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Comparison of concepts for high-altitude wind energy generation with ground based generator

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Abstract

While the wind energy of the atmosphere increases significantly with increasing altitude, no electrical power is currently generated from wind at high altitudes. This paper presents and compares several concepts for wind energy exploitation from high altitudes winds. The comparison in this paper is limited to concepts that have the generator located on the ground. The concepts make use of lifting bodies, called wings. The wings are attached to a tether that drives the generator while the wings are pulled up by the wind. Such systems enable large single-unit outputs because the size of the wings connected to the tether can be much larger than the blades of conventional windmills.
From several concepts, the most promising concepts were simulated using real historical high altitude wind data from the Royal Netherlands Meteorological Institute. Because of the more constant wind speeds at high altitudes, around 70% of the installed power can be actually generated on average, which is higher than the results for conventional windmills. Because of the high altitude at which the concepts operate, even sites that are not cost effective for conventional windmills may still be used for high altitude wind energy production.
Finally, it is shown that the moving mass (the wings and the tether) of a 5MW version of the most promising concept can be significantly lower than the mass of the blades of a 5 MW conventional windmill.

1. Introduction

This paper presents and discusses several concepts that can be used to exploit high altitude wind energy. While the wind energy content of the atmosphere increases significantly with increasing altitude, no electrical power is currently generated from high altitude winds. This paper presents and compares several concepts for wind energy exploitation from wind at high altitudes.
The concepts presented in this paper make use of lifting bodies, called wings, connected to a tether that stretches into the higher regions of the atmosphere. The wings generate lift and pull the tether upwards; the motion of the tether drives the generator.
The first concept is the Laddermill [1], which makes use of a loop of wings, where the wings go up on one side of the loop and down on the other side, see Figure 1.
The second concept is the pumping mill, which makes use of only a single tether. The tether moves up and down alternately, see Figure 2.
The installed power of both concepts can be higher than that of conventional windmills. Since the wings are high up in the air, their size is not limited like the blades of a conventional windmill. Higher installed power will lead to a larger tether diameter and a larger, ground-based, generator. Larger single-unit outputs are expected to decrease the cost per kWh.
In the year 2000, 1.2% of the Dutch electricity consumed, came from renewable sources [2]. In 2000, the Dutch government has set targets in order to comply with the Kyoto protocol, to reduce the Dutch CO_2 emissions. The targets are to generate 5% of

the electricity consumption from renewable sources by 2010 and 10% by 2020 [2].
The wind at higher altitudes is more constant. Current estimates show both concepts discussed in this paper can produce about 70% of its installed power, while the installed power of a single unit may be as high as 50 MW. This will enable generating substantial percentages of a country's electricity requirements from wind. It will take only about 32 units to generate 10% of the Dutch electricity demand.

2. Presentation of concepts

Two different concepts for high altitude wind energy exploitation will be discussed in this section. Variations on these concepts are considered, some of them will be mentioned in other sections.

2.1. Laddermill

The first concept is the Laddermill [1,3]. The Laddermill consists of an endless tether with wings attached to it, presented in Figure 1.

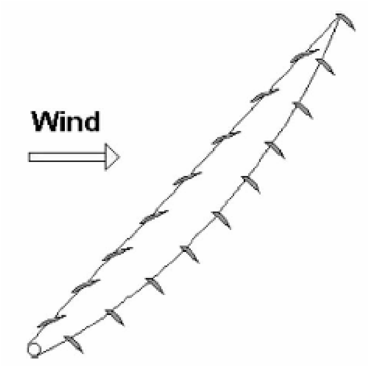

Figure 1: The Laddermill concept [1]

On the ascending end, the wings are adjusted to deliver maximum lift. On the descending end, the wings deliver only just enough lift to stay up. The resulting tension difference in the tether is used to power a ground based generator.

2.2. Pumping mill

The second concept consists of a single tether, with a number of wings spread evenly over it, as shown in Figure 2. It is in fact half a Laddermill. This concept will alternately move up and down, and is thus called the pumping mill. During the ascent, the tension in the rope drives a generator. During the descent, no power is generated. A comparable idea with a single wing at the top of the tether is presented by Lloyd [4].

