Design of a 100 MW laddermill for wind energy generation from 5 km altitude

Bas Lansdorp, M.Sc.
Delft University of Technology
bas.lansdorp@lr.tudelft.nl

Prof. dr. W.J. Ockels
Delft University of Technology

This paper presents the design of a 100 MW Laddermill. The Laddermill is a novel concept to generate electricity from high altitude winds. The concept allows very large single unit powers. It generates electricity by pulling a rope from a generator, with lift generated by kites. For a 100 MW Laddermill 50 kites are distributed evenly in the top 5 km of a 6.5 km long rope. 500 m of the rope is wound around the generator. The kites pull the 500 m of rope from the generator, thus driving it. Subsequently the kites fly down in a configuration that generates significantly less lift than during the ascent. This way the tether is retrieved and the process is repeated.
The 50 kites required for a 100 MW Laddermill each have the wing surface of two soccer fields, or 13.000 m^2. Large controllable kites are thus an enabling technology for the Laddermill. Preliminary results including a practical demonstration exist.
The tether will be tapered, with a diameter of 24 cm at ground level to 4 cm at the altitude of the highest kite. The groundstation will feature a large drum for the cable, a gearbox and some cable guidance equipment. The whole groundstation can be rotated to align with the wind direction. The groundstation is connected to 2000 tons of ballast which prevents the kites from lifting the groundstation from the ground.
This paper discusses several design options considered for the Laddermill concept and the groundstation. It also reports on the results of tests that are performed in which the Laddermill principle is demonstrated and the first Laddermill electricity is produced.

1. Introduction

While the wind energy content of the atmosphere increases significantly with increasing altitude, no electrical power is currently generated from high altitude winds. Figure 1 shows the average wind over 20 years in the Netherlands versus the altitude. This paper presents the design of a novel concept that enables wind energy generation from high altitude winds; the Laddermill.
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. Recent simulations show the Laddermill can have a capacity factor of about 65%, while the installed power of a single unit may be up to 100 MW. This will enable generating substantial percentages of a country's electricity requirements from wind. It will take only about 20 Laddermills to generate 10% of the Dutch electricity demand.

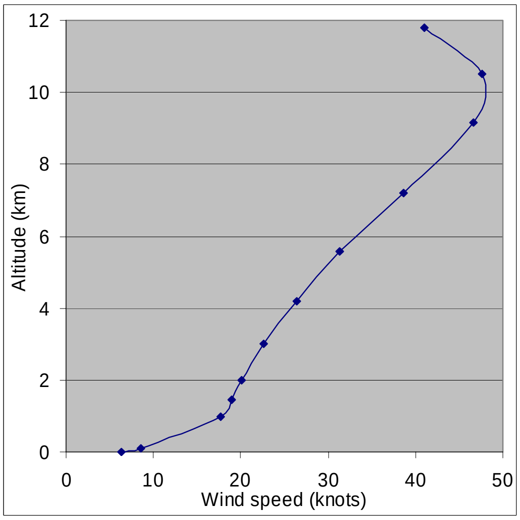

Figure 1: Average wind over the Netherlands versus the altitude [1]

2. The Laddermill concept

The Laddermill concept makes use of lifting bodies, called wings, connected to a tether that stretches into the higher regions of the atmosphere. The tether of the kite is wound around a drum. The tension that the kite creates in the tether pulls the rope off the drum, thus powering a generator.

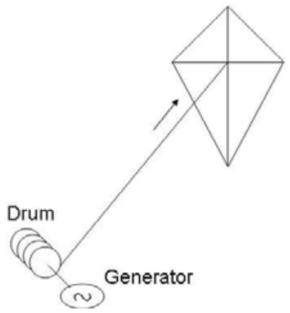

Figure 2: Simple illustration of the Laddermill principle

When the kite is moving up the angle of attack is high to generate high lift and a large tension in the cable, shown in Figure 3.

