Chapter 14
Model-Based Efficiency Analysis of Wind Power Conversion by a Pumping Kite Power System

Uwe Fechner, Roland Schmehl

Abstract Airborne Wind Energy is gaining increasing attention. Compared to conventional wind turbines, this class of innovative technologies can potentially generate more energy at a lower price by accessing wind at higher altitudes which is stronger and steadier. In this chapter, first a theoretical system model of a kite power system in pumping mode of operation is presented. Then it is validated with electrical and mechanical measurement results. The model is used to predict the electrical power output and the size of the major components. The terms *pumping efficiency*, *cycle efficiency* and *total efficiency* are introduced. It is shown that the kite power demonstrator of Delft University of Technology currently achieves a maximum total efficiency of 20%. The analysis indicates that it will be possible to design small to medium sized kite power systems with a total efficiency of 50% to 60%. The terms *nominal power* of a ground station and *system power* of a kite power system are introduced, noting their particular difference: the nominal power is the installed electrical generator power whereas the system power is defined as the average net electrical power output at nominal wind velocity.

14.1 Introduction

Wind power is an important factor in the transition towards renewable energies. However, the material resource requirements of conventional tower-based wind turbines are substantial. This holds true especially for offshore wind parks and is even more critical for deep sea deployment which requires costly floating platforms. Furthermore, wind turbines have a considerable impact on the environment. Wind parks, especially onshore, are often criticized for their visual impact and effect on

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the wildlife, e.g. birds and bats, which negatively affects the public acceptance of the technology.

Kite power systems are an attractive alternative, using the traction power of a tethered wing for wind energy conversion. Replacing the tower and rotor blades of a wind turbine by a lightweight tensile structure reduces on one hand the investment costs and on the other hand decreases the environmental footprint. Since wind at higher altitudes is stronger and steadier the productivity of such an installation can be increased considerably. Building on earlier conceptual analyses [6], the kite power research group of Delft University of Technology has developed a prototype with 20kW nominal generator power [7]. For continuous energy conversion, the system is operating in periodic pumping cycles. Each cycle consists of an energy generating reel-out phase, in which the kite is operating in figure-of-eight flight maneuvers to maximize the pulling force, and a reel-in phase in which the kite is de-powered and pulled back towards the ground station using a small fraction of the generated energy.

Fig. 14.1 Kite power system with 20kW nominal generator power in operation at the Maasvlakte 2 test site: photo composite of figure-eight flight maneuver with $\Delta t = 1s$ (left), view from ground station to the 14m^2 kite for high wind speed (right)

The characteristic figure-of-eight maneuver is illustrated in Fig. 14.1 using video footage recorded at a technology demonstration in June 2012 at the Maasvlakte 2 test site. During reel-in, the generator is operated as a motor and the kite is pulled back towards the ground station. To minimize the amount of energy required for this retraction phase the wing is de-powered by decreasing its angle of attack.

In general, each pumping cycle consists of 60 to 180 seconds of reeling out, followed by 60 to 90 seconds of reeling in. For the small off-grid system, a rechargeable battery is used to buffer the energy over the cycles. For a group of interconnected systems, the buffer capacity can be reduced by phase-shifted operation. An important consequence of the periodic alternation of energy generation and consumption is the requirement of efficient conversion processes. For example, the fraction of energy that is used to retract the kite is passing the conversion chain in both directions, from mechanical to electrical, into short-term storage, and then from electrical back to mechanical. Conversion efficiencies basically apply twice to this particular flow of energy. Next to the efficiencies, the ratio of generation and consumption time periods have a significant effect on the total efficiency.

This is analyzed systematically by first compiling a system model in Sect. 14.2, which is then validated by comparison to experimental data in Sect. 14.3. Following, an improved kite power system design for 31 kW is presented in Sect. 14.4.

14.2 System model

The system model is averaging over the reel-out phase and iterating over the reel-in phase. It uses quasi-static equations and neglects the dynamics of the kite and of the drum of the ground station. To compensate the non-ideal real-world behavior a dead time of five seconds without any power generation between reel-in and reel-out is used. Additionally, crest-factors (ratio of maximal and average value) are used to adapt the model to the real world.

14.2.1 Kite kinematics

To simplify the calculations, it is assumed that the tether is a straight line between the kite and the winch. If the average length $\bar{l}$ of the tether and the elevation angle β are known, the average height $\bar{h}$ of the kite can be calculated as follows

$$\bar{h} = \bar{l} \sin\beta \tag{14.1}$$

14.2.2 Atmospheric model

To determine the wind speed $v_{w,g}$ at the height of the kite, the least-square power law [1] is used. Input parameters are the ground wind speed $v_{w,g}$ at 10 m height and the average height during the reel-out phase $\bar{h}$ of the kite. It establishes the relationship between v_w and $v_{w,g}$ as

$$v_w = v_{w,g} \left(\frac{\bar{h}}{10\,m} \right)^{\alpha}. \tag{14.2}$$

The standard value of the exponent α is 1/7, whereas for offshore applications a value of $\alpha = 0.11$ is used.

The air density ρ must also be known for the calculation of the tether force. If we assume a constant temperature of 15 °C, according to [8, p. 6] the air density can be calculated as

$$\rho = \rho_0 \ \exp\left(-\frac{\overline{h}}{H_\rho}\right), \tag{14.3}$$

where $H_\rho = 8.55\ km$, and where the average sea-level density $\rho_0 = 1.225\ kgm^{-3}$.

14.2.3 Aerodynamic performance of tethered kites

The aerodynamic performance of a kite depends on the following parameters:

- projected area[1] of the kite A
- lift to drag ratio L/D
- max. wing loading [N]
- depower capability (quotient of L/D during reel-out and L/D during reel-in)

The lift to drag ratio L/D determines the speed gain, that you get by flying crosswind. Flying crosswind is usually done by flying a figure of eight. This avoids twisting of the tether, which happens, if flying a circle. The pulling force of the kite depends on the apparent wind speed v_a as derived in Chap. 2. $v_{t,o}$ is the reel-out speed of the tether, v_w the wind-speed at the height of the kite and β the elevation angle.

$$v_a = (\cos\beta\cos\phi - \frac{v_{t,o}}{v_w})\ v_w \sqrt{1+\left(\frac{L}{D}\right)^2} \tag{14.4}$$

Because the maximum force shall be calculated we can assume the azimuth angle ϕ to be zero. This results in $\cos\phi = 1$.

