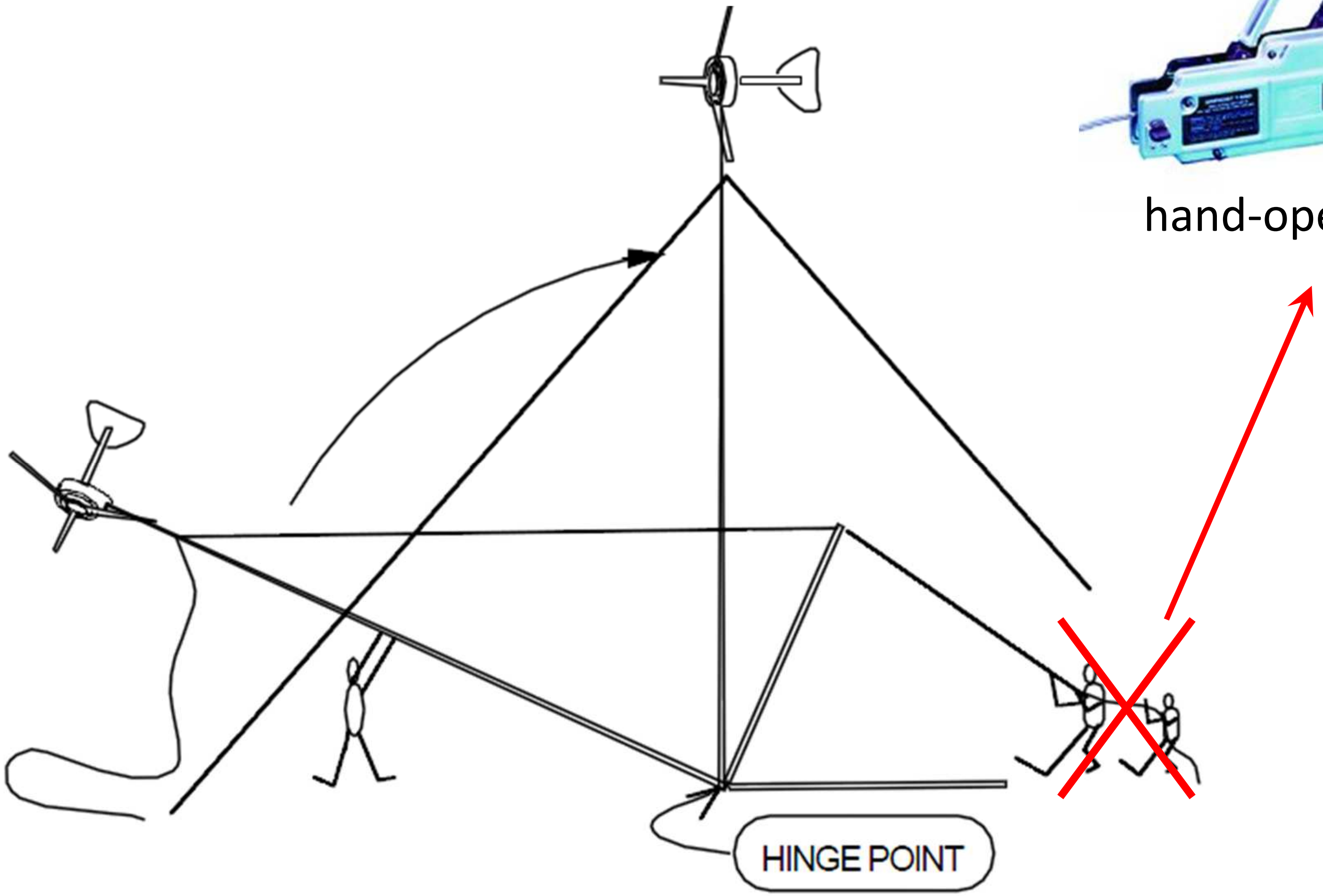
$$P = Q \cdot \omega$$
$$= (F_l - F_w) \cdot R_p \cdot \omega$$



Electrical circuit



Lifting the turbine



hand-operated winch

Performance in yawed flow

TSR = omega * R / U

TSR decreased

Higher U is required to get the same rpm