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Downscaling of Airborne Wind Energy Systems

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Abstract. Airborne wind energy systems provide a novel solution to harvest wind energy from altitudes that can not be reached by wind turbines with a similar nominal generator power. The use of a lightweight but strong tether in place of an expensive tower provides an additional cost advantage, next to the higher capacity factor and much lower total mass. This paper investigates the scaling effects of airborne wind energy systems. The energy yield of airborne wind energy systems, that work in pumping mode of operation is at least ten times higher than the energy yield of conventional solar systems. For airborne wind energy systems the yield is defined per square meter wing area. In this paper the dependency of the energy yield on the nominal generator power for systems in the range of 1 kW to 1 MW is investigated. For the onshore location Cabauw, The Netherlands, it is shown, that a generator of just 1.4 kW nominal power and a total system mass of less then 30 kg has the theoretical potential to harvest energy at only twice the price per kWh of large scale airborne wind energy systems. This would make airborne wind energy systems a very attractive choice for small scale remote and mobile applications as soon as the remaining challenges for commercialization are solved.

1 Introduction

The average size of wind turbines has been increasing continuously during the last decades. However, there are many applications, where efficient and easily deployable small-scale renewable energy systems are needed. Examples for mobile applications are sailing boats, electronic systems like cell phone transmitters, remote, rural homes or disaster recovery. Solar cells can work efficiently even at a very small scale, but not at every location sufficient sunlight is available. Furthermore solar systems are much larger and heavier than Airborne Wind Energy (AWE) systems, that can harvest a similar amount of energy. For conventional wind turbines the costs per kWh at a given location rise considerably when downscaling the turbine. Small-scale wind turbines are usually mounted on a low-rise tower and cannot harvest the wind at large heights, where the wind is stronger and steadier. The question is: Can this effect be mitigated by using airborne wind energy systems? How much can they be downsized before the efficiency drops to unacceptable level?

In [1] an efficiency analysis of an airborne wind energy system was presented. It was concluded, that the product of the cycle efficiency and electrical efficiency should be higher than 50% to become competitive with conventional wind turbines. Furthermore it was shown in a simulation, that this efficiency can be achieved with off-the-shelf generators for a system with 50 kW nominal power.

The question arises: How much can this nominal power level be reduced while still reaching the desired level of efficiency? Which physical effects limit the efficiency of small scale systems? How would the performance of the smallest, economically feasible AWE system compare with equally rated solar power systems and conventional wind turbines?

Previous research [2] was focused on the question, how should the sizes of the system components (generator, tether, wing) be chosen to minimize the levelized costs of energy, but the costs as a function of total system size where not depicted.

2 Problem analysis

The scalability of an AWE system depends on the scalability of its components and their interaction. The influence of these components and their interaction on the power density is analyzed in the following sections.

2.1 Wind environment

The wind profile as measured at the location Cabauw, The Netherlands is used [3]. For heights above 300 m a novel approximation was derived, which is defined in Eqs. 8, 9 and 10, depicted in Fig. 1 and based on measurement data from Lindenberg, Germany [5].

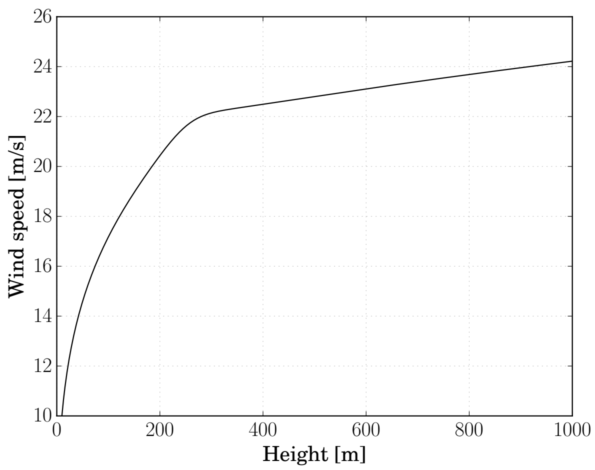

Figure 1. Wind profile, used for this analysis. The wind profile up to 200 m height is based on measurement data from Cabauw, The Netherlands [4]. The reduced increase of the wind speed above 300 m height is based on wind profiler measurements at Lindenberg in Germany [5].