To calculate the lift over drag ratio $L/D \ = \ C_L^k/C_D$, it is not sufficient to know the lift C_L^k and drag C_D^k coefficients of the kite. The effective tether drag coefficient $C_{D,eff}^t$ has to be taken into account, too[3]. If the diameter of the tether is known, the tether drag coefficient can be calculated with the following approximation formula, where A_p is the projected area of the kite, d the tether diameter and C_D^t the drag coefficient of the tether with respect to the perpendicular component of the wind.

$$C_{D,eff}^t \approx \ 0.31\ \bar{l}\ \frac{d}{A_p}\ C_D^t \tag{14.5}$$

Because only the upper end of the tether is moving with the speed of the kite and the lower end is not moving at all we need to approximate the average effective tether drag. The amount of this drag is about 31% [2] of the drag that the tether would have, if the full length of it would move with the speed of the kite through the air. This value was derived by simulating a straight tether where one end was fixed and

[1] The area of the shape of the kite, projected on a plane perpendicular to the tether, while the angle of attack is zero.

[2] Without any wind shear this constant would be 1/3. It can be calculated by integrating the drag force over the length of the tether. Because there is wind shear we use the lower value of 31 %.

the other end moved on a circle. The value of C_D^t for a cylinder at Reynolds numbers of about 1e3 is approx. one. Now the total drag C_D and thus L/D can be calculated:

$$C_D = C_D^k + C_{D,eff}^t \tag{14.6}$$

The maximal tether force $F_{t,max}$ can then be calculated, as derived in Chap. 2), as

$$F_{t,max} = \frac{1}{2}\,\rho\, v_a^2 A_p\, C_D \sqrt{1 + \left(\frac{L}{D}\right)^2}. \tag{14.7}$$

This is the force, that the tether and the kite must be able to withstand during normal operation. It must be smaller or equal to the breaking force F_b divided by the safety factor S_t:

$$F_{t,max} \leq \frac{F_{t,b}}{S_t} \tag{14.8}$$

The safety factor S_t must be chosen as high as needed to avoid that the tether breaks before the weak link[3] even if the tether is old and slightly damaged.

The average force is lower, because the kite is not always flying in the center of the wind window. To take that into account, the crest factor CF_f is introduced, defined as the ratio of the maximal and effective tether force. The effective tether force is the quotient of the average mechanical reel-out power $\overline{P_{m,o}}$ and the average reel-out velocity $\overline{v}_{t,o}$. By combining these equations we get:

$$\mathrm{CF}_f = \frac{F_{t,max}\,\overline{v}_{t,o}}{\overline{P_{m,o}}} \tag{14.9}$$

If CF_f is known, then the average mechanical reel-out power can be calculated:

$$\overline{P_{m,o}} = \frac{1}{\mathrm{CF}_f}\,F_{t,max}\,\overline{v}_{t,o} \tag{14.10}$$

The expression $\frac{1}{\mathrm{CF}_f}$ has a similar meaning as the ”performance coefficient of the pumping kite generator”, that was introduced in [2]. For ”representative solutions”, Argatov found a performance coefficient of 0.9, which would result in a crest factor of 1.11. Because Argatov does not take into account the variations of the wind velocity and the impact of gravity (a kite is going downwards faster than upwards, because of it’s weight), in reality the crest factor is higher.

Advantages of defining a crest factor: First it can be easily measured in practical tests; second, it can be compared to the theoretical optimum found by Argatov; and third, it can also be used for calculating of the average power output. On the other hand the crest factor depends on the wind fluctuations. Therefore it must be averaged over a longer period and is fully valid only for a specific location.

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[3] At the top of the tether there should be a weak link that disconnects the kite from the tether in case of a high overload. In this situation the kite must become fully depowered and should stay attached to the main tether with a safety line.

14.2.4 Simulating the reel-in phase

Simulating the reel-in phase is more difficult than simulating the reel-out phase because the elevation angle during reel-in cannot be actively controlled by steering the kite; only when flying crosswind the elevation angle can be actively controlled. Without flying crosswind the elevation angle rises according to Eq. (14.11). This can only be avoided with a lift over drag ration of zero, which is difficult to achieve. Our approach is to assume a quasi-steady equilibrium and steer the kite towards zenith, while trying to keep the azimuth angle zero. Then the derivative of the elevation angle can be calculated as function of the kite properties $C_{L,i}$ and $C_{D,i}$, the reel-in speed $v_{t,i}$ and the elevation angle β. To calculate the average reel-in speed and reel-in force the following method was used:

1. Initialize the elevation angle of the reel-in phase with the last optimized elevation angle of the reel-out phase.
2. Optimize the actual reel-in speed such that the average power over the whole cycle is maximized, assuming the relation between reel-in speed and reel-in force to be constant over the whole reel-in phase.
3. Increase the simulation time by the time step of the iteration Δt which was chosen to be 100 ms.
4. Increase the elevation angle by $\Delta\beta$ according to Eq. (14.11) . $v_{t,i}$ is the actual reel-in speed.
5. Repeat step 2 to 4 until the minimal reel-in length is reached.

$$\Delta\beta = \frac{v_w}{l}\left(\frac{L}{D}\left(\cos\beta - \frac{v_{t,i}}{v_w}\right) - \sin\beta\right)\,\Delta\,t \tag{14.11}$$

Equation (14.11) is derived from the formula for the tangential velocity in Chap. 2.

In Fig. 14.2 the reel-in trajectory of the kite, using this algorithm, is shown as a solid line. The wind is coming from the left side. We reel out from $x = 200\ m$ to $x = 385\ m$. Then we reel in while the elevation angle is rising according to Eq. (14.11). Finally a transition phase is needed to decrease the elevation angle and reach the optimal reel-out angle again. In the simulation the path of the transition phase is not calculated, instead an experimentally determined time without power production (5 s) is used.