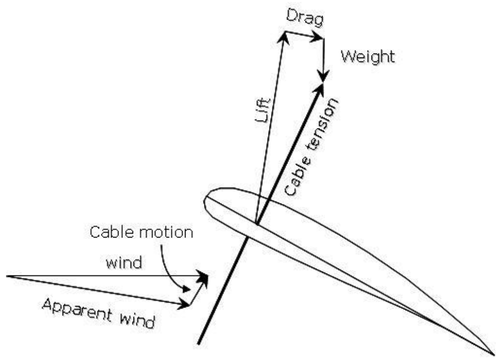

Figure 3: Kite ascending

When the entire tether has been pulled of the generator, the tether must be retrieved. In order to do this efficiently, i.e. without sacrificing substantial amounts energy to pull the cable back in, the lift of the kite is reduced by lowering the angle of attack, shown in Figure 4.

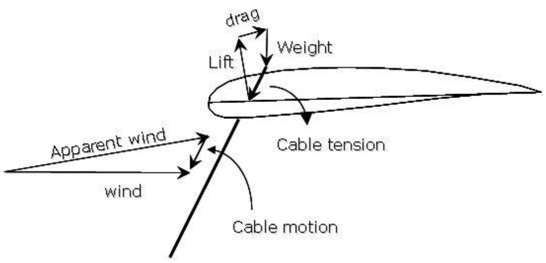

Figure 4: Kite descending

The actual Laddermill will have several wings connected in the upper section of the tether.
The installed power of a Laddermill 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.

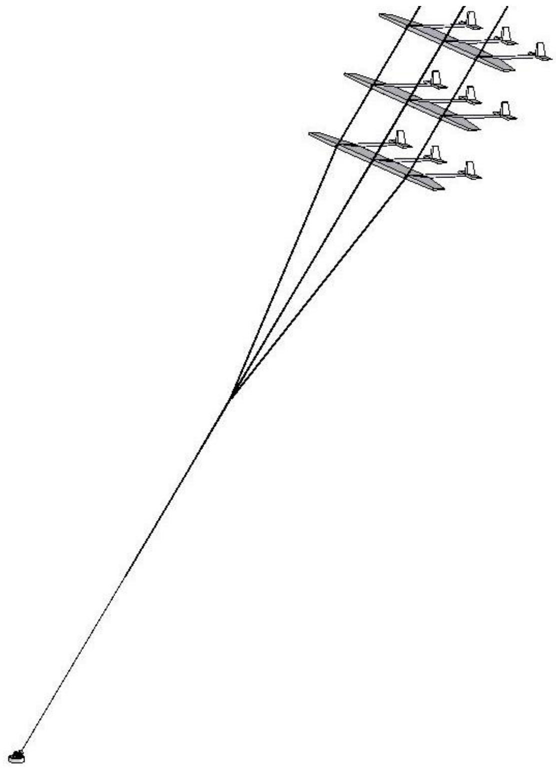

Figure 5: Artist impression of the Laddermill

3. Design of a 100 MW Laddermill

In this section, a Laddermill will be generated that can is optimized to generate 100 MW of power in the average wind profile that is presented in figure Figure 1. This wind profile is the average wind over the Netherlands between 1960 and 1980. The data was obtained from the Royal Dutch Meteorological Institute (KNMI) [1].
The laddermill that is created in this wind profile consists of a number of wings and a number of tether segments. The power generation of this laddermill is then simulated in the historic high altitude wind data.

3.1. Boundary conditions

As was mentioned, a Laddermill will be created that generates 100 MW of power in the average wind profile.
As a simplification of the wind profile of Figure 1, a linear wind profile as a function of the altitude is assumed, with different profiles above and below one kilometer. The profile below one kilometer is given by:

$$v_{wind} = 3.48 + 0.00573 \cdot h \ , \ 0 < h < 988 \text{ m} \qquad (1)$$

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

$$v_{wind} = 7.85 + 0.00146 \cdot h \ , \ 988 \le h \le 5000 \text{ m} \qquad (2)$$

The profiles change at 988 meters because this is the altitude of one of the measurement points in the dataset.
For the tether material, Dyneema was selected. The properties for a tether made of Dyneema can be found in Table 1.

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

Table 1: Dyneema properties [3]

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.

$$m_{wing} = C_m \cdot S \cdot \rho \cdot v^2 \qquad (3)$$

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 [4]. The mass of the plane from reference [4] 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:

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

Other inputs used in the sizing process are given in Table 2.