2.2 Wing

A wing with properties as described in [6] was used for the default scenario. An aspect ratio of four, a lift over drag ratio of 9.2 and an average lift coefficient during reel-out of 1.3 was chosen. The sensitivity for changing the lift over drag and the lift coefficient is investigated. The value of the lift coefficient is much more important than a low wing drag, because in most cases the tether drag is the limiting factor. In Tab. 1 the parameters of the three investigate scenarios are shown. The value of f_{opt}, the ratio of the optimal reel-out speed and the wind speed for the soft wing was derived in [3]. For the high efficient wing it is assumed that it can be reeled in a very short time, therefore the optimal, average reel-out speed reaches the high value of one third of the wind speed. In all other scenarios the reel-in time can not be neglected. Therefore the reel-out speed has to be reduced to reach the optimal power over the full cycle.

2.3 Generator

The efficiency of a generator depends on many parameters. Most important is the type of the generator. For a good efficiency in this study only Permanent Magnetic (PM) generators are considered. Two types of PM generators were investigated: First, conventional PM generators, using rear earth magnets and second, high efficient PM generators, using traditional (and cheap)

Table 1. Wing and control parameters of the investigated scenarios. The average lift coefficient of the wing during reel-out C_L, the lift-over-drag ratio of the wing L/D and the ratio of the reel-out speed v_{ro} and the wind speed at the height of the wing v_w are shown. The lift over drag of the wing does NOT include the effective tether drag, that is changing during reel-out.

Scenario	C_L	L/D	$f_{opt} = v_{ro}/v_w$
Default Scenario	1.3	9.2	0.22
High efficient wing	1.5	12.2	0.33
Soft wing	1.0	6.2	0.207

ferrite magnets. In Fig. 2 the efficiency as function of the nominal power of these generators from two different companies are shown.

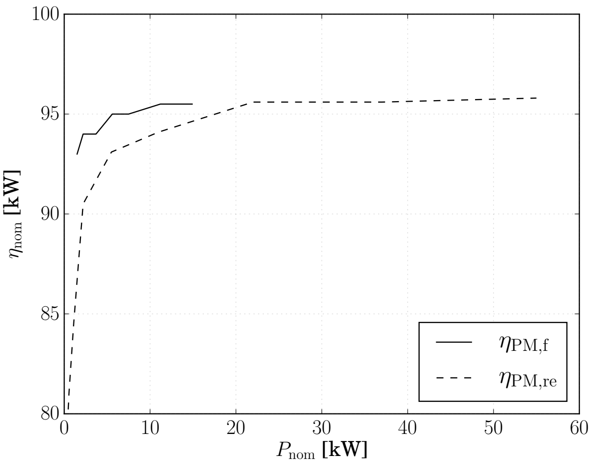

Figure 2. Efficiency of two types of permanent magnetic generators as a function of the nominal power rating. The first dataset shows the efficiency $\eta_{PM,f}$ of highly optimized ferrite magnets generators [7] and the second data set shows the efficiency of standard PM generators, using rare earth magnets [8]. It can be seen that even a generator with just 1.5 kW nominal power can achieve a nominal efficiency of about 93%, which meets the efficiency criteria for the smallest, viable AWE system.

2.4 Tether

For a tether of 4 mm diameter a nominal force of 4000 N is assumed. This allows a safety factor of three, if Dyneema® is used as tether material. A detailed analysis of the lifetime and other properties of this material can be found in [9].

3 Computational approach

To calculate the nominal energy per square meter wing, the following approach was chosen: Two functions are used to calculate the tether force. The results of both functions must be equal. Furthermore, a cost function is calculated. The costs as a function of the wing area A and average reel-out height $\overline{z}$ shall be minimized:

Table 2. Cost factors in arbitrary units. The costs include tether and wing replacements, but not any development costs, capital costs or the man-hours needed for maintenance.

Cost factor	**Value**	**Explanation**
c_{fix}	1500	Fixed costs, e.g. for the control system.
c_{wing}	7.5 $[m^{-2}\ N^{-0.5}]$	Costs per m^2 effective wing area and sqare root of N force.
c_{t}	430000 $[m^{-3}]$	Costs per m^3 tether volume.
c_{gen}	100 $[kW^{-0.5}\ N^{-0.75}]$	Generator costs, depending on power and force.
c_{pc}	100 $[kW^{-1}]$	Costs per kW for power conversion.
c_{st}	150 $[kW^{-1}]$	Balance-of-station costs per kW.