14.2.5 Pumping efficiency, cycle efficiency and duty cycle

After the average mechanical reel-out power is determined in Eq. (14.10), the average mechanical power over a full cycle shall be calculated. If it would be possible to reel in with zero force, then the duty cycle D would be sufficient to calculate the average mechanical power. The duty cycle is defined as ratio of the reel-out duration Δt_o and the total cycle time:

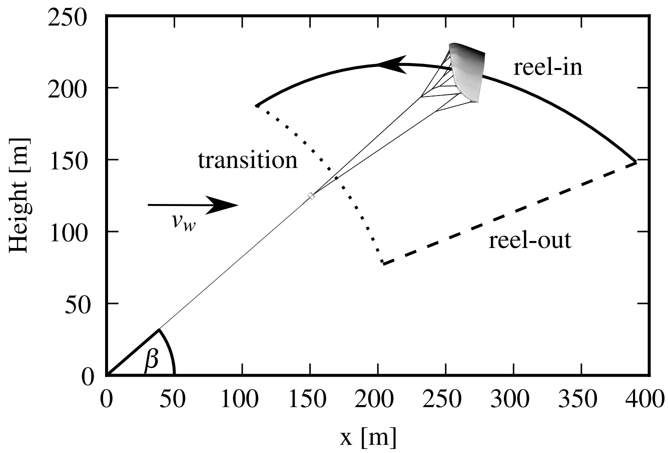

Fig. 14.2 Trajectory of the 29.5 m^2 kite at 7 m/s wind speed that was assumed in the simplified 2d-model of the simulation.

$$D = \frac{\Delta t_o}{\Delta t_o + \Delta t_i} \tag{14.12}$$

The duty cycle is determined by the winch and the wind speed: if the maximal reel-out and reel-in speed of the winch are the same, then a duty cycle of about 50% gives the highest power output at high wind speeds. At lower wind speeds (and a lower reel-out speed) a better duty cycle can be reached.

To improve the duty cycle at high wind speeds, a winch with a high maximal reel-in speed and a low maximal reel-out speed (at high torque) is needed.

To determine the optimal duty cycle, we need to know the average reel-in speed. It should be chosen by a power optimization algorithm, taking the following restriction into account:

$$v_{t,i} \leq \frac{v_{t,i,max}}{\mathrm{CF}_{v,i}} \tag{14.13}$$

The minimal crest factor $\mathrm{CF}_{v,i} > 1$ is a system property that depends mainly on the transition time between reel-in and reel-out.

To determine the duty cycle, not only $v_{t,i}$ and $v_{t,o}$ are needed, but also Δt_i and Δt_o. They can be determined, if the reel-in length Δl_t is known. For one cycle, Δl_t is assumed to be the same as the reel-out length. It should be chosen as long as possible, without flying too low (risk of crash and low wind speed) or too high (because of airspace regulations, but also because the weight and the drag of the tether impose a limit). The reel-in duration Δt_i and reel-out duration Δt_o can now be calculated as

$$\Delta t_i = \frac{\Delta l_t}{v_{t,i}}, \qquad \Delta t_o = \frac{\Delta l_t}{v_{t,o}}. \tag{14.14}$$

A certain amount of energy is needed for reeling in. To take this into account, the pumping efficiency η_p of the kite power system is introduced as quotient of the net mechanical energy $E_{m,o} - E_{m,i}$ and the mechanical energy $E_{m,o}$, gained during reel-out:

$$\eta_p = \frac{E_{m,o} - E_{m,i}}{E_{m,o}} \tag{14.15}$$

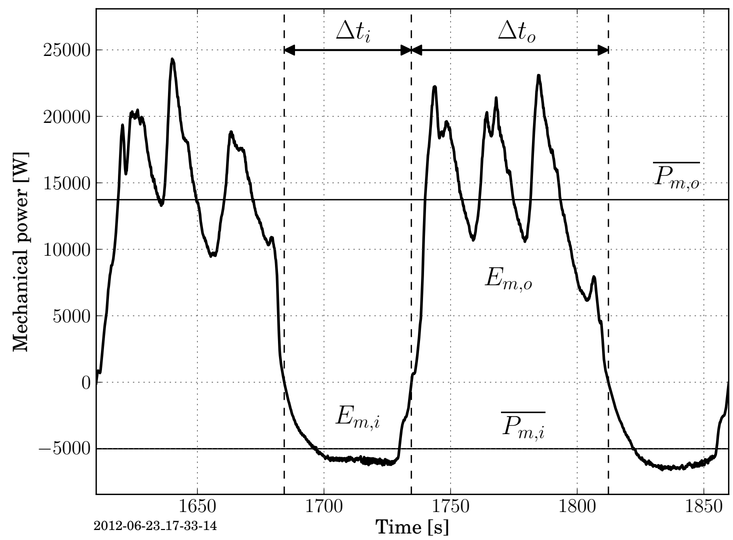

Fig. 14.3 Mechanical power and energy during two cycles. The power curve was measured using a 14 m^2 kite on June 23, 2013.

This efficiency is mainly determined by the depower capability of the kite, but also by the control system (how fast can the kite switch between power and depower mode). Now the average mechanical power over the full cycle $\overline{P_m}$ can be calculated:

$$\overline{P_m} = D\ \eta_p\ \overline{P_{m,o}} \tag{14.16}$$

The last two factors can be combined to the cycle efficiency:

$$\eta_{cyc} = D\ \eta_p = \frac{\overline{P_m}}{\overline{P_{m,o}}} \tag{14.17}$$

This efficiency is a good indication for the performance of a kite power system. It increases at low wind speeds, because in this situation the reel-out time increases, but the reel-in time (limited by the max. reel-in speed of the winch) stays nearly constant. As consequence the duty cycle and thus the cycle efficiency increases.

Therefore η_{cyc} should be given for at least two wind speeds, e.g. the average wind speed and the wind speed that is needed for the nominal power output.

14.2.6 Optimization

Equations (14.16) can be used for a numerical optimization, to determine the optimal height, tether angle and reel-out speed for a given kite-power system, depending on the wind speed.

