Chapter 19
Multicopter-Based Launching and Landing of Lift Power Kites

Florian Bauer, Christoph M. Hackl, Keyue Smedley and Ralph M. Kennel

Abstract Crosswind kite power is a promising alternative wind power technology. However, unlike the rotor blades of a conventional wind turbine, a kite needs to be launched prior to power generation and needs to be landed during low-wind conditions or for maintenance. This study proposes multicopter-based concepts for an autonomous solution. Basic system components and different system configurations are discussed. Static and dynamic feasibility analyses are carried out. Results show that such systems are feasible and have advantages compared to other launching and landing concepts. However, also the weaknesses of such systems become apparent e.g. the increased airborne mass.

19.1 Introduction

Crosswind kite power is becoming more and more attractive in both academia and industry (see e.g. [2, 8, 31] and references therein) and is considered as promising alternative wind power technology: Compared to conventional wind turbines, kites can harvest wind power at higher altitudes with stronger and steadier winds, but

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only by needing a fraction of the construction material. Hence, it promises to have a higher capacity factor, lower capital investments, and in the end a lower levelized cost of electricity [2, 31]. Mechanical output powers of two megawatts were already achieved by a commercial product of the company SkySails [11].

Two beneficial concepts to generate power with a kite are also referred as “crosswind kite power” [2, 8, 31]: (i) In “lift power” [31],[1] the kite is tethered to a winch on ground which is connected to an electrical drive that can be operated as motor or generator. The kite is flown in crosswind motions like figure eights with a high speed and a high lift force and pulls the tether from the winch. The winch drive counteracts by generative braking, i.e. it is operated as generator and electric energy is generated. Before the tether is pulled out completely, the kite is flown towards a low force position like the zenith and then reeled in. A rigid kite can also dive towards the ground station. During this reel-in phase the ground winch drive is operated as motor, but only a fraction of the generated energy is dissipated. (ii) In “drag power” [31],[2] onboard wind turbines are attached to a rigid kite or to an airborne unit beneath a soft kite. The kite is also flown in crosswind motions with a high speed, but with constant tether length. The turbines generate electric power which is transmitted to the ground via electrical cables that are integrated in the tether.

Unlike the rotor blades of a conventional wind turbine, the kite needs to be launched prior to power generation and needs to be landed during low-wind conditions or for maintenance. This challenge can be seen as solved for the drag power principle with rigid kites which is pursued e.g. by the company Makani Power/Google [2, 33]: They are developing rigid kites with a tether with integrated electrical cables. The kite is launched and retrieved by using the turbines as propellers in motor mode like a multicopter. This concept seems very successful, robust and autonomous. It is independent of the wind speed near the ground station. Most components required for launch and retrieval are already present. However, in contrast to the lift power principle, the drag power principle incorporates that the masses of all generators are carried by the kite and the need for a tether with integrated electrical cables. The latter results in a more expensive tether which is also heavier and thicker and thus reduces efficiency. To reduce the tether’s mass, a high voltage is chosen for the cables but complicates the electrical system. Another challenge is the reduction of the noise of the propellers.

The implementation of completely autonomous and robust launch and retrieval is a major challenge for the lift power principle. Most tested launch and retrieval concepts for lift power kites suffer at least one of the following: (i) A material-intensive and complex ground station, (ii) requirement of strong and constant wind near the ground, or (iii) challenging control. This is contrary to the drag power principle and Makani Power’s/Google’s successful multicopter launch and retrieval. Another advantage can be seen in a simpler implementation of “dancing kites” [23, 42] as the two kites can hover with a low speed side-by-side for the launching and landing. These are motivations for this study: It considers multicopter-based con-

[1] Also called “traction power“, “ground-”, “pumping mode power generation” or “ground-gen”.

[2] Also called “onboard-”, “continuous power generation” or “fly-gen”.

cepts for lift power-operated kites. In fact, the companies e-kite and TwingTec recently announced in [7, 32] to pursue such a concept. Also the company Kitemill pursues such a concept now [28]. However, no detailed studies can be found. The contributions of this study can thus be summarized as follows: (i) Exploration of multicopter-based launching and landing concepts for lift power kites, (ii) proposal of two new concepts for soft kites and proposals for low-weight solutions through detachable electrical cables, (iii) formulation of simple models for static feasibility analyses with example results and (iv) presentation of results of dynamic feasibility analyses (multi-body simulation) for a soft kite solution.

This chapter is organized as follows: The next section presents previously investigated launch and retrieval concepts. Section 19.3 discusses different concepts of a lift power system with multicopter launching and landing. Sections 19.4–19.5 present static and dynamic feasibility analyses. Section 19.6 discusses the results as well as advantages and disadvantages of such multicopter concepts for lift power kites. Finally, Sect. 19.7 gives conclusions and an outlook. The preliminary content of the present chapter has been presented at the Airborne Wind Energy Conference 2015 [4].

19.2 Other Launching and Landing Methods–Related Works

For first experiments for both, soft kites and rigid kites, many companies and research groups use a conventional winch launch with the ground station winch after the kite is placed at some distance by the testing team. For the landing, a rigid kite may be disconnected from the tether and land like a conventional sailplane while a soft kite may be steered to one side of the wind window for a "soft crash landing". In the following, existing launch and retrieval concepts for a commercial deployment found in literature are summarized.

The company SkySails [38, 41] uses a telescope mast to pull a ram-air kite out of its storage. An extra tether connects the leading edge of the kite with the mast's tip. When the kite is inflated by the wind, it is released upwards. The retrieval is performed in the reverse order. This concept seems successful, robust and autonomous (neglecting the storing of the folded kite). However, a relatively strong and constant wind near the ground and/or a high mast is required. The dutch company e-kite also experimented with a similar mast-launch for ram-air kites [7]. Unlike SkySails, no extra tether is connected to the kite's leading edge. Instead the kite is lifted by a metal rack. However, the concept did only work under "ideal situations" [7].

Geebelen and Gillis [19] propose a centrifugal launch and retrieval. This is also persued by the company EnerKite [10] and is being further investigated e.g. in [17, 18]. A (rigid) kite is attached to a rotating arm. Through its inertia and lift forces the kite is released and finally flies downwind with a helical-like flight path. An advanced control method e.g. nonlinear model predictive control is used to control the kite's trajectory. Bontekoe [5] extended this concept by adding a propeller to the rigid kite to support the launch and retrieval with longitudinal thrust. A centrifugal launch and retrieval is independent of the wind speed near the ground. It works well in simulations and small prototypes. A disadvantage is the relatively complex and material-intensive ground station.

In his master thesis, Haug [22] started from scratch and evaluated several part solutions from a mind map. He also considered a concept in which multicopters lift the kite, but discarded such concepts because an "unexpected reaction of one UAV [unmanned aerial vehicle] can lead to hazardous outcomes" [22, p. 35]. Instead he proposed a mast or crane-like construction on which the soft kite hangs upside down and is launched with the help of the wind. Haug was able to launch and retrieve the kite several times, but the kite also crashed several times into the mast or into suspension lines. A video of a successful launch is online available [36]. A similar concept was pursued by the company KiteGen [27] with the additional support of fans on ground. It is not clear if such a mast concept can be implemented with the required robustness. Another disadvantage of the mast launching and landing is the relatively complex ground station and the need for a relatively strong and constant wind near the ground station. These could be reasons why KiteGen now also seems to experiment with multicopters [25].

The company NTS [2, 35] pursues to use several kites, each tethered to a railroad trolley moving on a circular track. The kite pulls the trolley which counteracts by generative braking similar to an electric train for deceleration. NTS could use the trolley in motor mode and launch and retrieve the kite similar to SkySails' mast concept. Since the trolley can generate enough true air speed, this would particularly also work with no wind near ground and with a small mast. However, a disadvantage of such track- or carousel concepts is the high material demand of the track.

To bring the kite into a starting altitude, Breukels [6] successfully used a helium-filled airship. He did not consider the retrieval of the kite. The company Festo Cyberkite [39] used a helium filled kite such that the kite pulls itself into the air even without wind. In their master theses Bontekoe [5] and Haug [22] also reviewed lighter-than-air concepts to launch the kite. However, only few pursue such concepts today. Reasons may include the helium leakage through any membrane or controllability issues of aerostats.