$$\min_{A,\overline{z}} costs(A, \overline{z}) \tag{1}$$

$$\text{subject to } A_{\mathrm{min}} \leq A \leq A_{\mathrm{max}} \tag{2}$$

$$\overline{z}_{\mathrm{min}} \leq \overline{z} \leq \overline{z}_{\mathrm{max}} \tag{3}$$

$$F_1(A, \overline{z}) \ = \ F_2(A, \overline{z}) \tag{4}$$

The costs are calculated according to Eq. 7, where c_{fix} are the fixed costs, c_{wing} the costs for the wing as function of the wing size A and the reel-out force, c_{t} the costs per m^3 tether volume, c_{gen} the generator costs for a direct drive permanent magnet machine, c_{pc} the costs for the power conversion and c_{st} the balance-of-station costs, which include transport and installation.

This cost model is based on [2] with the following modifications: First, the costs of the wing were depending only on its size. In our model we also include the wing loading (force per area) as cost factor, using an exponent of 0.5. This exponent was chosen because twice the wing loading increases the material costs by a factor of two, but we assume, that the material costs are only half of the total costs, and furthermore, that for higher wing loadings different materials and structures can mitigate the rise of the costs. The original formula for the costs of the wing is shown in Eq. 5, the new formula in Eq. 6.

$$costs_{\mathrm{wing}} \ = \ c_{\mathrm{wing\_area}}\ A^{1.5} \tag{5}$$

$$costs_{\mathrm{wing}} \ = \ c_{\mathrm{wing}}\ A^{1.5} \sqrt{\frac{F}{A}} \ = \ c_{\mathrm{wing}}\ A\ \sqrt{F} \tag{6}$$

Second, we include fixed costs, because they are important for small system sizes. Finally we assume, that the wing and the tether have to be replaced 10 times during the system lifetime, therefore we adapted their cost factors accordingly.

The nominal electrical generator power is the main input parameter of the optimization. It is varied in the range of 1 kW to 1 MW.

$$costs(A, \overline{z}) \ = \ c_{\mathrm{fix}} + \ c_{\mathrm{wing}}\ A\ \sqrt{F} \ + \ c_{\mathrm{t}}\ V_{\mathrm{t}} \ + \ c_{\mathrm{gen}}\ \sqrt{p_{\mathrm{nom}}}\ F^{0.75} \ + \ (c_{\mathrm{pc}} + c_{\mathrm{st}})\ p_{\mathrm{nom}} \tag{7}$$

The first equation for calculating the nominal tether force is Eq. 13, where $p_{\mathrm{m,nom}}$ is the nominal, mechanical reel-out power and v_{nom} the average reel-out speed. The mechanical reel-out power is calculated according to Eq. 12 where η is the total efficiency of generator, electric drive and gearbox. Eq. 8, 9 and 10 are used to calculate v_{w}, the wind speed at the average reel-out height z. The exponential wind profile law is used with an exponent $p = 0.23375$ and a height of the boundary layer of $z_{\mathrm{b}} = 300\ m$. Furthermore, a ground wind speed of $v_{\mathrm{w,g}} = 6.0\ m/s$

at a height of $z_{\rm ref} = 10\ m$ was assumed, because under these environmental conditions with a soft wing a capacity factor of $\geq 40\%$ can be achieved.

$$\delta z = z - z_{\rm b} \tag{8}$$

$$z' = z - 0.4 \left\{ 1 + \tanh\left(\frac{1}{6} \left[\delta z + 50 \right] \right) \right\} \delta z \tag{9}$$

$$v_{\rm w} = v_{\rm w,g} \left(\frac{z'}{z_{\rm ref}} \right)^p \tag{10}$$

$$v_{\rm nom} = f_{\rm opt}\ v_{\rm w} \tag{11}$$

$$p_{\rm m,nom} = \frac{p_{\rm el,nom}}{\eta} \tag{12}$$

$$F_1 = \frac{p_{\rm m,nom}}{v_{\rm nom}} \tag{13}$$

The second equation for calculating the nominal tether force is Eq. 17, where ρ is the air density at the height z, $v_{\rm a}$ the apparent wind speed at the wing, A the projected wing area, $C_{\rm D}$ the total drag of wing and tether and $C_{\rm L}$ the average lift coefficient of the wing during reel-out. In Eq. 15 the total drag as the sum of the drag of the wing and the effective tether drag is calculated, where $C_{\rm D,t}$, the tether drag coefficient is about one, $l_{\rm t}$ is the average tether length and $d_{\rm t}$ the tether diameter. In Eq. 14 the tether diameter is calculated based on the nominal force F_1 and the nominal, tensile stress of the tether σ. For Dyneema a value of one third of the tensile strength, $\sigma = 3.18e8\ N/m^2$ is used. Eq. 15 is derived in [1], Eq. 17 and Eq. 16 are derived in [10],