Parameter	Value	Units
Maximum operating altitude	5000	m
Lift coefficient of wings	1	-
Drag coefficient of wings	0.15	-
Minimum required tether angle	45	degrees
Distance between wings	100	M
Descend/ascent ratio	0.5	-

Table 2: Boundary conditions

It has been found that the maximum allowed operating altitude does not influence the power production to a large extend [5]. The 5 km altitude was selected because a 100 MW laddermill requires many large wings. A high operating altitude with a long tether has more space for more wings, which can then be somewhat smaller.
The lift and drag coefficients of the wings were selected somewhat conservatively.
The minimum required tether angle is the angle between the horizontal and the tether. By restricting the minimum value of this angle, it is assured that the Laddermill will not range too far.

The distance between the wings determines the number of wings. Selecting a larger distance between two wings will result in bigger wings.
The descent/ascent ratio is the time it takes the Laddermill wings to fly down divided by the time during which power is generated. The ratio of 0.5 indicates that flying down goes twice as fast as going up, meaning that power is generated 66.7% of the time [6]. Faster descend is subject of ongoing research.

3.2. Laddermill sizing

Sizing of the concepts was performed by placing the first wing at the maximum operating altitude and calculating the forces acting upon it. To calculate the forces, the aerodynamic forces, the motion of the tether and the wing mass are into account. The wing mass is determined by equation (3). The wind speed is given by equation (2). The calculation results in a tether angle θ, as presented in Figure 6. 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.

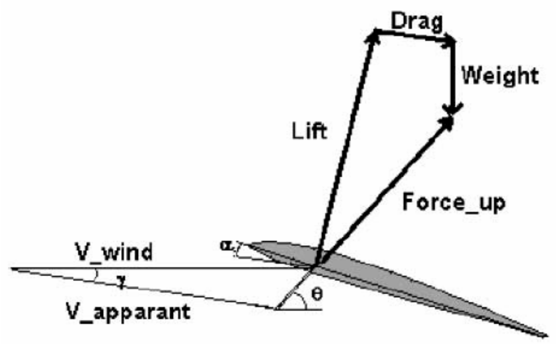

Figure 6: Forces on upper wing [1]

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.
While the cable turns out to be 6900 m long, only 50 wings are placed at the Laddermill. The lowest wing is located at 1260 m altitude. The wings that are left out would deliver only a small contribution to the power. Furthermore leaving the lower wings out will reduce visual pollution.

3.3. Resulting Laddermill

The laddermill that results from the sizing process consists of 69 cable segments of 100 meters in length each, and 50 wings. The cross sectional area of the cable increases from the top to the ground. This is shown in Figure 7.

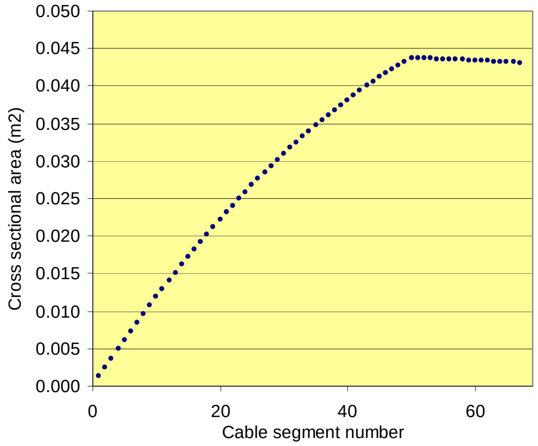

Figure 7: 100 MW laddermill cable segment mass

The wing mass decreases from top to ground because the wind speed the wings are designed for is smaller. This can be seen in Figure 8.

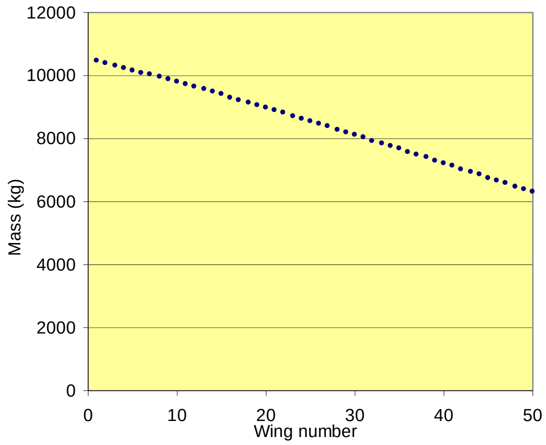

Figure 8: 100 MW laddermill wings mass

3.4. Wings

The baseline concept for the wings of a Laddermill is a semi-rigid inflatable plane, bridled at several point along the leading edge, such as presented in Figure 9. Such kites could in principle be controlled in a similar way as airplanes.