Alula Energy [3, 40] proposes to catapult a rigid kite into the air. The kite is retrieved by landing slowly on the catapult platform. The launch was tested already on small prototypes, but no references were found if the landing can be performed that way. A disadvantage of Alula's ground station concept is its comparably high material demand. A similar concept is being pursued by the companies Ampyx Power [30] and ABB [14]: Similar to a fighter jet on an aircraft carrier, a rigid kite shall be started in a catapult launch with a high acceleration powered by the winch or by a catapult technology, such as linear motors which are also used e.g. for roller coasters. Small onboard propellers may help to climb to the operation altitude. To allow for a short landing strip, the kite is caught and stopped by the ground winch or an additional braking system such as a hook on the kite and lines on the landing strip. However, the feasibility and robustness of such a concept (without the help of a human pilot) is yet to be demonstrated.

As mentioned in the introduction, most of those concepts suffer at least one of the following: (i) A material-intensive and complex ground station, (ii) requirement of strong and constant wind near the ground, or (iii) challenging control.

19.3 Lift Power Kite Concepts With Multicopter Launching and Landing

In this section the basic system components and different concepts for soft and rigid lift power kites with multicopter launching and landing are explored.

19.3.1 Basic System Components

The basic system components or “building blocks” can be summarized by Fig. 19.1: The kite is attached via one or more force-transmitting tethers to one or more winches on ground. The airborne system (blue in Fig. 19.1) comprises three main functions (from right to left in Fig. 19.1):

- The rigid wing or soft kite generates the aerodynamic forces for power generation.
- If the kite is not solely steered by all ground winches on its flight path during power generation, an airborne control unit is required: In the case of a soft kite, this could be a control pod with winches and steering tethers, whereas a rigid kite

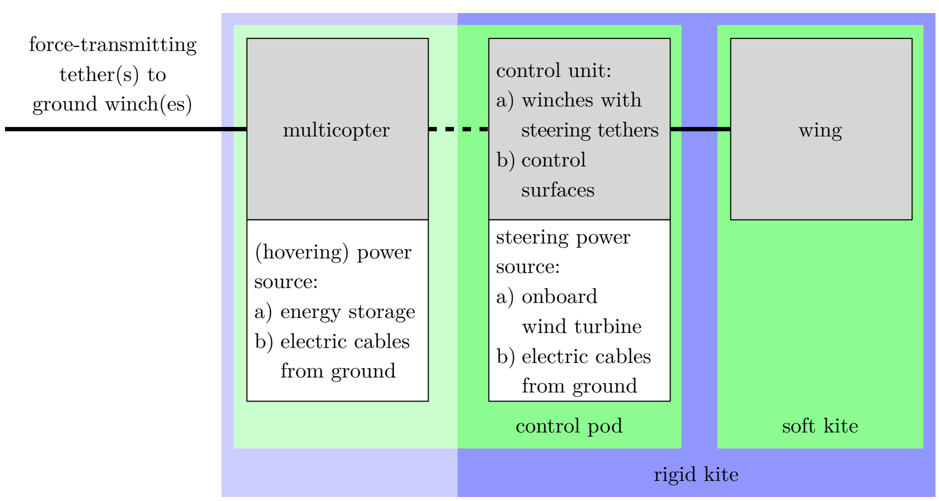

Fig. 19.1 Basic system components or “building blocks” of lift power kites with multicopter launching and landing

can comprise control surfaces. The steering unit needs a steering power source which can either be an onboard wind turbine or electrical cables from ground.

- Finally, a multicopter for launching and landing is required. Its power source can either be an energy storage like lithium-type batteries (which are recharged before/after launching/landing) or electrical cables from ground (which could be identical to the steering power source). The multicopter can be part of the control pod of a soft kite. In the case of a rigid kite, all three functions (wing, control unit, multicopter) can be integrated in one assembly. Note however, that the rated power required by the multicopter should be much lower than the rated system power (i.e. of the ground winch), otherwise it might be more meaningful to use the "drag power" principle.

One or more separate multicopters might be used to launch and land the kite. However, such a concept is not considered here, since it seems too challenging to dock such a drone to the kite for retrieval, particularly in strong and gusty wind conditions. However, a multicopter that can be attached to and detached from the control pod or the rigid kite and moved along the tether, and is thus guided by the tether (light part in Fig. 19.1), is part of the considerations of this study.

19.3.2 Soft Kite Concepts

In the case of a soft kite, a control pod solution, as pursued e.g. by SkySails [38] or TU Delft [15, 29], seems meaningful as one can find the following advantages: (i) Only one winch on ground is required, because the steering is performed by small steering winches onboard the control pod. (ii) The tether drag is minimal, as only one tether connects the airborne system to the ground station. (iii) The steering is direct, as the steering lines are short. (iv) For accurate control a GPS sensor, an inertial measurement unit and further sensors can be integrated into the control pod. (v) Lighting and collision avoidance systems, which might be mandatory in future, can be integrated into the control pod. (vi) A communication system to exchange the information with the onboard systems can also be integrated into the control pod.

However, the control pod needs continuously electric power for steering (see Fig. 19.1). To avoid a tether with integrated electrical cables and its disadvantages, one or more onboard wind turbines (each with electrical drive in generator mode) can be used. One proposal of this study is to use those wind turbines as propellers (by operating their electrical drives in motor mode) for the launching and landing with certain flight maneuvers, and thus turning the control pod into a multicopter. For low mechanical complexity, several fixed pitch propellers are considered. In the following, two possible launch and retrieval maneuvers are proposed, one with upwind mounted propellers and one with downwind mounted propellers. Hereby upwind and downwind refers to the propeller's position at the control pod with respect to the relative air velocity vector during normal flight, see Fig. 19.2.

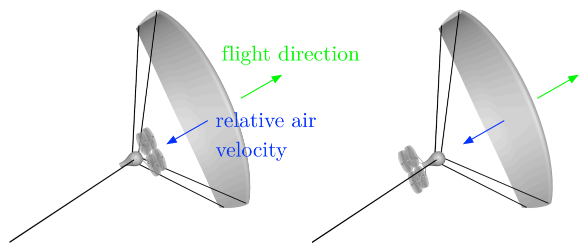

Fig. 19.2 Control pod with upwind mounted propellers (left) and control pod with downwind mounted propellers (right)

Launch and Retrieval Maneuver with Upwind Propellers. Figure 19.3 illustrates the proposed launch maneuver with upwind propellers: The propellers are operated in motor mode with which the pod hovers downwind and into higher altitudes while the kite hangs below and the tether is slack. Then, the tether is pulled from the ground station winch, which should erect the kite. Alternatively or additionally, the pod is steered by its propellers accordingly to erect the kite. The kite then flies towards the zenith, the propellers are turned off and energy generation can be started.

This launch maneuver is similar to a launching paraglider pilot: The pilot unfolds his/her paraglider on ground the same way the kite hangs below the control pod in Fig. 19.3. Then the pilot starts running which erects the kite above the pilot.

Figure 19.4 illustrates the retrieval maneuver with upwind propellers: The kite is flown towards the zenith. At a low altitude, the propellers are powered with full thrust while the tether is slack. In this way the pod accelerates upwards while the kite approximately remains on its position which can be supported by depowering the kite. The pod is partly forced on a circular path by the tethers between pod and kite. As soon as the pod is above the kite, the pod is again operated like a multicopter and hovers back to a landing site.

A disadvantage of the concept with upwind propellers is that during hovering the trailing edge of the kite instead of its leading edge faces towards the wind vector. Consequently, the kite might be out of control. To avoid this risk, a second concept with downwind propellers is proposed.

Launch and Retrieval Maneuver with Downwind Propellers. Figure 19.5 illustrates the launch: Initially the propellers are operated again in motor mode with which the pod hovers downwind and into greater altitudes while the kite hangs below and the tether is slack. Hereby, unlike Figs. 19.3 and 19.4, the leading edge of the kite faces towards the wind vector and thus should be controllable. Then, the tether is pulled from the ground station winch, which should erect the kite. Alternatively or additionally, the pod is steered by its propellers accordingly to erect the kite. After the propellers are turned off, the kite is turned over and energy generation can be started.

Figure 19.6 illustrates the retrieval maneuver with downwind propellers: The kite is flown from the zenith towards the ground. The kite's speed may be reduced by depowering the kite. Then, the propellers are operated in motor mode with full thrust, while the tether length is kept constant or the tether is slack. The pod stops and the kite swings below. Finally, the pod is again operated as multicopter and hovers back to a landing site.