$$d_{\rm t} = 2 \sqrt{\frac{F_1}{\pi\ \sigma}} \tag{14}$$

$$C_{\rm D} = C_{\rm D,k} + C_{\rm D,t}\ 0.32\ \frac{l_{\rm t}\ d_{\rm t}}{A} \tag{15}$$

$$v_{\rm a} = (\cos\beta - f_{\rm opt})\ v_{\rm w} \sqrt{1 + \left(\frac{C_{\rm L}}{C_{\rm D}} \right)^2} \tag{16}$$

$$F_2 = \frac{1}{2}\ \rho\ v_{\rm a}^2\ A\ C_{\rm D} \sqrt{1 + \left(\frac{C_{\rm L}}{C_{\rm D}} \right)^2} \tag{17}$$

The optimization problem was solved using IPopt, a library for large-scale nonlinear optimization [11]. Furthermore the JuMP (Julia for Mathematical Programming) framework was used [12], which provides automated differentiation of the costs function.

4 Simulation results

4.1 Results for the range of 1 kW to 1 MW

The optimal generator power per square meter wing area is shown is shown in Fig. 3. It can be seen, that for 1 kW of nominal electrical generator power a power density of 1.5 $\mathrm{kW/m^2}$ is achieved. This value rises to 5.8 $\mathrm{kW/m^2}$ at about 270 kW and then increases even faster to 7.6 $\mathrm{kW/m^2}$ for 1 MW generator power. It is rising first slowly and then faster, because for 270 kW generator power an optimal height of about 180 m is reached. Above this height the wind speed is only increasing slowly. Therefore for higher powers the force has to rise faster with the power level, which means a thicker tether, less relative tether drag and therefore an even faster rising power density.

In Fig. 4 the optimal wing area as function of the nominal generator power is shown. In the double-logarithmic plot the relationship is nearly linear. A generic approximation is given

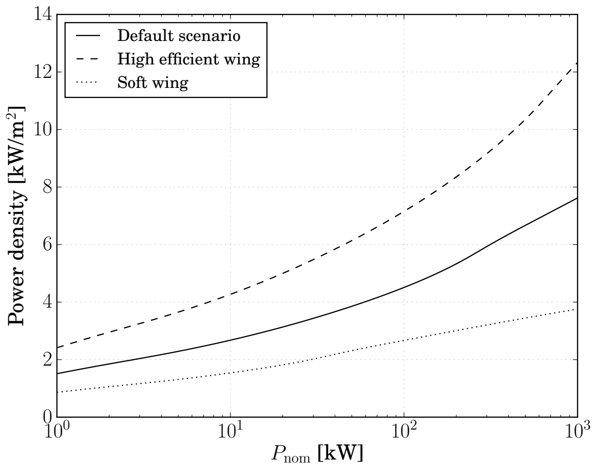

Figure 3. Power per square meter of wing area. As comparison: Average silicon solar modules achieve currently (2015) a power density of just about 0.15 kW per m^2.

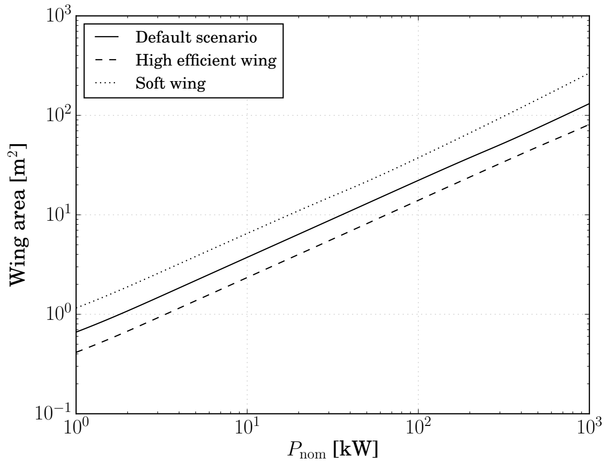

Figure 4. Wing area of an optimized airborne wind energy system for different power ratings. A good approximation for the default scenario is the following equation: $A = 0.62\ p_{\mathrm{nom}}^{0.77}$. The resulting error is $\leq 5\%$.