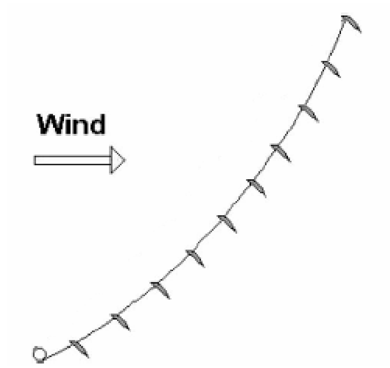

Figure 2: Pumping mill [after 1]

3. Conceptual comparison

Some differences in operation between the Laddermill and the pumping mill can be found in Table 1.

	Laddermill	Pumping mill
Power generation	Constant	Alternating
Material use	Half of the Laddermill always unused	No power production during descent
Wings & Tether	All wings identical	Wings optimized for altitude
	Full tether identical	Tether tapered
Weather adjustability	Wings and tether can be replaced real-time	Delay in power generation required to adjust. Only length can be adjusted.
Tether strain	Strain always on same side of generator	Alternating strain will cause losses
Generator-tether interaction	Whole tether used to drive generator	Lower tether optimized to drive generator
Inspection	In situ inspection possible	Remote inspection necessary
Groundstation	Complex	Simple

Table 1: Intuitive comparison of concepts

The differences will be discussed in more detail in the remainder of this section.

3.1. Power generation

The alternating nature of the power generation of the pumping mill could be problematic if this power is delivered directly to the grid. Several solutions are envisioned. Firstly, the pumping mills can be installed close to hydro power plants, and can be used to 'recycle' the water passing through the dam. Secondly, a cluster of pumping mills can be placed together, phasing their up/down cycle frequencies such that a constant output power is acquired from the cluster.

3.2. Material use

For the Laddermill, the half of the loop that is descending has no contribution to the electricity production. Since the tether speed of the descending part is equal to the ascending part, half the material is unused at any time. In the case of the pumping mill, all of the material is unused during the descent. The time of the descent however is not necessarily equal to the ascent and can be lower. Simulations show the power producing phase can be at least 67% of the total cycle. The simulations were performed with the program presented in reference [5]. If power is produced 67% of the time, on average one third of the material is unused. Even shorter descent times are under investigation.

3.3. Wings & tether

All wings of the Laddermill will have to be the same, since they are all used in all conditions while they travel the loop. The same holds for the tether. In the pumping mill however, the wings and tether can be optimized for their position in the system; the upper wings can be strong to sustain high wind speeds, while the lower wings can be lightweight since the experience only lower wind speeds. If the contribution of the lower wings is too low, they can even be left out, in case of the pumping mill. This idea will be discussed in more detail in the conclusions of this paper. The tether of the pumping mill can be tapered; the top part of the tether can be optimized for tension caused by the top wing. Downward, the tether diameter will increase after each wing.

3.4. Weather adjustability

All the wings of the Laddermill move through the ground station where the generator is located. There, they may be replaced with other wings, when required by changing weather conditions. This may enable the Laddermill to keep up the power generation when the wind speed is lower. On the other hand, it implicates that there are unused wings stored in the ground station.

The pumping mills wings cannot be replaced easily, since the upper part of the pumping mill never approaches the ground station. It is however possible to add or remove lengths of the tether. This procedure would result in some losses in power generation because of the time needed to connect additional tether.

3.5. Tether strain

When a tether is subjected to tension, it will deform, leading to strain in the tether. In the Laddermill concept, the strain is always present. In the pumping mill, the strain is present during the ascent phase, but not during descent. This means that before power generation can begin after the descent phase, the tether needs to be stretched. Because of the length of the tether, which may be several kilometers, a strain one percent means stretching the tether several tens of meters. The time consumed by this action introduces losses in power generation.

3.6. Generator-tether interaction

When the tether drives the generator, the strain is removed from the tether. This results in a length reduction, which causes micro-slip to occur between the generator surface and the tether surface. It may be necessary to reinforce the tether surface with a coating to cope with micro-slip.