A disadvantage of the concept with downwind propellers is, that the kite can generate a high aerodynamic force counteracting the propeller forces. Moreover, in both concepts the propeller downwash can hit the kite which is not desirable. Such issues are addressed in the following.

Design Considerations. To solve the challenges imposed by the proposed concepts, certain design criteria are required for both, control pod and kite. In the following the challenges are stated and possible solutions are sketched.

As derived later in Sect. 19.4, the higher the airborne mass and the lower the overall propeller disk (or swept) area (i.e. the higher the disk loading), the higher the power and energy demand of the propellers to hover. Since the propeller disk area and the energy storage size are limited, a combination of the following measures should be taken: (i) The control pod should be made from lightweight materials, e.g. carbon-fiber. Additionally, the kite should be as light as possible. (ii) The energy storage should consist of rechargeable lithium batteries, ultra capacitors and/or other high energy density and high power density storage technologies. (iii) The energy storage should be recharged on ground before launch, such that it needs to be dimensioned only for one launch or one retrieval, respectively. (vi) The propeller disk area should be maximized to obtain a high propeller efficiency (or figure of merit) through low disk loading. However, such big propellers might be disadvantageous during normal flight because the onboard loads and the recharging of the energy storage require less power than large propellers can provide. So the load factor of the propellers in wind turbine mode could be rather low and generate undesired drag during crosswind flight. To avoid a high propeller drag, all or some propellers may be carried out as folding propellers, single blade propellers or variable pitch propellers. Additionally, a small optimized wind turbine could be used at the pod which is the only propeller operated in generator mode. (v) Contra rotating propellers could be a possibility to increase propeller efficiency. (vi) Ducted propellers could be another possibility to increase propeller efficiency and decrease propeller noise. Although the downwind or upwind placement of the propellers with the respective launching and landing maneuvers decreases the possibility of collisions between propeller blades and kite or tethers (see Figs. 19.2–19.6), the ducts would give a further protection. However, the last two measures (v) and (vi) also increase mass, so that a good compromise has to be found.

To avoid a negative effect of the propeller downwash to the kite during hovering, a combination of the following measures is proposed: (i) Change the pitch angle of the kite such that the kite area which is affected by downwash is small. (ii) Change

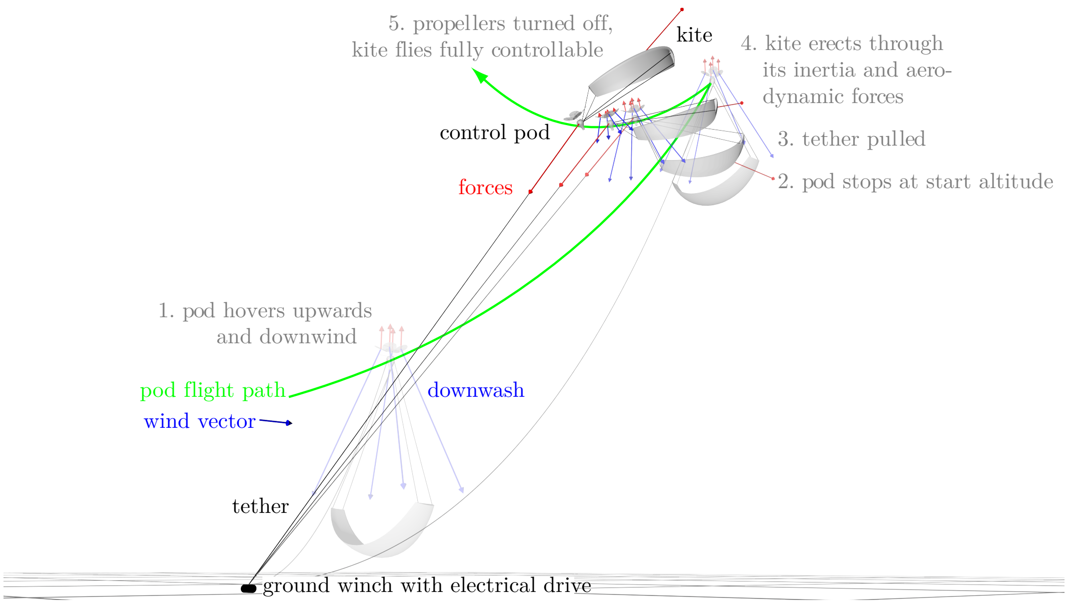

Fig. 19.3 Illustration of the launch maneuver with upwind propellers

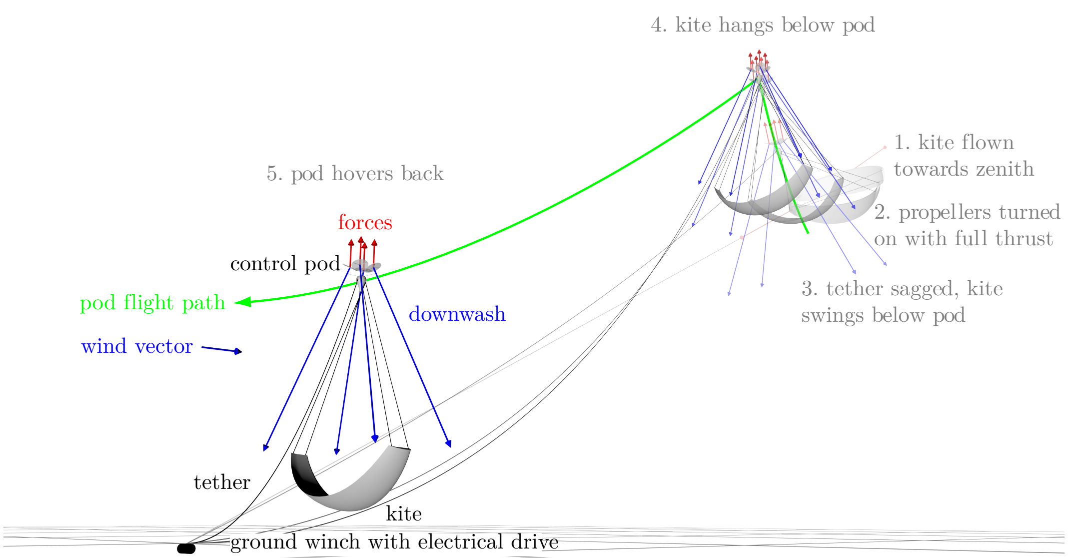

Fig. 19.4 Illustration of the retrieval maneuver with upwind propellers

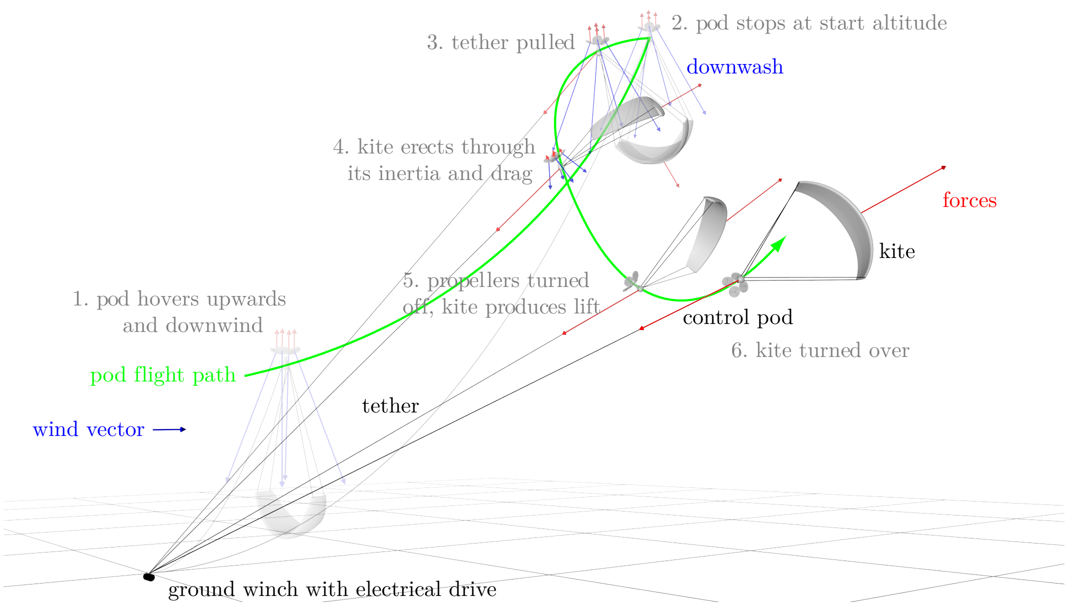

Fig. 19.5 Illustration of the launch maneuver with downwind propellers [4]. Reprinted with permission of R. Schmehl