in Eq. 18. For the default scenario the values $A_{\mathrm{1kW}} = 0.626\ m^2$ and $k = 0.75$ are the best approximation in the power range of 1 kW to 100 kW. For the full power range of 1 kW to 1000 kW the values $A_{\mathrm{1kW}} = 0.62\ m^2$ and $k = 0.77$ are a better approximation. This means, that a system one magnitude more powerful needs about 5.9 times the wing area.

$$A = A_{\mathrm{1kW}}\ \left(\frac{p_{\mathrm{nom}}}{kW}\right)^k \tag{18}$$

In Fig. 5 the optimal, average reel-out height is shown. It is rising with the power level, because a larger power reduces the effective tether drag per tensile strength and thus allows a longer tether without sacrificing the lift-over-drag too much. It can also be seen, that the optimal height for a more efficient wing is lower than for a wing with a low lift-over-drag. Furthermore, in no case the optimal, average reel-out height exceeds 270 m. The exact value depends on the weather conditions and the cost model.

In Fig. 6 the effective lift-over-drag of the combination of the wing and the tether is shown. In the default scenario it stays quite constant for a nominal power up to 200 kW. For higher power levels it is rising proportional to the logarithm of the power. This is the result of two competing effects: Higher power needs a thicker tether and therefore less tether drag per force. On the other hand, a higher rated system has a larger optimal height, which means it needs a longer tether witch increases the tether drag. For up to 200 kW this two effects nearly compensate each other. For larger power levels the height is not rising very much any more, therefore the reduced relative drag of a thicker tether is dominating.

In Fig. 7 the force per effective area is shown. The reason for the small difference between the default scenario and the high efficient wing is the following: The high efficient wing is reeled out 1.5 times faster than in the default scenario. Therefore the higher power is mainly a result of the higher speed, not much more force is needed. It has a higher, optimal reel-out speed because it can be reeled in much faster. For a high duty cycle a low reel-out speed is not needed.

Fig. 8 shows the per per nominal reel-out force. This power density mainly depends on the reel-out speed. Higher values can be achieved firstly by flying higher, where the wind is stronger, and secondly by a increasing the relative reel-out speed f_{opt}. This optimum increases when the

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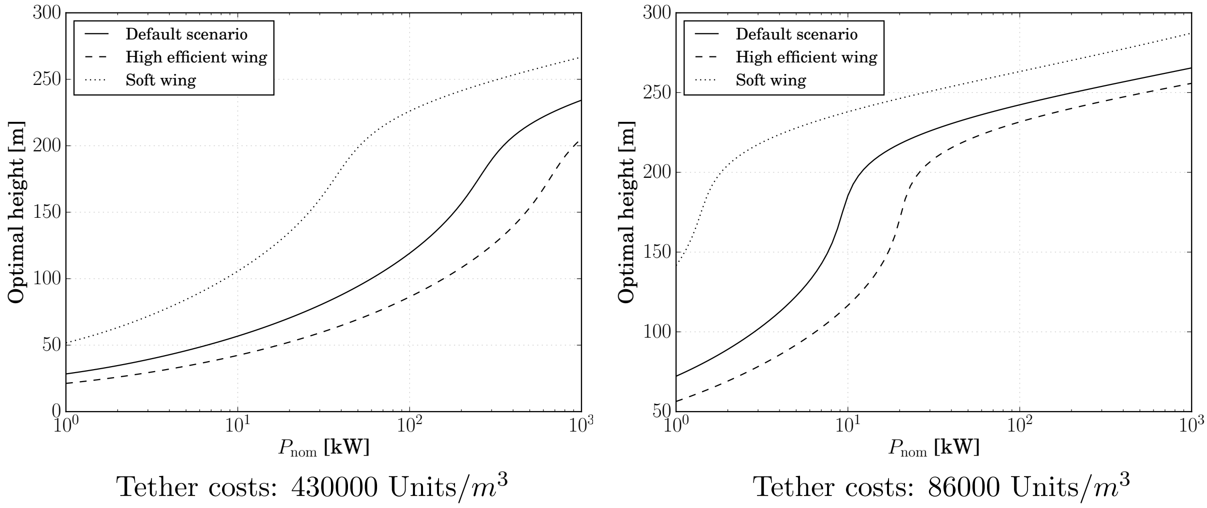

Figure 5. Optimal, average reel-out height. For low and medium power levels the optimal height depends a lot on the tether replacement costs: The lower these costs, the larger the optimal height. The left diagram takes the costs for 9 tether replacements into account, the right diagram for one replacement. For low heights the acceleration of the wing while flying turns becomes very high: If the limit set by the durability of the wing structure and the robustness of the sensors is set to 10 g, then the minimal height for a 1.4 kW system has to be increased to 60 m.