In addition to Eq. (14.8) the following side condition must be fulfilled during the optimization:

$$v_{t,o} \leq \frac{v_{t,o}^{max}}{S_{v,o}} \tag{14.18}$$

A safety factor $S_{v,o} > 1$ is needed to be able to keep the tether force and the reel-out speed below the allowed limits, when there is a wind gust. The force can be reduced by increasing $v_{t,o}$ very fast (mainly depending on the inertia of the generator and the drum). It can also be reduced by increasing β, but this takes much more time. The safety factor for the reel-out velocity is different from the safety factor for the tether force that was introduced in Eq. (14.8). When the maximum reel-out velocity is exceeded the winch usually stops and the mechanical brakes are activated (to avoid over-voltage and damage to the motor controller). If the wind is strong enough this will result in a force peak that breaks the weak link which should result in a soft landing. The safety factor $S_{v,o}$ should be chosen such that this becomes sufficiently unlikely without sacrificing more potential power output than necessary.

14.2.7 Maximal tether force

According to the data sheet the ultimate tensile strength of Euroneema®HMPE rope (SK75) from Lankhorst Ropes, The Netherlands is 1073.4 N/mm^2. Therefore the breaking force $F_{t,b}$ can be calculated using the following equation:

$$F_{t,b} = \frac{\pi}{S_t} \left(\frac{d}{2} \right)^2 1073.4 \, \frac{N}{mm^2} \tag{14.19}$$

If a stronger rope is used the diameter of the tether can be reduced, but not only the strength of the tether, but also the lifetime should be taken into account when choosing the tether. It is suggested to choose a safety factor S_t of 3.0. A risk analysis should be performed to determine the adequate safety factor for a given application.

14.2.8 Electrical efficiency and total efficiency

For the calculation of the electrical efficiency of the winch first the efficiency of the components have to be determined. This can be done by measurements or by the use of mathematical models, based on the data sheets.

The following efficiencies are taken into account. First of all, the efficiency of the motor and the generator (η_{ei} and η_{eo}). Even if the motor and generator are the same component, these efficiencies won't be the same, because the point of operation will be different. It is very important to take the real point of operation into account, because the efficiencies from the data sheets are usually valid only for the optimal point of operation. Additionally the efficiency of the battery (η_{bat}) is taken into account, but we ignore the system efficiency for now and take it into account later.

If η_p is known, Eq. (14.15) can be solved for $E_{m,i}$:

$$E_{m,i} = (1 - \eta_p)\, E_{m,o} \tag{14.20}$$

To calculate the winch efficiency, we need to calculate the electrical energy, that is produced during one cycle. First the electrical reel-out energy is calculated:

$$E_{e,o}^{gro} = E_{m,o}\, \eta_{e,o} \tag{14.21}$$

Then the electrical energy that is needed for reeling in is calculated:

$$E_{e,i}^{gro} = \frac{E_{m,i}}{\eta_{e,i}} = \frac{(1 - \eta_p)\, E_{m,o}}{\eta_{e,i}} \tag{14.22}$$

To calculate the net energy, we have to subtract the energy that is needed for reel-in, divided by the battery efficiency from the electrical reel-out energy:

$$E_e^{gro} = E_{e,o}^{gro} - \frac{E_{e,i}^{gro}}{\eta_{batt}} = \frac{E_{m,o}\, (\eta_{e,o}\ \eta_{e,i}\ \eta_{batt} - 1 + \eta_p)}{\eta_{e,i}\ \eta_{batt}} \tag{14.23}$$

Now the mechanical net energy is calculated:

$$E_m = E_{m,o} - E_{m,i} \tag{14.24}$$

The ratio of the electrical gross energy and the mechanical energy is the electrical gross efficiency:

$$\eta_e^{gro} = \frac{E_e^{gro}}{E_m} = \frac{\eta_{e,o}\ \eta_{e,i}\ \eta_{bat} - 1 + \eta_p}{\eta_{e,i}\ \eta_{bat}\ \eta_p} \tag{14.25}$$

This result shows that the electrical efficiency of the winch depends on the pumping efficiency and the battery efficiency. Fig. 14.4 shows two examples for this dependency. In both cases a battery with 95% efficiency is used.

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[4] The 20 kW demonstrator is described in Sect, 14.3.1, the 53.5 kW ground station is described in Sect. 14.4.

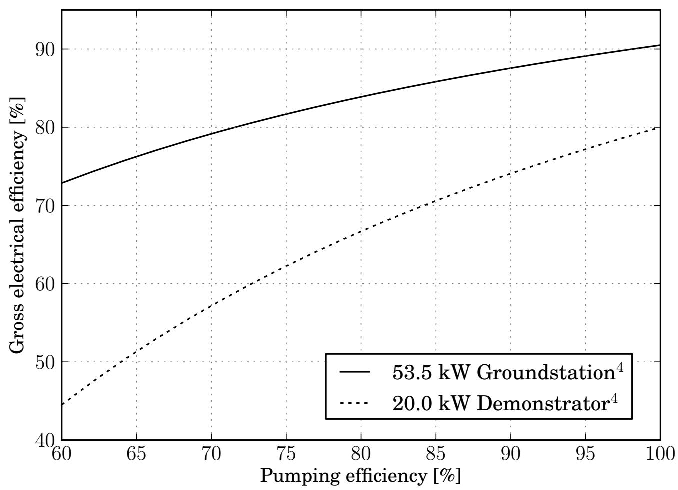

Fig. 14.4 Gross efficiencies of two ground stations. The graph shows that the ground-station efficiency is dependent on the pumping efficiency. The pumping efficiency depends on the aerodynamic performance of the kite.

For the 20 kW demonstrator a generator efficiency of 80% and a motor efficiency of 79% is assumed. For the 53.5 kW direct drive ground station a motor and generator efficiency of 90% is assumed. A low pumping efficiency has a negative influence on the electrical efficiency. For this kind of kite power system the gross electrical efficiency is always lower than the efficiency of the generator alone!

Now the system efficiency η_{sys} is introduced and defined as

$$\eta_{sys} = \frac{E_e^{net}}{E_e^{gro}} = \frac{E_e^{gro} - E_e^{brk} - E_e^{sp}}{E_e^{gro}}, \tag{14.26}$$

where E_e^{brk} is the energy, needed to release the motor brakes, E_e^{sp} is the energy, needed for the spindle motor that moves the drum and E_e^{gro} is the electrical gross energy as defined in Eq. (14.23).