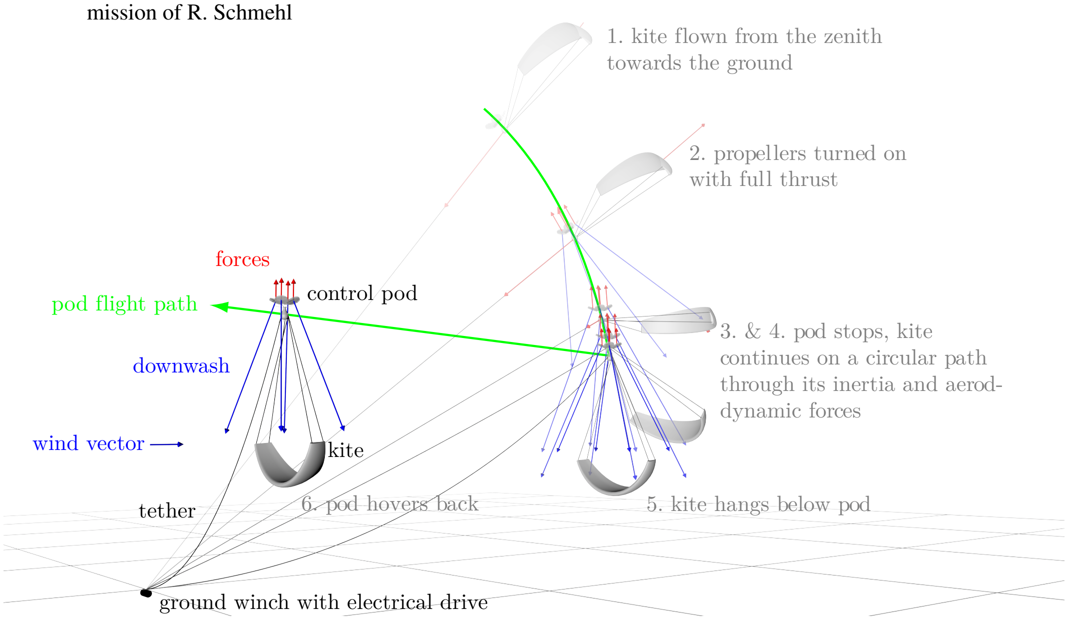

Fig. 19.6 Illustration of the retrieval maneuver with downwind propellers [4]. Reprinted with permission of R. Schmehl

the kite's geometry: The kite might be folded or flagged. The latter means that the right or the left tethers between pod and kite are slack. (iii) Design the thrust system so that downwash passes the kite to the left and to the right side and a downwash free zone occurs below the pod in which the kite can swing in and out. E.g. use propellers which are inclined or can be inclined to the left and the right side, see Figs. 19.3–19.6. Another possibility might be to mount the propellers on (long, telescoping) arms to the right and left side. Yet another possibility is to use baffles and/or design the casing of the pod such that downwash is slightly deflected to create a downwash free zone.

Particularly for the downwind propeller concept where the kite's leading edge faces towards the wind vector while hanging below the pod, see Figs. 19.5 and 19.6, the kite can create a significant aerodynamic force counteracting the propellers' thrust and could lead to a considerably higher power demand to keep the system aloft. To reduce the kite's force a combination of measures (ii) and (iii) of the last paragraph may be applied. However, the controllability would be affected negatively with these solutions. A better solution might be to use a ram air kite and reduce its aerodynamic efficiency while hanging upside down by a combination of the following measures: (i) Partly close the leading edge inlets. (ii) Partly open trailing edge outlets. (iii) Change the airfoil of the kite to a symmetric one or an inverted one to reduce the generated lift. This could be achieved by shortening tethers between leading edge and trailing edge.

The propellers, their drives and particularly the energy storage add significant mass to the control pod. This not only can reduce efficiency during energy generation but also can reduce stability: In dynamic simulations (details in Sect. 19.5) it was observed that with a high mass the control pod could oscillate perpendicularly to the tether. To avoid this oscillation, a combination of the following measures may be applied: (i) The oscillation may be damped actively by steering actuations of kite or ground winch(es). (ii) Small stabilizer wings may be attached to the pod to damp the oscillation passively. The wings may also be rotatable or have flaps to damp the oscillation actively. Additionally, these actuators may be used to generate some lift to counteract the mass of the control pod.

The system needs a set of additional sensors: E.g. to control the hanging kite during hover mode, the control pod could have a camera. Data processing extracts the kite's position and attitude. To enable this concept during night, a spotlight is also required.

19.3.3 Rigid Kite Concepts

Rigid kites (gliders/airplanes) equipped with propellers have been proposed e.g. in [21, 32, 33]. One can imagine a rigid kite with propellers at various locations and with various orientations. The wings can be placed to support the propellers during hovering with aerodynamic lift. The evaluation of a specific design is out of scope of this study. Instead, the aerodynamic forces of the wings of a rigid kite are considered negligible. Thus a worst case is considered where only the thrust of the propellers is available during hovering.

19.3.4 Electrical Cables-Based Hovering Power Sources

So far, only concepts were considered where the multicopter control pod carries an energy storage. Besides its high mass and cost, the energy density of an energy storage diminishes over time. To avoid these disadvantages, concepts which partly or completely replace the energy storage by an electrical cable are discussed in the following: Figure 19.7 illustrates the considered solutions for a soft kite, which are applicable similarly to a rigid kite.

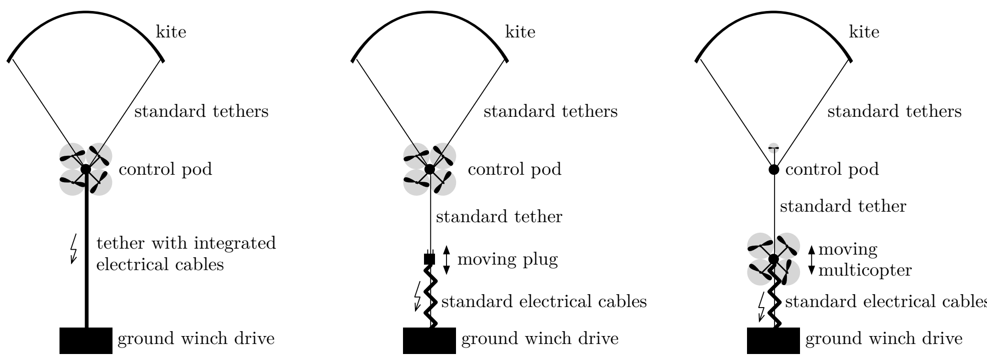

Fig. 19.7 Partly or complete replacement of the onboard energy storage: by a tether with integrated electrical cables (left), by external electrical cables which can move along the tether (the control pod has a small energy storage to buffer fluctuations, middle) and by a separate multicopter that can move along the tether (the control pod has a small wind turbine and a small energy storage, right)

Tether with Integrated Electrical Cables. One solution is using a tether with integrated electrical cables (with all its disadvantages) and thus replace completely the onboard energy storage, see Fig. 19.7 (left). However, this solution has a similar disadvantage as an energy storage solution: Both are designed for the propeller power during launch and retrieval, because they need much more power than the onboard loads during normal flight. Neither a big energy storage nor a high power electrical cable is needed in the latter phase. Moreover, it is questionable if such a tether for a lift power system can be made durable enough to withstand the tear imposed by winding.

External Electrical Cables. A high power electrical cable is only needed during launch and retrieval. Figure 19.7 (middle) visualizes the idea to plug an electrical cable in the control pod for launch and retrieval only: A small carriage moves along the tether from the ground station to the control pod prior to the retrieval. After launch the carriage moves back to the ground station. There it may decouple itself from the tether, because the tether can move fast during the pumping cycles. As a consequence, the mass which is to be lifted is smaller, the providable power should be high and the providable energy is practically unlimited.