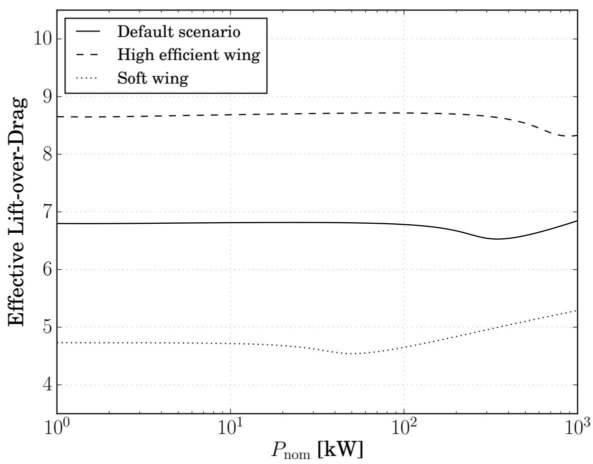

Figure 6. The effective lift-over-drag of the wing and the tether.

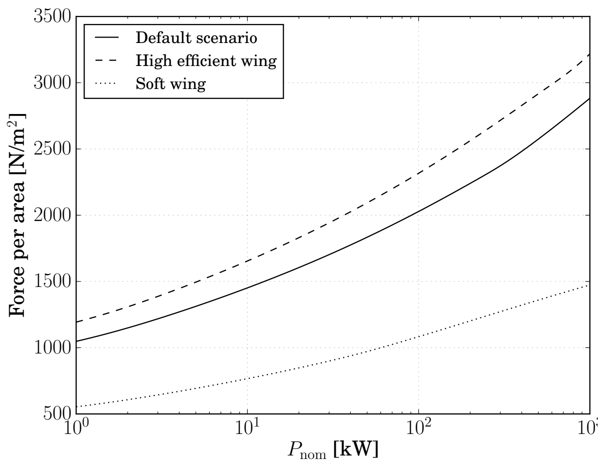

Figure 7. The force per effective wing area, also called "wing loading".

optimal duty cycle increases by using a wing that requires lower reel-in forces and a ground station that can reel-in faster.

Fig. 9 shows the the costs per W nominal generator power. On the one hand side the system efficiency increases with the size, mainly due to the reduced, relative tether drag for thicker tethers. On the other hand the costs for the wing and the generator are rising faster than linearly. Therefore there is a price optimum in between the largest and the smallest systems. The minimum for the default scenario is 0.81 Units/W at 15.2 kW nominal generator power.

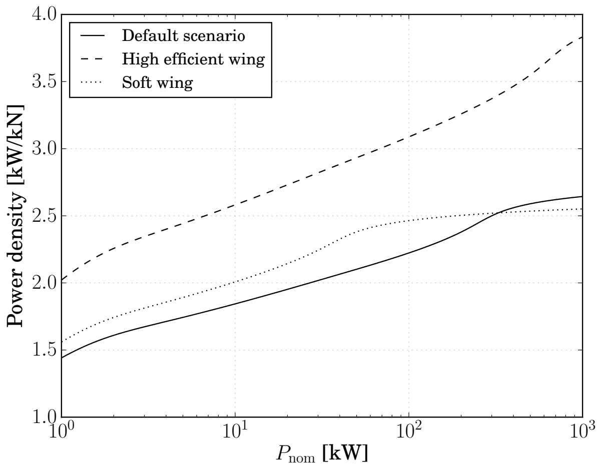

Figure 8. The power per nominal reel-out force.