The total efficiency is defined as the product of the cycle efficiency, the electrical efficiency and the system efficiency:

$$\eta_{tot} = \eta_{cyc}\ \eta_e^{gro}\ \eta_{sys} = D\ \eta_{sys}\ \frac{\eta_{e,o}\ \eta_{e,i}\ \eta_{bat} - 1 + \eta_p}{\eta_{e,i}\ \eta_{bat}} \tag{14.27}$$

The total efficiency expresses the relation between the average electrical net power output over the full cycle and the average mechanical power, that the kite produces during the reel-out phase. As you can see η_{tot} is only positive, if η_{sys} is positive and the following inequality holds:

$$\eta_{e,o}\ \eta_{e,i}\ \eta_{bat} + \eta_p\ >\ 1 \tag{14.28}$$

14.2.9 Modeling the efficiency of the generator

Using a constant efficiency for the motor/generator in the simulation will result in an over-optimistic estimate for the power output of a kite-power system. Better results can be achieved by modeling the efficiencies as two-dimensional scalar fields as a function of the rotational speed and torque. The friction torque of the 20 kW demonstrator was measured experimentally. This was approximated by a combination of a static contribution τ_c and a dynamic, velocity-dependent contribution $c_{v,f}\,\omega_0$ as defined by the following equation:

$$\tau_{f,o}\ =\ \tau_c\ +\ c_{vf}\ \omega_o \tag{14.29}$$

When the input tether force is known the effective generator torque can now be calculated. We assume a quasi-steady rotational equilibrium, therefore it is sufficient to take only the tether force, drum radius and friction torque into account:

$$\tau_g\ =\ \frac{F_{t,o}}{r}\ -\ \tau_{f,o} \tag{14.30}$$

Using the generator constant c_g the generator current and the electrical losses can now be calculated:

$$I_o\ =\ \tau_g\ c_g \tag{14.31}$$

$$L_{e,o}\ =\ 3\ R_g\ I_o^2\ k \tag{14.32}$$

The DC resistance of each phase, R_g can be taken from the data-sheet. To take the higher resistance at operating frequency due to the skin effect, stray-road-losses and other not explicitly modeled losses into account the factor k is introduced.

The power output and the electrical efficiency can now be calculated:

$$P_{e,o}\ =\ P_{m,o}\ -\ L_{e,o}\ -\ \tau_{f,o}\ \omega_o \tag{14.33}$$

$$\eta_{e,o}\ =\ \frac{P_{e,o}}{P_{m,o}} \tag{14.34}$$

If at least four values for the motor efficiency are known (for different torques and rotational speeds) the parameters can be fitted to the motor/ generator to obtain a sufficiently accurate efficiency model. An even more accurate (but also more difficult to use) efficiency model can be found in [9].

14.2.10 Modeling the efficiency of the motor

For the reel-in phase, either a separate motor is needed or the generator should be operated as a motor. The efficiency can be calculated in a similar way as the generator efficiency. The differences are the signs in Eq. (14.35 and 14.38) and the commutation of the numerator and denominator in Eq. (14.39) compared to Eq. (14.34).

$$\tau_m = \frac{F_i}{r} + \tau_{f,i} \tag{14.35}$$

$$I_i = \tau_m \, c_m \tag{14.36}$$

$$L_{e,i} = 3 \, R_m \, I_i^2 \, k \tag{14.37}$$

$$P_{e,i} = P_{m,i} + L_{e,i} + \tau_{f,i} \, \omega_i \tag{14.38}$$

$$\eta_{e,i} = \frac{P_{m,i}}{P_{e,i}} \tag{14.39}$$

14.2.11 Specifying the power of a kite power system

It is suggested to use two figures to specify the power output of a kite power system, the nominal electrical generator power (this is easy to determine and to a certain degree reflects the costs of a ground station) and the system power, which is the average net electrical output at nominal wind speed. The system power is much harder to determine as it depends not only on the ground station but also on the kite, the wind and the performance of the control system.

To describe the cost efficiency of a kite-power system with respect to the generator costs the cost factor CoF is introduced. It is defined as the quotient of the nominal electrical generator power[5] and the system power:

$$CoF = \frac{P_{nom}}{P_{sys}} \tag{14.40}$$

This is not the same as $1/\eta_{sys}$ because the system efficiency depends on the average traction power, which can be higher or lower than the nominal generator power (depending on the wind, the kite and the control system).

[5] The nominal electrical generator power is the power, that the generator or the combination of generator and motor (if both are used in parallel) can provide continuously at nominal reel-out speed, if they have a constant mechanical power input. The nominal reel-out speed is the max. reel-out speed by design divided by the safety factor $S_{v,o}$ (here: 1.2).

14.2.12 Python implementation of the system model

The implemented model is based on the theoretical framework defined by Eqns. (14.1) to (14.40). The kite is assumed to be massless and represented by a pair of aerodynamic lift and drag forces (the effect of the mass was simulated, but because it was very small it was neglected). The crosswind motion of the kite is taken into account according to Eq. (14.7). Equation (14.10) is used to calculate the average reel-out power. The global optimizer module interalg [5] is used to optimize the power over the full cycle. The parameters available for optimization are the reel-out speed, average height and elevation angle. The difference between the minimal and maximal tether length was assumed to be constant (200 m). The reel-in phase is simulated as described in Sect. 14.2.4. Several iterations are needed for the optimization of reel-in and reel-out phases in order to resolve the interdependencies. For more details the reader is referred to the method "optimizeFullCycle" of the class "Model" of the simulation program [4]. The program suite is available under an open-source license (GPL).

14.3 Model validation

14.3.1 Implemented technology demonstrator

The current technology demonstrator of Delft University of Technology has a generator with a nominal electrical power of 20 kW. It uses a single cable to connect the kite to the ground station and implements the steering of the kite in a control unit suspended below the kite. In Table 14.1 the properties of the demonstrator and of an up-scaled system (see: Sect. 14.4) are presented.