Once launched, this solution has the advantage to be a relatively light airborne system without heavy energy storage and a thin, light and inexpensive tether. The additional electrical cable may be as heavy as the kite or the multicopter control pod can carry, i.e. a low voltage level and an inexpensive off-the-shelf electrical cable may be used. While the carriage moves towards the control pod, the kite may stay in the zenith. If the wind is too calm while the carriage is moving, the kite may also be powered mechanically by the ground winch through reverse pumping [5, 20] or winching [5].

Separate Multicopter. Another idea is to split the control pod into two parts, see Fig 19.7 (right): The first part is a conventional control pod only with a small wind turbine to power the onboard devices and with a small energy storage to buffer fluctuations. The second part is a multicopter with greater propellers and is docked at the control pod for launch and retrieval only. To reduce mass, that multicopter is preferably powered by electrical cables from ground rather than an energy storage onboard of the multicopter. To simplify the docking, the multicopter moves along the tether from the ground station towards the control pod by using the propellers or a small onboard winch. The undocking is the reverse.

Contrary to the additional electrical cables solution in Fig 19.7 (middle), no additional mass and drag through propellers are present at the control pod during normal flight. However, the docking and undocking as well as the construction are more challenging, because the mass of a multicopter is higher than the mass of a small carriage which moves just a plug to the control pod.

19.4 Static Feasibility Analyses

In the following, feasibility analyses are carried out to show that the propellers can generate enough thrust to lift a kite, both powered by an energy storage or electrical cables. The flight maneuvers are not considered in these analyses. A simplified model is formulated and solved with example parameters for a soft kite and for a rigid kite.

19.4.1 Model for Energy Storage Powered Solutions

The following assumptions and equations are employed to allow for simplified analyses:

Assumption 19.1: *The power of a single propeller $P_{\mathrm{p,s}}$ to generate thrust $T_{\mathrm{p,s}}$ with propeller disk area $A_{\mathrm{p,s}}$ is given by*

$$P_{\mathrm{p,s}} = \sqrt{\frac{T_{\mathrm{p,s}}^3}{2\rho A_{\mathrm{p,s}}}}, \tag{19.1}$$

where ρ is the air density (actuator disk or momentum theory). [16, pp. 152]

For n propellers and to lift the mass m in hovering flight, each propeller must generate the thrust $T_{\mathrm{p,s}} = mg/n$ with gravitational acceleration $g \approx 9.81\,\mathrm{m/s^2}$. Then the total propeller power is

$$P_{\mathrm{p}} = nP_{\mathrm{p,s}} = n\sqrt{\frac{\left(\frac{mg}{n}\right)^3}{2\rho A_{\mathrm{p,s}}}} = \sqrt{\frac{(mg)^3}{2\rho \frac{n^3 A_{\mathrm{p,s}}}{n^2}}} = \sqrt{\frac{(mg)^3}{2\rho \underbrace{nA_{\mathrm{p,s}}}_{=A_{\mathrm{p}}}}} = \sqrt{\frac{(mg)^3}{2\rho A_{\mathrm{p}}}}, \tag{19.2}$$

where $A_{\mathrm{p}} = nA_{\mathrm{p,s}}$ is the total propeller disk area.

Assumption 19.2: *The energy storage must provide the constant electric power*

$$P_{\mathrm{e}} = s\frac{1}{\eta}P_{\mathrm{p}}, \tag{19.3}$$

where η is the efficiency (i.e. the ratio of the power drawn from the energy storage and the power required to generate thrust mg in Eq. (19.2)*) and s is a safety factor which regards e.g. the needed power for steering actuations or other electrical loads.*

The airborne mass is

$$m = m_{\mathrm{k}} + m_{\mathrm{p}} + m_{\mathrm{e}} + m_{\mathrm{o}} \tag{19.4}$$

with the kite mass m_{k}, the propellers' mass m_{p}, the energy storage mass m_{e} and the mass of other parts m_{o}, such as control pod winches, control pod casing, tethers etc. in the case of a soft kite with control pod. The following assumptions are made for the mass portions:

Assumption 19.3: *The kite mass is*

$$m_{\mathrm{k}} = \mu_{\mathrm{k}} A_{\mathrm{k}}, \tag{19.5}$$

where μ_{k} is the specific kite mass and A_{k} is the kite's projected area.

Assumption 19.4: *The mass of the propulsion unit (i.e. propellers and electrical drives) is*

$$m_\mathrm{p} = \mu_\mathrm{p} P_\mathrm{e}, \tag{19.6}$$

where μ_p is the specific mass of the propellers.

Assumption 19.5: *The mass of the energy storage is*

$$m_\mathrm{e} = \max\left\{\frac{E_\mathrm{e}}{\gamma_\mathrm{e,E}}, \frac{P_\mathrm{e}}{\gamma_\mathrm{e,P}}\right\}, \tag{19.7}$$

where $E_\mathrm{e} = P_\mathrm{e} t_\mathrm{h}$ is the electric energy needed to hover for the time t_h, and $\gamma_\mathrm{e,E}$ and $\gamma_\mathrm{e,P}$ are the energy and power densities of the energy storage technology.

Note that the max-function of Eq. (19.7) ensures that the energy storage is large enough to provide the required energy *and* the required power.

Assumption 19.6: *The mass of other parts is*

$$m_\mathrm{o} = \mu_\mathrm{o} A_\mathrm{k}, \tag{19.8}$$

where μ_o is the specific mass of other parts.

Remark 19.1: *Assumption 19.1 is a simplification as it assumes a propeller disk (Betz' analysis). Real propellers require more power (i.e. their "actuator disk efficiency" is less then* 100 %*), which can be covered by Assumption 19.2 through an adequate value of η. Also a possibly high power demand due to the kite's aerodynamic force that counteracts propeller thrust during hovering can be covered by Assumption 19.2 through an adequate value for s. Assumption 19.3 with constant μ_k is only valid within tight bounds of A_k, as the kite mass does not increase linearly with its area. Similar limitations apply for Assumptions 19.4 through 19.6.*

Combining Eqs. (19.1) to (19.8) yields

$$P_\mathrm{e} = s\frac{1}{\eta}\sqrt{\frac{\left(A_\mathrm{k}[\mu_\mathrm{k}+\mu_\mathrm{o}] + P_\mathrm{e}\left[\mu_\mathrm{p} + \max\left\{\frac{t_\mathrm{h}}{\gamma_\mathrm{e,E}}, \frac{1}{\gamma_\mathrm{e,P}}\right\}\right]\right)^3 g^3}{2\rho A_\mathrm{p}}} \tag{19.9}$$

which was solved numerically for P_e (note that the unknown P_e is on the left hand side and on the right hand side of Eq. (19.10)),[3] i.e.

$$P_\mathrm{e} = f(s, \eta, A_\mathrm{k}, \mu_\mathrm{k}, \mu_\mathrm{o}, \mu_\mathrm{p}, t_\mathrm{h}, \gamma_\mathrm{e,E}, \gamma_\mathrm{e,P}, A_\mathrm{p}). \tag{19.10}$$

The masses of the propellers and of the energy storage can then be calculated by inserting the numerical result of Eq. (19.10) into Eqs. (19.6) and (19.7).

[3] It is also possible to convert Eq. (19.9) to the form $0 = p_0 + p_1 x + p_2 x^2 + p_3 x^3$. So there should be an analytical solution $x = P_\mathrm{e}$. However, numerical solving was preferred for sake of simplicity.