In the Laddermill, the whole length of the tether would need this coating, adding to the weight. For the pumping mill however, only the part of the tether that has contact with the generator needs to be reinforced.

3.7. Inspection of tether and wings

The wings and the tether will be subject to wear and malfunctions. It will occasionally be necessary to replace the tether or parts of it, which also holds for the wings.

In the Laddermill, the tether and the wings can be inspected once every full rotation and a part of the tether or a wing can be replaced inside the groundstation with little or no delay in the power production. For the pumping mill this procedure is not possible. The whole pumping mill will have to come down in order to replace parts of the tether or the wings. Inspection will have to happen by means of remote sensing or with an inspection device that climbs the tether.

3.8. Groundstation

The groundstation houses the generator, guides the tether and has to provide a solid mechanical connection to the Earth.

Guiding the tether will be simpler in the case of the pumping mill because there are no wings to be detached from the tether and there is only one tether entering the groundstation.

The groundstation will also have to align the tether with the wind direction, which will be simpler in the case of the pumping mill with only a single tether. To what extent the second rope and detaching and re-attaching the wings complicate the Laddermill compared to the simpler pumping mill has not been inspected.

4. Numerical comparison

In this section the Laddermill and the pumping mill will be compared by sizing a 5 MW Laddermill and pumping mill under equal wind circumstances and examining the wing mass, the tether mass and the required generator size.

4.1. Concept sizing

Inputs in the sizing process are the operating altitude and the required power. By fixing the value for the output power, the material requirements for the concepts can be compared.

Sizing of the concepts was performed by placing a first wing at the maximum operating altitude and calculating the forces acting upon it. To calculate the forces taken, the aerodynamic forces, the motion of the tether and the wing mass are into account. The wing mass is determined by equation 1. The calculation results in a tether angle θ, as presented in Figure 3. With given distance between two wings, the tether angle gives the location of the second wing. The resulting force determines the strength and thus the thickness of the tether.

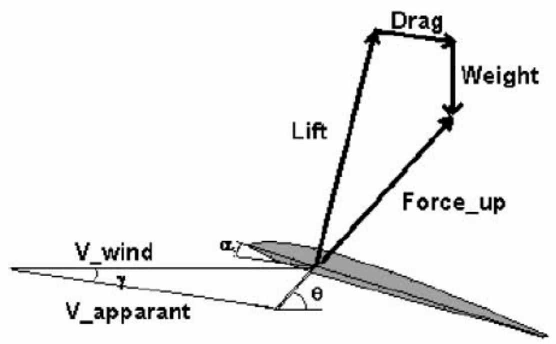

Figure 3: Forces on upper wing [1]

The same procedure is used for the second wing, but the forces caused by tether lift & drag and tether mass of the tether above the wing are added, as well as the tether tension. A new tether thickness is determined.

This is performed for all the wings in an iterative loop, decreasing the tether speed when the tether angle becomes too small and adjusting the wing surface to match the desired power generation.

4.2. Assumptions and boundary conditions

For the tether, Dyneema was selected. The properties for a tether made of Dyneema can be found in Table 2.

Dyneema rope properties	Value	Unit
Tensile strength	1100	MPa
Density	700	kg/m^3
Factor of Safety	2	-

Table 2: Dyneema properties

For the mass of the wing a formula was derived. The mass of the wing is considered linearly dependent on the force acting upon it. The force will be primarily the lift generated by the wing. Therefore, the mass of the wing will be considered linearly dependent on the lift.

$$m_{wing} = C_m \cdot S \cdot \rho \cdot v^2 \quad (1)$$

where C_m is a constant, S is the wing surface ρ is the local air density and v is the encountered wind speed.