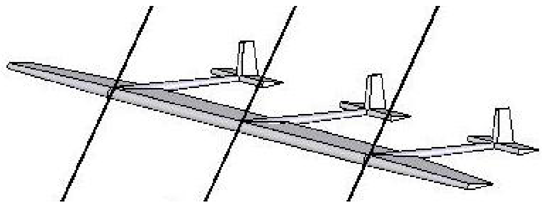

Figure 9: Baseline concept for Laddermill wings

Also more flexible wings such as parapentes and surfkites are investigated. The controllability of these types of kites require a different control mechanism. Each wing will have a wing area of about 13.000 m^2, or the size of two soccer fields.

3.5. Groundstation

At the groundstation the cable is rather massive: the cable diameter d is 24 cm. The rule of thumb for bending Dyneema states that the smallest diameter it can be bent to is 10·d [3]. This results in a large drum radius of 2.4m. Because of the high tension in the tether, a safety factor of 2 is applied on the bending radius, which gives a 4.8m drum radius, such as is presented in Figure 10.

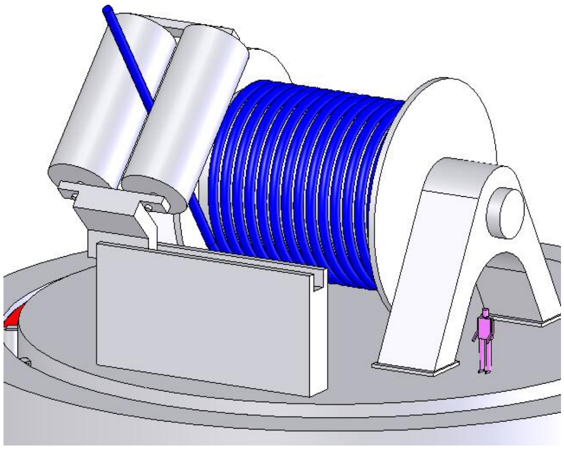

Figure 10: Groundstation baseline concept

An advantage of the large bending radius is that the drum of the groundstation can hold 500m of tether without piling up the tether on top of itself. This protects the tether from being damaged. This 500m of tether is used for power generation; it will be pulled off the drum by the wings to power the generator. When it is windless and the whole Laddermill needs to be retrieved, the tether will be piled on top of itself, but this will happen under low tension circumstances.

3.6. Simulation

Now a virtual laddermill is created, consisting of cable segments with given mass and diameter, and wings with given properties.

This Laddermill will now be simulated using historic wind data from several altitudes obtained from the Royal Netherlands Meteorological Institute [1]. The historic wind dataset consists of 20 years of measurements, performed twice per day at several altitudes between ground level and 12000 m. The virtual Laddermill is simulated in every wind profile in the dataset, so a simulation consists of about 10.000 measurements of generated power. The simulation will result in a number of useful results such as average power, number of days or times that the Laddermill comes down and seasonal variation in the power production.

As shown in Figure 7 and Figure 8, the Laddermill is basically a string of different wings and tether segments. Each tether segment has a given strength and each wing has a maximum allowable lift. The masses of the wings and tether segments are known. If the wing load is kept below the design load, the tension in the tether will never be higher than the strength allows.

The first wing is placed at the altitude for which the pumping mill was designed, or 5km. The wind speed at this altitude at day 1 is retrieved from the dataset. From the wind speed, the wing mass and the tether motion the tether angle is determined, as in Figure 6. When the wind speed is higher than the wing can sustain, it is assumed that the lift can be reduced to exactly 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 for this specific day in the data set 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, could be calculated by hand.

3.7. Simulation results

The most interesting result of the simulation is the capacity factor. The simulation gives a capacity factor of the 20 years of the simulation of 0.553. The capacity factor varies over time, as is presented in Figure 11.