Symbol & Value	**Comment**
Parameters (for both, soft kite or rigid kite).	
$s/\eta = 3$	assumed
$\mu_o = 0.25\,\mathrm{kg/m^2}$	assumed
$\mu_p = 0.2\,\mathrm{kg/kW}$	assumed; taken from [26]
$t_h = 5\,\mathrm{min}$	assumed to be enough for one launch or one retrieval incl. safety factor
$\gamma_{e,E} = 130\,\mathrm{Wh/kg}$	assumed for lithium batteries; taken from a recent model making battery [9]
$\gamma_{e,P} = 5\,\mathrm{kW/kg}$	assumed for lithium batteries; taken from a recent model making battery [9]
$A_p = 1\,\mathrm{m^2}$	design decision
$\rho = 1.2\,\mathrm{kg/m^3}$	assumed (for low elevation flight)
Soft kite specific parameters.	
$A_k = 20\,\mathrm{m^2}$	size of a commercial surf kite or paraglider [1]; the system could have a rated power of about 22 kW (from Loyd's analysis [31] with lift coefficient 1.0, drag coefficient 0.2, overall system efficiency 50 %, wind speed 10 m/s)
$\mu_k = 0.25\,\mathrm{kg/m^2}$	assumed; typical for commercial paragliders of the regarded size [1]
Rigid kite specific parameters.	
$A_k = 15\,\mathrm{m^2}$	size of a commercial hang glider [34]; the system could have a rated power of about 56 kW (from Loyd's analysis [31] with lift coefficient 1.5, drag coefficient 0.2, overall system efficiency 50 %, wind speed 10 m/s)
$\mu_k = 2.5\,\mathrm{kg/m^2}$	assumed; typical for commercial hang gliders of the regarded size [34]
Soft kite solutions.	
$P_e \approx 2.5\,\mathrm{kW}$	solution of Eq. (19.10)
$m_p \approx 0.5\,\mathrm{kg}$	solution of Eq. (19.10) inserted into Eq. (19.6)
$m_e \approx 1.6\,\mathrm{kg}$	solution of Eq. (19.10) inserted into Eq. (19.7)
Rigid kite solutions.	
$P_e \approx 36\,\mathrm{kW}$	solution of Eq. (19.10)
$m_p \approx 7.2\,\mathrm{kg}$	solution of Eq. (19.10) inserted into Eq. (19.6)
$m_e \approx 23.1\,\mathrm{kg}$	solution of Eq. (19.10) inserted into Eq. (19.7)

Table 19.1 Considered parameters and numerical results for a soft kite with battery-powered control pod and a rigid kite with battery-powered propellers

19.4.2 Example Results for Battery-Powered Solutions

Table 19.1 lists possible parameters of a soft kite prototype system as well as the numerical results. Figure 19.8 (left) shows also a plot of the results for varied s/η and A_p, since s/η could be higher due to the kite's aerodynamic force that counteracts propeller thrust during hovering. Additionally, μ_k is likely to be higher since a commercial paraglider, from which the value of μ_k originates, is not designed to generate electricity. Figure 19.8 (right) shows a plot of the results for higher μ_k and varied A_p. Note that Eq. (19.10) has no solution for high s/η with low A_p or for high μ_k with low A_p, i.e. the propellers cannot generate enough thrust to lift the masses or it can only hover for a time smaller than t_h.

Table 19.1 and Fig. 19.9 show the considered parameters and results for a lightweight rigid kite which is designed similarly to a hang glider. The differences to the soft kite concept are that the specific kite mass μ_k is higher and the kite area A_k is smaller.

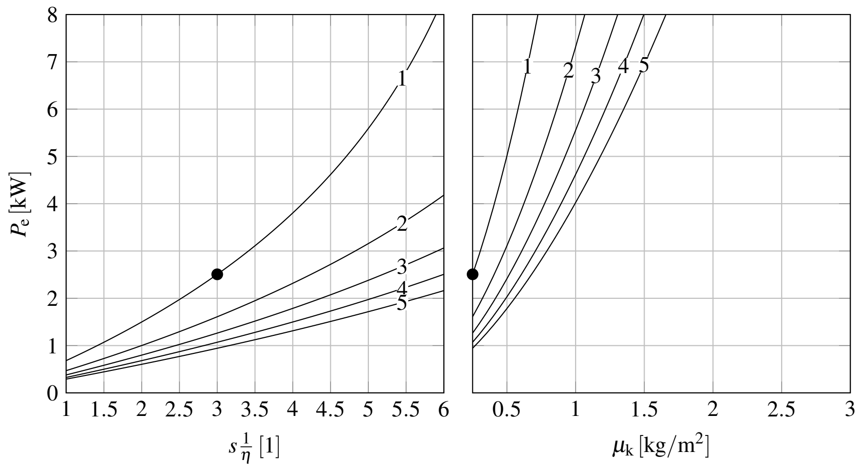

Fig. 19.8 Numerical results for a soft kite with the data of Table 19.1 (black dot) and for varied s/η (left) and for higher μ_k (right) each for $A_p \in [1\,\mathrm{m}^2, 2\,\mathrm{m}^2, \ldots, 5\,\mathrm{m}^2]$ and otherwise unchanged parameters

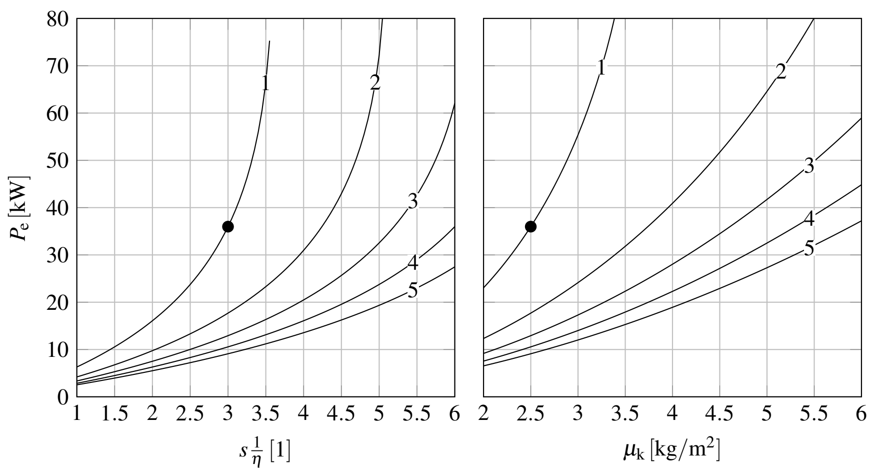

Fig. 19.9 Numerical results for a rigid kite with the data of Table 19.1 (black dot) and for varied s/η (left) and for varied μ_k (right) each for $A_p \in [1\,\mathrm{m}^2, 2\,\mathrm{m}^2, \ldots, 5\,\mathrm{m}^2]$ and otherwise unchanged parameters

19.4.3 Model for Electrical Cables-Powered Solutions

The same assumptions and equations from Sect. 19.4.1 are taken for feasibility analyses of electrical cables-powered solutions. Hereby, Assumption 19.5 is replaced by the following assumption:

Assumption 19.7: *The mass of the electrical cables is*

$$m_\mathrm{c} = \mu_\mathrm{c} l_\mathrm{c} P_\mathrm{e} \tag{19.11}$$

where μ_c is the specific cable mass and l_c is the carried cables' length.

With that, the required electric power is given by

$$P_\mathrm{e} = s\frac{1}{\eta}\sqrt{\frac{\left(A_\mathrm{k}[\mu_\mathrm{k}+\mu_\mathrm{o}]+P_\mathrm{e}\left[\mu_\mathrm{p}+\mu_\mathrm{c} l_\mathrm{c}\right]\right)^3 g^3}{2\rho A_\mathrm{p}}} \tag{19.12}$$

which was again solved numerically for P_e, i.e.

$$P_\mathrm{e} = f(s, \eta, A_\mathrm{k}, \mu_\mathrm{k}, \mu_\mathrm{o}, \mu_\mathrm{p}, \mu_\mathrm{c}, l_\mathrm{c}, A_\mathrm{p}). \tag{19.13}$$

The masses of propellers and electrical cables are again given by inserting the numerical result of Eq. (19.13) into Eqs. (19.6) and (19.11).

19.4.4 Example Results for Electrical Cables-Powered Solutions

Table 19.2 lists possible parameters for a prototype system similar to the last section as well as numerical results. Figure 19.10 (left) shows a plot of the results for a soft kite for varied s/η and A_p and Fig. 19.11 (right) shows a plot of the results for varied μ_c and A_p. Figure 19.11 shows plots of the results for a rigid kite.