Table 14.1 Groundstation and tether properties

	Demonstrator	**Ground-station**	**Description**
	20 kW	53.5 kW	
$v_{t,i,max}$	8.0	8.8	maximal reel-in speed by design [m/s]
$v_{t,o,max}$	8.0	4.4	maximal reel-out speed by design [m/s]
$F_{t,max}$	4000	20000	maximal pulling force [N]
P_{nom}	20000	53500	nominal electrical generator power [W]
r	0.1615	0.105	radius of the drum [m]
d	0.004	0.009	diameter of the tether [m]

Table 14.2 Kite properties

Property	**Mutiny V2** kite	**29.5** m^2 kite	**Description**
m	20	43.0	total mass of kite, tether and control unit [kg]
A_p	16.5	29.5	projected area of the kite [m^2]
$C_{L,o}$	1.0	1.4	lift coefficient of the fully powered kite
$C_{D,o}$	0.2	0.2	drag coefficient of the fully powered kite
$C_{L,i}$	0.14	0.14	lift coefficient, kite fully depowered
$C_{D,i}$	0.07	0.14	drag coefficient, kite fully depowered

14.3.2 Comparison with experimental data

Fig. 14.5 shows the simulated power output for the 20 kW Demonstrator of Delft University of Technology. The crosses represent measured values. The main reason for most of the measured values being lower than the simulated values, is that the force control loop of the ground station was not fast enough to reach the C_f factor of 1.1 that was assumed in the simulation. At a wind speed of 3 m/s the force limit is not reached, the force control loop is inactive and simulation matches the measured power output very well.

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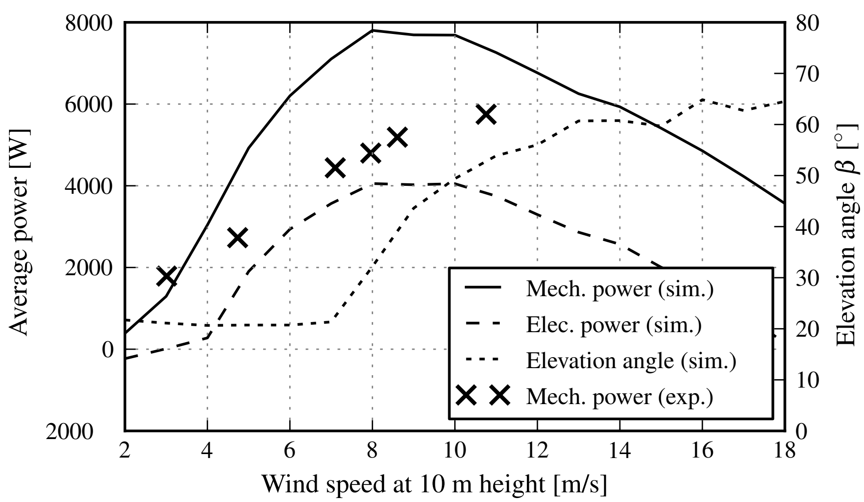

Fig. 14.5 Power output demonstrator

Fig. 1: Power output demonstrator

The fact that the measured power output at 10.8 m/s wind speed does not drop can be explained by the fact that in this situation a smaller kite with a projected area of only 11 m^2 was used. The reader might ask: Why is the maximal average electrical output of a kite-power system with a 20 kW generator only 4 kW? To understand the reasons for this, it is good to look at the efficiency figures in Fig. 14.6:

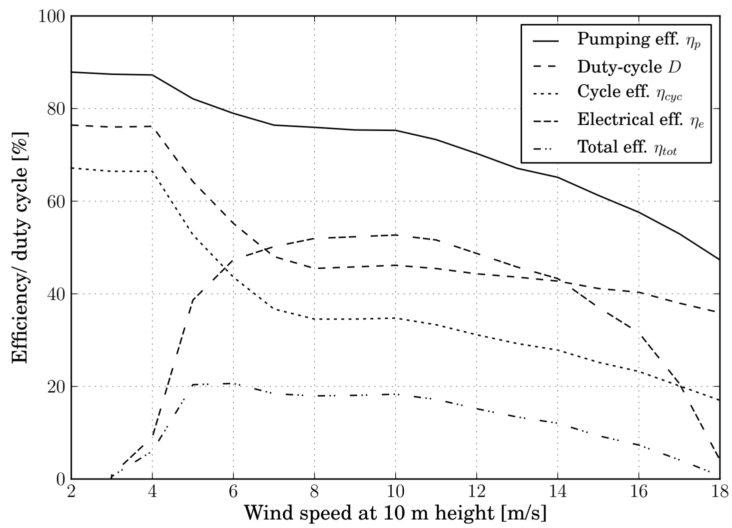

Fig. 14.6 Efficiencies of the demonstrator, simulated. The model parameters for calculating the electrical efficiency were fitted to measured values.

At 8 to 10 m/s wind speed the pumping efficiency is about 77%. This could be improved by changing the kite such that it doesn't collapse at a lower lift-over-drag ratio than two. The duty cycle is also quite low, about 47 %. The best way to improve this is to build a winch that can reel out slower with a higher force. For a kite of this size a much stronger winch is a better choice so that reeling out at about 1/3 of the wind speed becomes possible. The electrical efficiency is also very low, only 54 %. Reasons for this: An asynchronous, squirrel cage generator was used together with a very inefficient gearbox and a synchronous belt. One way to get a much better electrical efficiency is to use a synchronous direct drive generator. When all the efficiencies are multiplied the resulting total efficiency is only about 20%. Therefore we end up with 4 kW electrical power from a 20 kW generator.

Further model validation is needed, using a controller that optimizes elevation angle, lift-over-drag ratio and reel-in speed in the same way as the model. Additionally more accurate wind profiles are needed for model validation. The real wind speed at the height of the kite can be very different from the estimation, based on the wind profile law Eq. (14.2).

14.4 Design of a 31 kW kite power system using a 53.5 kW ground station

Using the experience with the demonstrator and the described model, a kite power system with a much higher total efficiency was designed. Design goals were a high capacity factor[6] at an average wind-speed of 5.5 m/s in 10 m height and a cut-out speed of at least 18 m/s.