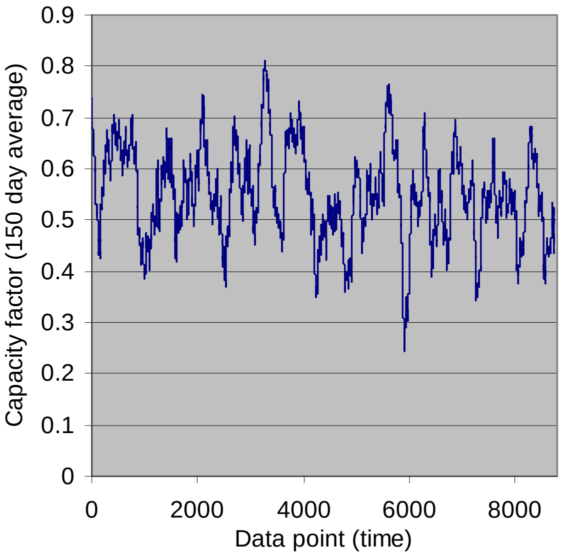

Figure 11: 150 day walking average capacity factor versus time.

Careful inspection of the graph did not reveal any seasonal changes; the peaks and valleys of the graph appear at random.

4. Alternative options

The Laddermill concept as described in the previous sections is the current baseline design. Three alternative options will be discussed in this section.

4.1. Wings

While the current baseline wing is an inflatable glider-like structure, two other types of wings are considered: cloth-type and surf-kite type. An example of a cloth type kite is given in Figure 12 [7], a surf kite is shown in Figure 13 [8]. The main advantage of these two wings is that they are possibly cheaper than inflatable structures. A disadvantage is that they the may be more difficult to control.

Figure 12: Cloth kite replacing sails of a sailing boat [7]

Figure 13: Surf Kite [8]

4.2. Cross wind power

The baseline laddermill wings go straight up and down. Another option, which is also used in normal windmills, is to make use of cross wind power. The Laddermill wings can perform a swinging motion to increase the relative wind speed. This will enable much smaller wings; if the relative velocity can be increased by a factor of 3, the wing surface can be 9 times smaller.

A disadvantage of smaller wings that use cross wind power is that it will be more difficult to restart a laddermill after downtime, because ground winds need to be high enough to lift the wing. However, a helium balloon could overcome this. Another disadvantage is the higher complexity and stability requirements of kite control when using cross wind power. Recent experiments involving radio control of a surf kite revealed that sufficient control authority might be feasible with rather simple effectuaters [9].

4.3. Groundstation

The groundstation concept presented in Figure 14 has some advantages over the baseline concept. The tether does not have a (normal) round shape, but a rectangular shape. It is thus a tape. While the round tether of the baseline concept has a diameter of 24 cm, the tape has a thickness of 7 cm and a width of 70 cm. Because of this, the diameter of the drive shaft can be more than three times smaller. This results in a higher frequency of about 70 RPM. An even wider and thinner tape will result in higher frequencies.

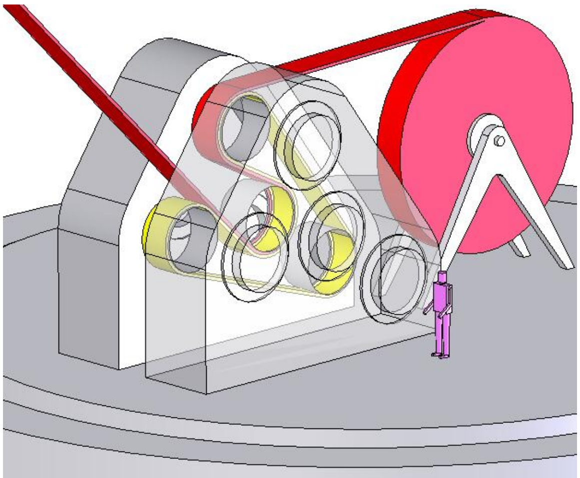

Figure 14: Tape tether with pressure band

5. Conclusions

The Laddermill has several good qualities which make it an interesting concept for further development. The Laddermill concept allows large single unit powers, which may lead to low costs per kWh. Simulation shows that the Laddermill can achieve a capacity factor of about 55%, which is quite high compared to other renewable energy sources.

Several options such as the groundstation concept, the concept for the wings and the possibility of using cross wind power are currently under research.

6. Acknowledgements

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