Symbol & Value	**Comment**
Parameters (for both, soft kite or rigid kite).	
$\mu_\mathrm{c} \approx 3\cdot10^{-6}\,\mathrm{kg/m/W}$	assumed; taken from two cables used for photovoltaics applications [24]
$l_\mathrm{c} = 100\,\mathrm{m}$	assumed to be enough to safely launch and retrieve the kite with the proposed maneuvers
Soft kite solutions.	
$P_\mathrm{e} \approx 2.2\,\mathrm{kW}$	solution of Eq. (19.13)
$m_\mathrm{p} \approx 0.4\,\mathrm{kg}$	solution of Eq. (19.13) inserted into Eq. (19.6)
$m_\mathrm{c} \approx 0.7\,\mathrm{kg}$	solution of Eq. (19.13) inserted into Eq. (19.11)
Rigid kite solutions.	
$P_\mathrm{e} \approx 22.7\,\mathrm{kW}$	solution of Eq. (19.13)
$m_\mathrm{p} \approx 4.5\,\mathrm{kg}$	solution of Eq. (19.13) inserted into Eq. (19.6)
$m_\mathrm{c} \approx 6.8\,\mathrm{kg}$	solution of Eq. (19.13) inserted into Eq. (19.11)

Table 19.2 Considered parameters that differ from Tab 19.1 and numerical results for a soft kite with electrical cables-powered control pod and a rigid kite with electrical cables-powered propellers

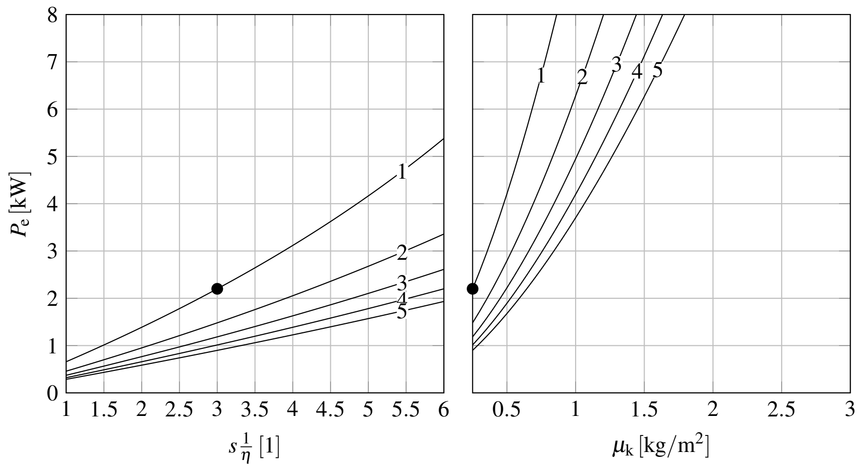

Fig. 19.10 Numerical results for a soft kite with the data of Table 19.2 (black dot) and for varied s/η (left) and for higher μ_k (right) each for $A_p \in [1\,\mathrm{m}^2, 2\,\mathrm{m}^2, \ldots, 5\,\mathrm{m}^2]$ and otherwise unchanged parameters

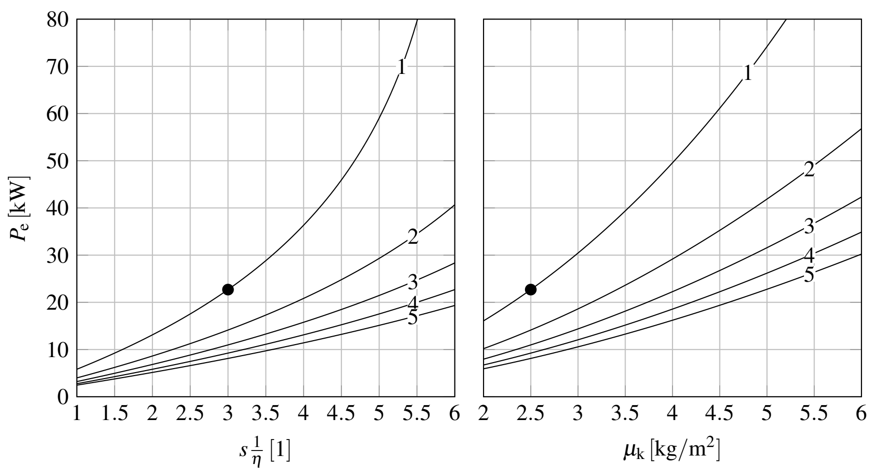

Fig. 19.11 Numerical results for a rigid kite with the data of Table 19.1 (black dot) and for varied s/η (left) and for higher μ_k (right) each for $A_p \in [1\,\mathrm{m}^2, 2\,\mathrm{m}^2, \ldots, 5\,\mathrm{m}^2]$ and otherwise unchanged parameters

19.5 Dynamic Feasibility Analyses

The flight maneuvers of rigid kite solutions are feasible: videos of such maneuvers have been presented by e-kite [7] and TwingTec [32]. Moreover, for a few years Makani Power/Google has successfully been demonstrating the multicopter launching and landing as well as transitions to and from crosswind flight with their drag power rigid kite prototypes. Consequently, only the soft kite solutions need to be investigated, whereby the following analyses focus on the proposed maneuvers of the downwind propeller concept (see Figs. 19.5–19.6). A multicopter control pod with lithium-type battery energy storage without the possibility to separate the multicopter is considered in these first dynamic analyses.

A multi-body modeling approach is employed where kite and control pod are modeled as rigid bodies connected by spring-dampers as tether models. No collisions between tethers, pod nor kite are modeled. The kite follows the turning rate law formulated in [11] and its angle of attack can be changed actively. The shaft of the propellers and of the ground winch are modeled with Newtonian dynamics and the propellers are modeled to generate thrust and torque proportional to the square of the propeller speed. No downwash is modeled which implies the assumption that downwash never effects the kite (due to inclined propellers as in Figs. 19.3–19.6). For the kite a controller similar to [13] and for the control pod a simple multicopter controller is employed. For the overall system control, a state machine is used. Feedback of all for the control necessary quantities are regarded as available without offset, delay, noise or other disturbances. All controller parameters were tuned by hand and are thus not optimized. Model and controller are implemented in C++. Table 19.3 lists important model parameters. Note that the parameters correspond to a soft kite system sketched in Table 19.1. A more detailed description is omitted due to space limitation.

Parameter	**Symbol & Value**
Logarithmic Wind Model: $v_\mathrm{w}(z) = v_\mathrm{w,ref}\ln(z/z_0)/\ln(z_\mathrm{ref}/z_0)$.	
reference wind speed	$v_\mathrm{w,ref} = 6\,\mathrm{m/s}$
reference altitude	$z_\mathrm{ref} = 50\,\mathrm{m}$
surface roughness	$z_0 = 0.2\,\mathrm{m}$
Kite and Control Pod.	
lift coefficient during power generation[a]	$C_\mathrm{L} \approx 0.7$
drag coefficient during power generation[a]	$C_\mathrm{D} \approx 0.15$
lift coefficient during hovering[a]	$C_\mathrm{L} \approx 0.1$
drag coefficient during hovering[a]	$C_\mathrm{D} \approx 0.1$
kite area	$A_\mathrm{k} = 20\,\mathrm{m}^2$
kite mass	$m_\mathrm{k} = 5\,\mathrm{kg}$
control pod mass	$m_\mathrm{pod} = 7.1\,\mathrm{kg}$
number of propellers	$n = 8$ (4 pairs of contra-rotating)
total propeller disc area	$A_\mathrm{p} = 1\,\mathrm{m}^2$

[a] Lift and drag coefficients are simulated as functions of angle of attack.

Table 19.3 Model Parameters

Figure 19.12 (a) shows the 3D flight trajectory of the kite and of the control pod for a launch maneuver. Figure 19.12 (b) shows the sum of the electric (propeller) power. Similar plots for the landing are shown in Figs. 19.12 (c) and (d). The plots show successful maneuvers, as sketched in Figs. 19.5–19.6.