Since lightweight structures are considered for the wings, an inflatable airplane was used as a reference [6]. The mass of the plane from reference [6] is about 11 kg for 18 m^2 wing surface, while the allowed wind speed is about 12 m/s and the air density at ground level applies. An additional 50% mass was added for mechanisms required. With these numbers C_m was determined:

$$C_m = \frac{1.5 m_{wing}}{S \cdot \rho \cdot v^2} \approx 5 \cdot 10^{-3} \text{ [kg/N]}$$

In order to compare the concepts, a wind profile as a function of the altitude was assumed, with different profiles above and below one kilometer. The profile below one kilometer is given by

$$v_{wind} = 3.48 + 0.00573 \cdot h \text{ , } 0 < h < 988 \text{ m}$$

where h is the altitude in meters. Above one kilometre the profile is given by

$$v_{wind} = 7.85 + 0.00146 \cdot h \text{ , } h \geq 988 \text{ m}$$

These profiles are a linear approximation of real wind data obtained from the Royal Netherlands Meteorological Institute [7]. The profiles change at 988 meters because this is a measurement altitude in the dataset. Other boundary conditions can be found in Table 3.

Parameter	Value	Units
Lift coefficient of wings	1	-
Drag coefficient of wings	0.15	-
Minimum required tether angle	45	degrees
Distance between wings	100	m
Pumping mill descend ratio	0.5	-

Table 3: Boundary conditions

The minimum required tether angle is the angle between the Earth surface and the tether. Controlling this angle is used to limit the horizontal range of the tether. The pumping mill descent ratio is the time needed for the descent, divided by the time required for the ascent. With these parameters, a Laddermill and a pumping mill can be sized under equal circumstances

4.3. *Sizing results*

The results of sizing both concepts for a power requirement of 5 MW and an operating height of 5 km can be found in Table 4. The tip range mentioned in the table is the horizontal range of the tether.

P=5MW H_{max}=5km	Ladder mill	Pumping mill	
Wing mass	49.7	22.8	Tonnes
Tether mass	15.8	7.9	Tonnes
Tether speed	5.2	5.9	m/s
Generator	5	7.5	MW
Tip range	4.0	4.1	Km

Table 4: Laddermill vs. pumping mill

Table 4 shows that the Laddermill wings are 2.2 times heavier than the pumping mill wings and the tether is 2 times more massive.

The results for a power requirement of 5 MW and an operating height of 3 km can be found in Table 5.

P=5MW H_{max}=3km	Ladder mill	Pumping mill	
Wing mass	57.5	26.1	Tonnes
Tether mass	11.2	5.6	Tonnes
Tether speed	4.3	5.2	m/s
Generator	5	7.5	MW
Tip range	2.3	2.6	km

Table 5: Laddermill vs. pumping mill

Table 5 shows that the Laddermill wing mass is 2.2 times higher than the pumping mill wing mass and the tether is 2 times more massive.

The reason for the mass difference is given in Table 1: The wings and the cable of the Laddermill are not optimized for a certain altitude. The heavy wing required for high altitudes with high velocity winds is also used for low altitudes. Likewise, the tether thickness of the Laddermill is determined by the maximum tension, but this thickness is also used at the top of the loop where the tension of only one wing is present. This is the first order effect of the inefficient use of mass. The second order effect is that the excessive weight of the tether and wings decrease the tension caused by the lift of the wings. Also, the excessive weight decreases the tether speed as can be seen in Table 4, because the tether angle becomes too small. Since the generated power is the product of tension and tether speed, a lower tether speed demands higher tension and thus a larger structure.

It was found that for varying operating altitudes and power requirements the mass ratios between the Laddermill and the pumping mill remain almost the same.

4.4. Cross wind power

The performance of both concepts can be improved by using the phenomenon of cross wind power. This can be done for the Laddermill by, instead of connecting the wing directly to the main tether loop, connecting it with an additional length of tether, presented in Figure 4. The kites can now make a swinging motion out of plane.