Because not only the generator efficiency, but also the motor efficiency is very important and because the efficiency of a motor drops significantly if it is operated at only 10 % or 20 % of its nominal power the design suggests a separate motor and generator: A generator with high torque and low rotational speed and a motor with about half the nominal power and twice the nominal rotational speed.

The generator is decoupled from the drum during reel-in with a clutch to reduce the friction and to avoid over-voltage. The motor is always connected to the drum and produces about 20 % of the total power during reel-out.

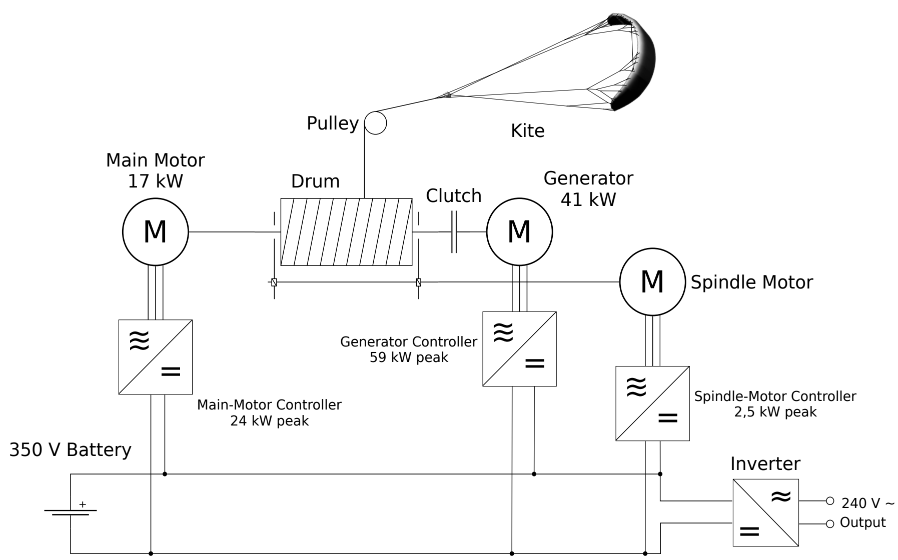

Fig. 14.7 Ground station schematics

For the design, we choose a generator and a motor that were available off-the-shelf. An additional selection criteria was the availability of detailed data sheets. We choose the type ”500STK8M” as generator and the type ”300STK8M” as motor, both from Alxion, France.

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[6] The capacity factor is defined as the quotient of the average power output over the whole year and the system power as defined in Sect. 14.2.11.

14.4.1 Simulation results

The simulated power curve is shown in Fig. 14.8. The kite-power system now reaches a nominal power output of 31 kW at a wind-speed of 7 m/s. The simulated efficiencies are shown in Fig. 14.9. The total efficiency now reaches a maximum of about 60 % and it reaches 54.6 % at a wind-speed of 7 m/s at nominal power output. At a wind speed of about 5.2 m/s the total efficiency reaches a maximum. In this example the design was done such that the maximum matches approximately the average wind-speed at the deployment site.

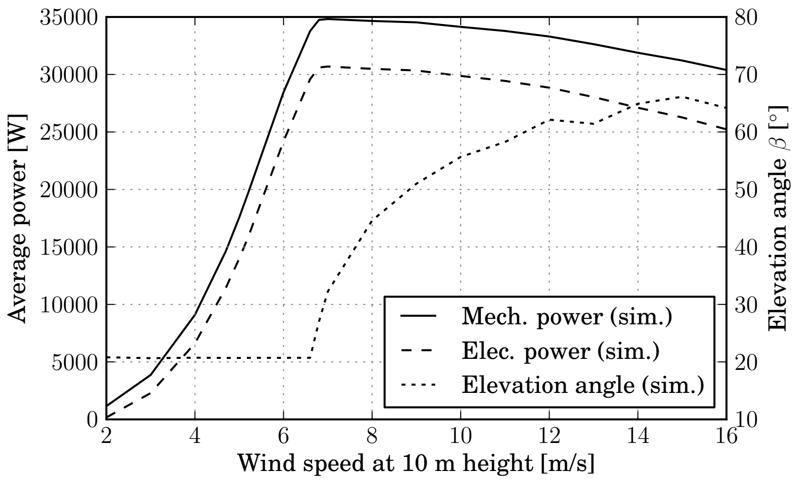

Fig. 14.8 Power output and elevation angle of the simulated direct drive system.

The simulated reel-in and reel-out velocities and the duty cycle are shown in Fig. 14.10. The diagram is divided into three regions:

1. In region I (for $v_{w,g} < 5.2\ m/s$) the optimal reel-out speed is rising proportionally and the tether force quadratically with the wind speed. Therefore the output power is rising approximately with the cube of the wind speed. The optimal duty cycle is nearly constant, in this example about 84 %.
2. In region II (for $5.2\ m/s < v_{w,g} < 6.8\ m/s$) the maximal tether force is reached and the reel-out speed is rising twice as fast as in region I. Therefore the output power is rising approximately linearly with the wind speed. The optimal duty cycle drops because the reel-in speed is constant and the reel-out speed rises.
3. In region III (for $v_{w,g} \geq 6.8\ m/s$) the maximal tether force and reel-out speed are reached, the reel-out power is constant and the elevation angle increases with the wind speed. The average output power is slowly falling because the needed reel-in power is rising with the wind speed. The optimal duty cycle is constant but at a lower level than in region I.