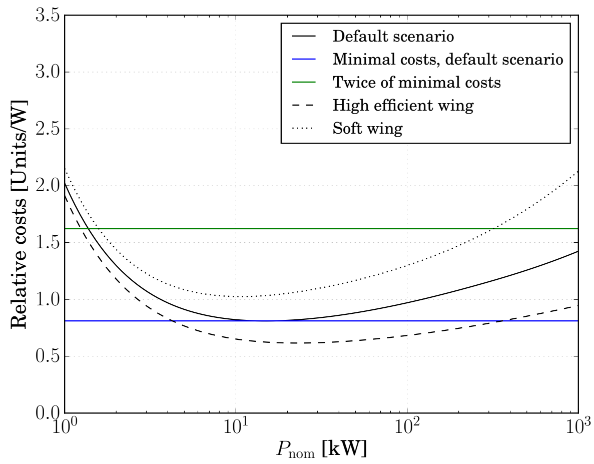

Figure 9. Costs per W nominal generator power.

Table 3. Median of the levelized costs of energy (LCOE) of small wind turbines, installed in the US in 2013 and 2014 [13]. The last column shows the values of a power regression, used to approximate the dependency of the LCOE from the turbine size.

Nominal power [kW]	LCOE (cents/kWh)	LCOE (approx.)
5	38	50.0
10	48	31.1
20	20	19.3
30	11	14.6
50	12	10.3
100	6	6.4

The minimal costs for the high efficient wing go down to 0.62 Units/W at 23.1 kW, for the soft wing the minimum is 1.03 Units/W at 10.7 kW. The blue line shows the minimal costs of the default scenario, the green line twice the minimal costs. The lower power level, where the black line crosses the green line is used to determine the minimal, economically feasible system size.

4.2 Minimal system size

After doing the analysis about the full power range from 1 kW to 1 MW we can now determine a minimal, economically feasible AWE system size. It should be noted that for all system sizes the simulation was done such that the capacity factor stays constant (at about 40%), therefore the energy, that can be harvested is proportional to the system size. We define a system with not more then twice the minimal costs per W as the smallest, economically feasible system. With this definition we can use the power level, where the green line crosses the black line in Fig. 9 as minimal, feasible system size. This price level is reached at about 1.4 kW nominal, electrically generator power.

4.3 Comparison with conventional wind turbines

With the same definition to determine the minimal, economically feasible system size for conventional wind turbines, in Tab. 3 it can be found between 30 kW and 50 kW. If the cost model, presented in Eq. 7 is correct, then economically feasible airborne wind energy systems

Table 4. Qualitative comparison between Airborne Wind Energy (AWE) systems, conventional wind turbines and photo-voltaic solar systems. While AWE systems offer large advantages in particular for small wind energy systems, their long term reliability still needs to be proven.

	Suitable for low power levels	Low system mass	Costs	Reliability
AWE	+	++	(+)	??
Wind turbines	-	-	+	+
Solar PV	++	-	0	++

can be build 21 to 36 times smaller than conventional wind turbines. The main limitation of the presented cost model is, that it does not take the costs for maintenance, permissions and land use into account. Future research must show, to which degree the theoretically found advantages of small AWE systems can be realized in practice.

4.4 Qualitative comparison

In Tab. 4 AWE systems are compared with conventional wind turbines and solar PV systems. Conventional wind turbines have low costs and and a good reliability, but are much heavier and not well suited for low energy requirements. While AWE systems are not suited for very low power levels (below 1 kW), they have low material costs (the total LCOE are not yet known) and offer by far the lowest system mass. The long term reliability of AWE is not yet known, and providing and proving this reliability is one of the main challenges of AWE research in the next years.

5 Conclusions

It was shown that for AWE systems in pumping mode of operation the power per square meter wing area and per unit tether force increases with the nominal generator size. For a system as small as 1.4 kW a power density of 1.7 kW/ m^2 wing area can be achieved. The area, needed per kW is increasing less than linearly with the nominal power and can be approximated with Eq. 18. An exponent of $k = 0.75$ .. 0.77 is a good approximation. The optimal, average reel-out height for such a small wind energy system is about 31 meters. The durability of the wing structure due to acceleration loads and the robustness of the sensors might require to fly on a longer tether. If the acceleration limit of the wing during turns is 10 g, then the minimal height for a 1.4 kW system has to be increased to 60 m. But even this increased height is so low, that in many countries such a system can be operated without special permissions. For small AWE systems the aerodynamic efficiency of the wing does not have a large impact on the costs, but to achieve a small wing, that can be deployed easily a high aerodynamic efficiency is of advantage. A high generator efficiency is also important, but since a few years highly efficient electrical machines are available even at power levels of only 1.4 kW.

The results show, that small scale AWE systems can become a viable alternative to conventional wind and solar, in particular for mobile applications, as soon as the remaining technical challenges are solved.

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