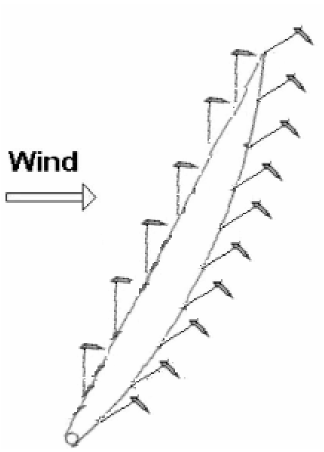

Figure 4: Laddermill with wings on ropes for cross wind power [after 1]

The same can be done for the pumping mill. The feasibility of this method for a large unit will have to be investigated. When the wings are very large, long tethers are required for the out of plane swinging motion.

Another option is to swing the whole structure in the out of plane direction. This can also be applied to both concepts.

4.5. Cross wind power results

Sizing with crosswind power was only performed for the pumping mill. The results of the sizing of the pumping mill with use of cross wind power for 5 and 3 km altitude are given in Table 6 and Table 7. It was assumed that the local wind speed can be tripled using cross wind power [4]. For comparison, the values for the pumping mill without crosswind power are repeated in the tables.

5MW 5km	Pumping Mill +cwp	Pumping mill	
Wing mass	14.3	23	tonnes
Tether mass	6.4	7.9	tonnes
Tether speed	7.0	5.9	m/s
Generator	7.5	7.5	MW
Tip range	2.1	4.1	km

Table 6: pumping mill with and without cross wind power

5MW 3km	Pumping Mill +cwp	Pumping mill	
Wing mass	14.7	26.1	tonnes
Tether mass	4.0	5.6	tonnes
Tether speed	7.0	5.2	m/s
Generator	7.5	7.5	MW
Tip range	1.5	2.6	km

Table 7: pumping mill with and without cross wind power

These figures show that an increase in performance can be expected by making use of cross wind power.

Using cross wind power also has an advantage when considering a variable wind speed: when the wind speed is higher, the local wind speed can be kept the same by reducing the out of plane motion.

5. Conclusion of the comparisons

In this section the results of the conceptual comparison and the numerical comparison will be analysed. Only some of the issues discussed in the conceptual comparison will be analysed in this section. These are (from Table 1): tether strain, weather adjustability, generator-tether interaction, inspection and groundstation. The other entries of Table 1 are included in the numerical comparison.

The changing tether strain in the case of the pumping mill will have a negative effect on the power production of the pumping mill. The simulations performed to determine the ascent time/descent time ratio of the pumping mill however show that several seconds are required to change the tether velocity from up to down. This time was already taken into account in the numerical simulation and is enough to change the strain in the tether.

The Laddermill concept provides better weather adjustability than the pumping mill. Further research must be performed to determine the effect of adjusting the concepts to changing weather conditions. However, the capacity factor of the pumping mill is already 70%, as is demonstrated in the next section.

The effect of tether-generator interaction will have to be inspected for both concepts. If modifications of the tether turn out to be required, the negative effect will be larger for the Laddermill. For the Laddermill the entire tether must be modified, while for the pumping mill only the lower part of the tether will have to be modified.

Inspection of the cable could have a negative impact on the efficiency of the pumping mill, but a simulation with real wind data indicates that the pumping mill will be down regularly, providing ample time for inspection and repair.

The groundstation of the two concepts both feature a generator, driven by an ascending tether. For the Laddermill, a number of extra features are required: a second, incoming cable, incoming wings and outgoing wings. It is therefore expected that a Laddermill groundstation will be more complex.

Finally, the numerical comparison of the two concepts shows that a Laddermill requires twice the amount of material of a pumping mill.

These conclusions suggest that the pumping mill may be a better option for exploiting high altitude wind energy than the Laddermill. Further research into issues mentioned in this section must be performed before a final conclusion can be made.

In the next section, a simulation with real wind data is presented. This was only performed for the pumping mills.

6. Real wind data simulation

The four pumping mills of Table 6 and Table 7 were simulated using historic wind data from several altitudes obtained from the Royal Netherlands Meteorological Institute [7]. The dataset consists of 20 years of measurements, performed twice per day at several altitudes between ground level and 12000 m.

Each generated pumping mill is a string of different wings and tether segments. The strength of each wing determines the maximum allowable wind speed at a certain altitude. If the wing load is kept below the design load, the tension in the tether will never be higher than the strength allows.