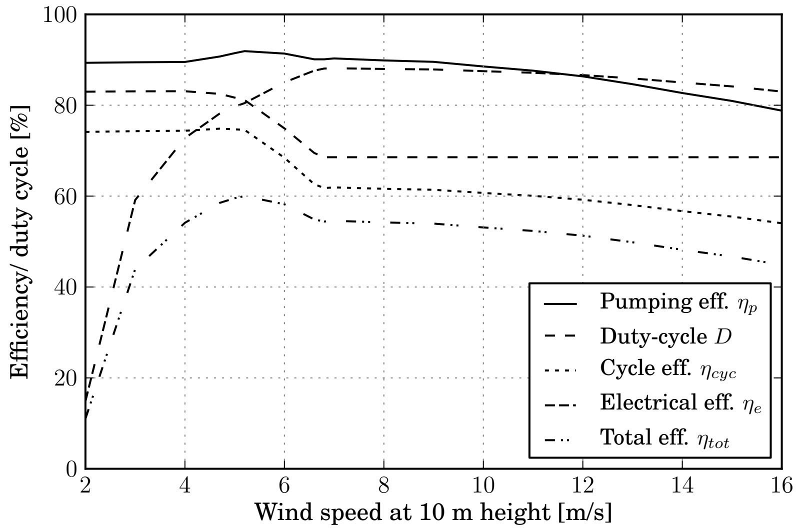

Fig. 14.9 Efficiencies of the simulated direct drive system. At 5.2 m/s the total efficiency reaches its maximum of 60 %.

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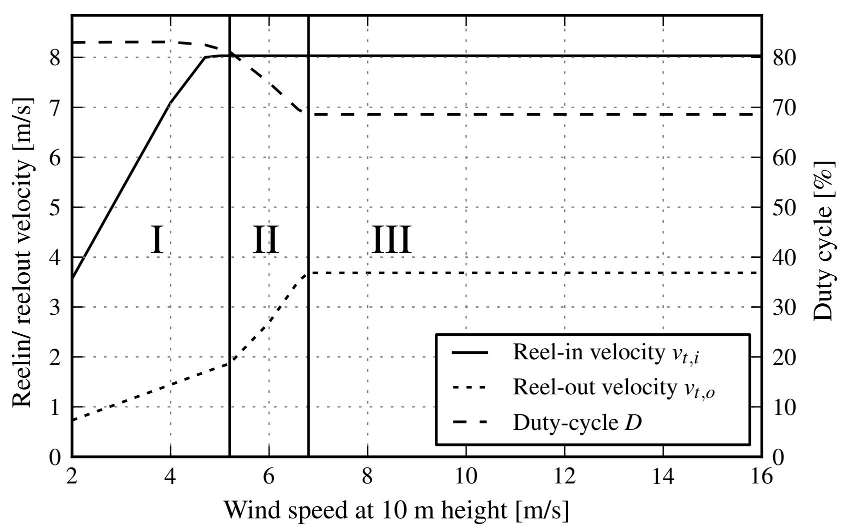

Fig. 14.10 Tether speeds. Region I: $v_{t,o}$ is rising linearly and the optimal tether force quadratically with the wind speed. Region II: the tether force reached its maximum, $v_{t,o}$ is rising twice as fast as in I. Region III: max force and $v_{t,i}$ reached, $P_{m,o}$ approx. constant.

Fig. 1: Tether speeds. Section I: $v_{t,o}$ is rising linearly and the optimal tether force quadratically with the wind speed. Section II: the tether force reached its maximum, $v_{t,o}$ is rising twice as fast as in I. Section III: max force and $v_{t,o}$ reached, $P_{m,o}$ approx. constant.

14.4.2 Performance factors

Table 14.3 gives an overview of the measured and simulated performance factors of the 20 kW[7] demonstrator and of the simulated 31 kW kite-power system, using a 53.5 kW ground station. The measured power output of the 20 kW demonstrator is about 34 % lower than the simulated power output. One of the reasons is that the crest factor for the reel-out force $CF_{f,o}$ is higher than necessary due to the current slow force control loop. Other possible reasons are the uncertainty of the kite properties, especially the lift-over-drag ratio (an error of 10% would result in 20 % less power output) and the uncertainty of the coefficient of the wind profile law α. This coefficient depends heavily on the time of the year and the weather conditions.

Table 14.3 Performance factors

	20 kW winch measured	**20 kW winch** simulated	**53.5 kW winch** simulated	**Description**
A_p	16.5	16.5	29.5	projected kite area [m^2]
$F_{t,max}$	4000	4000	20000	max. tether force [N]
η_p	77	77	90	pumping efficiency [%]
D	56	46.8	68.6	duty cycle [%]
η_{cyc}	43	36	61.7	cycle efficiency [%]
η_{tot}	21	18	57	total efficiency [%]
CoF	7.1	4.6	1.7	cost factor
$v_{t,o,max}$	8.0	8.0	4.4	max. reel-out speed by design [m/s]
$\overline{h}$	307	300	272	average height during reel-out [m]
v_w	n.a.	12.0	10.1	wind speed at height of the kite [m/s]
$v_{w,g}$	8.5	8.0	7.0	wind speed at 6 m height [m/s]
$v_{t,o}$	4.24	6.67	3.68	average reel-out speed [m/s]
β	25	25.9	27.9	elevation angle [°]
$\overline{P_{m,o}}$	14100	21638	59787	average traction power (reel-out) [W]
P_m	5190	7900	36054	average mech. power (full cycle) [W]
P_{sys}	2595	4000	31000	average electrical system power [W]
$S_{v,i}$	1.1	1.1	1.1	safety factor reel-in speed
$S_{v,o}$	1.2	1.2	1.2	safety factor reel-out speed
$S_{t,f}$	3.37	3.37	3.0	safety factor tether force
$CF_{o,f}$	1.25	1.11	1.11	crest factor reel-out force
$CF_{o,v}$	1.89	1.2	1.2	crest factor reel-out velocity

[7] Nominal electrical generator power.

14.5 Outlook and Conclusion

Kite-power systems are a promising alternative to wind turbines, but to become commercially interesting a high total efficiency is needed. When this is achieved, the improved capacity factor will reduce the requirements for high-voltage lines and/or energy storage significantly.

Larger generators have a better efficiency than the 20 kW and 53.5 kW generators discussed in this paper. Therefore, the total efficiency will be even better for bigger kite power generators. On the other hand the costs for the kite and for a direct drive generator are rising faster than linearly, therefore there will be an optimal size that is not known yet. The biggest challenges for designers of ground stations in kite-power systems are currently the efficiency and the implementation of automated launch and landing systems at low costs. In some markets kite power systems can have a big advantage over traditional wind turbines, for example for small off-grid and for offshore installations.

Further research and development has to be performed to find the best design. Better optimization algorithms and controllers, better models and more efficient designs are needed before kite-power systems can become a success story.

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