6.1. Explanation of the simulation

The pumping mills will be simulated in every wind profile in the dataset. The first wing is placed at the altitude for which the pumping mill was designed. The wind speed at this altitude is retrieved from the dataset. From the wind speed, the wing mass and the tether motion the tether angle is determined, as in Figure 3. When the wind speed is higher than the wing can sustain, it is assumed that the lift can be reduced to the maximum lift allowed, by adjusting the angle of attack.

The tether angle θ and the tether segment length give the position of the next wing. The procedure is done from the top of the pumping mill to the last wing. When the tether angle becomes too small, the tether speed is lowered. When the last wing is too high above the ground or below the Earth surface, the altitude of the highest wing is adjusted. When the pumping mill is successfully modelled, the generated power level is determined. If the tether speed falls below 0.8 m/s the power is set to naught and the next wind profile is simulated. When the whole dataset is processed, the average power is calculated. Please note that this "simulation" is actually an analytical solution which, although time consuming, can be calculated by hand.

6.2. Simulation results

The results of the simulations of the four pumping mills from Table 6 and Table 7 are

presented in this section. The results for two 7 km high laddermills are added to show the dependency of system mass and performance on altitude. Each of the pumping mills is designed to deliver 5 MW. Since the descent phase is half of the ascent (power generation) phase, the installed generator power is 7.5 MW.
The results of the simulation are presented in Table 8. The results for the REpower 5M windmill are also in the table for comparison. The wing mass for the REpower 5M is the mass of the three blades together and the average power is estimated at 27.5% [8].

Height (km)	Cwp	Wing mass (ton)	Tether mass (ton)	Average power (MW)
3	No	26.1	5.6	3.48
3	Yes	14.7	4.0	3.54
5	No	22.8	7.9	3.49
5	Yes	14.3	6.4	3.62
7	No	20.6	9.9	3.42
7	Yes	14.1	8.7	3.78
0.126	Yes	54 (blades)	750 (tower)	1.9

Table 8: Simulation results

Table 8 shows that the differences in the average power of the pumping mills are not substantial. The system mass for a pumping mill with cross wind power is lower than the pumping mill without cross wind power, shown in Figure 5.

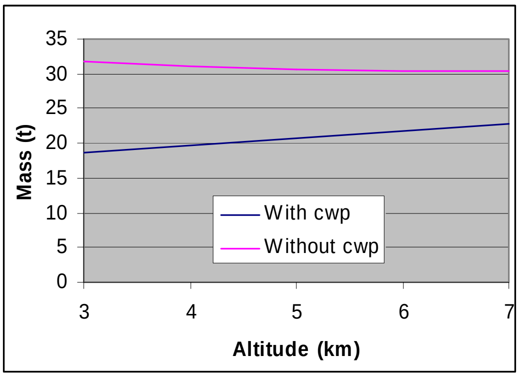

Figure 5: Pumping mill system mass

For comparison, the wing mass, tether mass and total mass for a pumping mill without cross wind power is given in Figure 6. The same is done for a pumping mill with cross wind power in Figure 7.

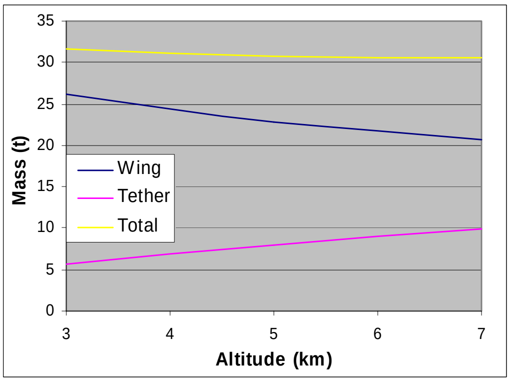

Figure 6: Pumping mill, without cwp

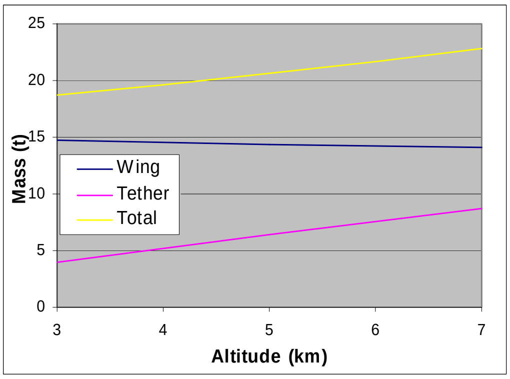

Figure 7: Pumping mill, with cwp

As mentioned, the system mass with cross wind power is lower than without it. However, it will have to be investigated if the mass savings justify additional effort of implementing the use of cross wind power for a pumping mill.

6.3. 5 MW windmill simulation

The dataset was also used to simulate the generated power of a conventional 5 MW windmill. The performance was extrapolated from the REpower MM82 wind turbine [9], which is a 2 MW windmill. The performance for different wind speeds is given in Figure 8. The same performance profile was applied for the REpower 5M, for which such a profile is not available yet.

Wind speed v [m/s]	Power P [kW]
3.0	0
4.0	58
5.0	155
6.0	290
7.0	487
8.0	731
9.0	1005
10.0	1288
11.0	1594
12.0	1834
13.0	1972
14.0	2000
15.0	2000
16.0	2000
17.0	2000
18.0	2000
19.0 – 25.0	2000

Figure 8: REpower MM82 performance [9]

One of the measurement altitudes of the dataset contains is performed at 111 m altitude, comparable to the 126 m hub height of the REpower 5M windmill.
With the wind speed / power profile used on the dataset an average power of 0.5 MW was achieved. This shows that a bad site for a conventional windmill is not necessarily a bad site for a pumping mill.

7. Conclusions

The Laddermill and the pumping mill were compared under equal circumstances. It was shown that a pumping mill will result in a more lightweight option for equal operating altitude and height. The pumping mill was put to the test with real historic wind data. This simulation showed that the pumping mill can generate on average 70% of the installed power, which is more than the average of a conventional windmill. Please note that the average ratio of produced power to installed power in the Netherlands was only 17% in 2003 [10].
Further comparison of the pumping mill to a conventional windmill with real wind data shows that the pumping mill can be located at areas that are not interesting for conventional windmills. Also, the estimated wing mass for a pumping mill may be lower than the mass of the windmill blades. The wing mass however is an estimation, further research will be dedicated to this issue.
Future research will also include simulation of other concepts, derived from the pumping mill. Examples are a pumping mill with only a single wing at the top of the tether, and a pumping mill with no wings on the lower half of the tether.

8. Acknowledgements

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9. References

[1] Ockels, W.J., 2001, "Laddermill, a novel concept to exploit the energy in the airspace", *Aircraft design 4* (2001), pp 81-97.
[2] Dutch Ministry of economic affairs, 2001, "Bestuursovereenkomst Landelijke Ontwikkeling Windenergie (Blow)", accesseble
[3] Laddermill patent, patent number US6072245.
[4] Loyd, M.L., 1980, "Crosswind Kite Power", *Journal of Energy*, vol. 4, No. 3, pp 106-111.
[5] Ockels, W.J., Lansdorp, B., Breukels, J., The Laddermill: work in progress, EWEC 2004, London, UK.
[6] Breukels, J., 2003, "Design of a high altitude inflatable kite", Master thesis report, Faculty of Aerospace Engineering Delft University of Technology, The Netherlands
[7] Royal Netherlands Meteorological Institute.
[8] Danish Wind Energy Association website, 2004, www.windpower.org, accessed 2-11-2004
[9] REpower website, 2004, www.repower.de, accessed 2-11-2004.
[10] Statistics Netherlands (Centraal Bureau voor de Statistiek), 2003, "Duurzame energie in Nederland", http://www.cbs.nl/nl/publicaties/publicaties/bedrijfsleven/energie-water/duurzame-energie-in-nederland-2003.pdf, accessed 3-11-2004.
at http://apps.ez.nl/publicaties/pdfs/blow-bw1.pdf accessed 3-11-2004.