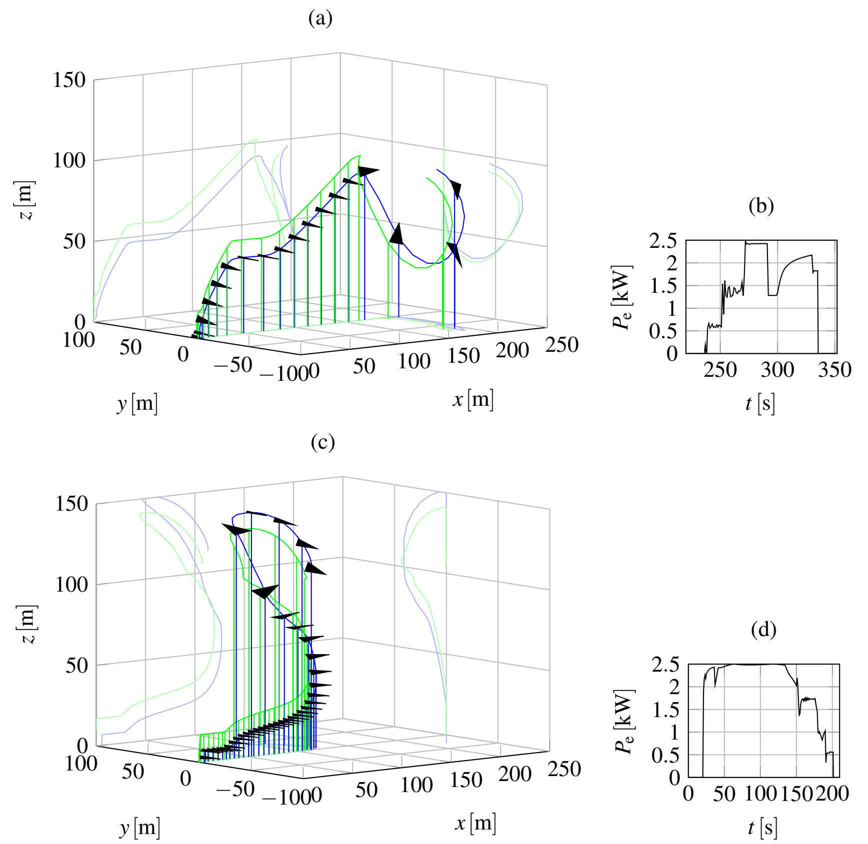

Fig. 19.12 Simulation results of the downwind propeller concept (compare with Figs. 19.5–19.6): 3D flight trajectories during launching from ground into crosswind figure eights (a) with sum of the electric propeller power in (b). The kite trajectory is printed in blue (with kite attitude visualization every five seconds) and control pod trajectory in green. Similar plots are given for the landing in (c) and (d)

Simulations for turbulent and rotating winds were also carried out. To handle the latter case, the control algorithm always turns the kite's leading edge towards the wind. Even under such non-ideal conditions, the simulations show that the airborne system stays aloft remarkably stably, i.e. almost without oscillations and without crashing. Moreover, simulations with a much lighter control pod (i.e. without energy storage and propellers) where carried out to investigate the effect of the added control pod mass on the efficiency, with otherwise unchanged model and controller parameters: With an unrealistic light control pod of $m_{\mathrm{pod}} = 0.5\,\mathrm{kg}$, the power increase in the reel out phase is $\approx 5.6\,\%$ and the average power increase for the pumping cycle is with $\approx -0.5\,\%$ even negative. The latter can be explained by a more efficient reel-in phase of the heavier system as gravity helps better to bring the airborne system back and a heavier control pod further depowers the kite. Yet another simulation with a stronger wind with $v_{\mathrm{w,ref}} = 10\,\mathrm{m/s}$ was carried out. Unfortunately, under such conditions the propellers are not able to generate enough thrust to keep the system aloft, i.e. the kite's downward pulling aerodynamic force is too strong.

19.6 Discussion

General Results of Analyses. The results of P_e, m_p and m_e of the static analyses seem to be feasible figures, for all, battery and cable power solutions, rigid and soft kites. Based on the simulation results with the underlaying simplifications/assumptions, the maneuvers of Figs. 19.5–19.6 also seem to be flyable. The kite is quite stable while hanging under the control pod even under turbulent and rotating wind and even with the hand tuned controller parameters. However, it cannot be excluded that this is just the result of the relatively simple simulation model, so that the control can be much more challenging with a more elaborate kite model or with a real demonstrator. A disadvantage of that soft kite concept is that the kite generates a significant lift force that opposes the propeller thrust. As visible in Figs. 19.12 (b) and (d), the full available power with $s/\eta = 3$ is required for a large portion of the time already at a wind speed of about $6\,\mathrm{m/s}$. For higher wind speeds, even for the arguably optimistically assumed parameters, the available propeller thrust is not sufficient to keep the system aloft. Consequently, more propeller power (and a bigger energy storage) and further measures to reduce the kite's lift, instead of just pitching the kite as in the simulation, are necessary. Contrary to the soft kite solutions, a rigid kite can be designed such that its aerodynamic force does not counteract propeller thrust, with the further advantage of a lower factor s/η. However, the mass of a rigid kite is higher, for which the required hovering power is very sensitive. An interesting observation of the dynamic simulations is that the average power of one pumping cycle with a heavy control pod is higher than the average power of a very light control pod (however, note that all system and controller parameters other than the control pod mass were not changed and that the controller parameters were not optimized). This apparent contradiction was also observed by [37]: An airborne mass greater than $0\,\mathrm{kg}$ results in a more efficient pumping cycle due to a more efficient reel-in phase. Consequently, a higher mass of control pod or rigid kite due to propellers and energy storage might not necessarily lead to critical system efficiency losses.

Hovering Power Source. Particularly the battery-powered solutions are very sensitive to worse s/η and to higher masses, visible in Figs. 19.8 and 19.9. This problem is more severe for larger systems as μ_k actually increases with A_k. Moreover, for a solution with a soft kite and control pod, A_p is limited also for high A_k. As rigid kites are usually heavier than soft kites, a battery-powered solution for such kites is only feasible for very light structures (e.g. through using a combination of soft and rigid materials similar to hang gliders). Note that, in the considered cases $m_\mathrm{e} = \max\{E_\mathrm{e}/\gamma_{\mathrm{e,E}}, P_\mathrm{e}/\gamma_{\mathrm{e,P}}\} = E_\mathrm{e}/\gamma_{\mathrm{e,E}}$ is driven by the energy density and not by the power density. Consequently, with today's energy storage technologies, lithium-type batteries are most suitable (compared to e.g. ultra-capacitors which have a higher power density but a lower energy density and are thus not suitable).

Electrical cables-powered solutions are less sensitive to worse s/η and μ_{k}, compare Figs. 19.8 and 19.9 with Figs. 19.10 and 19.11. For instance, a battery solution for a rigid kite would add $m_{\mathrm{p}} + m_{\mathrm{e}} \approx 30.3\,\mathrm{kg}$ while a solution with detachable electrical cable would only add $m_{\mathrm{p}} = 4.5\,\mathrm{kg}$. However, the propeller power of the rigid kite of this example is already about half of the expected rated power of the system, see Tabs. 19.1 and 19.2.

Comparison of the Detachable Electrical Cables Concept with Drag Power. A rigid lift power kite with detachable electrical cables is similar to the drag power concept developed by Makani Power/Google. The following advantages, but also disadvantages, can be found for such a lift power concept:

+ During power generation, up to about one fourth less airborne mass (due to absence of the conductive portion of the tether, compare with [21]).
+ During power generation, thinner and cheaper tether without integrated electrical cables.
+ More freedom to dimension voltage level, propellers and propeller drives, since (possibly heavy and thick low voltage) electrical cables are only present for launch and retrieval and (most of the) propellers are needed only to hover. This could also result in a lower price of system components.
+ (Almost) no noise during power generation (since a propeller or a small wind turbine is only used to power onboard electronics).
+ Improved control authority due to high power and high force ground winch, i.e. also the ground winch can help for the transition from hover to crosswind flight and back.
− Higher complexity e.g. through a carriage moving the electrical cable along the tether up and down.
− (Most of the) propellers might be unused during power generation, but generate drag. An alternative with foldable propellers (or similar) would (further) increase complexity.
− In a safety critical situation, the kite cannot be brought in a hovering state within seconds unless the electrical cable is already connected.

One must acknowledge that some challenges of the drag power principle might be solved within the coming years and thus diminish some advantages of a multicopter launching and landing lift power solution. As an example, the reduction of the turbine noise might be addressed by using "Bionic Loop Propellers" [12], ducted propellers, a large blade count or a combination of these. Additionally, the development of high force transmitting tethers with integrated high voltage electrical cables has just started. With new materials and higher production capabilities, the mass and the price of such tethers can be expected to be decreasing. Moreover, the mass of the system is only critical for low wind conditions. In high/rated wind conditions (in the magnitude of $\approx 12\,\mathrm{m/s}$) or already medium wind conditions (in the magnitude of $\approx 8\,\mathrm{m/s}$), the lift force generated by the kite is many times higher than its weight, also for the heavier rigid kites. Consequently, the justification of the increased complexity of a multicopter lift power system compared to a drag power system is subject to further studies.

19.7 Conclusions and Outlook

Multicopters are an interesting alternative to autonomously launching and landing kites. It has been successfully implemented by Makani Power/Google for a rigid drag power kite. This was motivation to explore possibilities how the multicopter principle can also be applied to lift power kites. Basic system components were introduced and new soft kite concepts were derived. As a relatively high power is demanded by the propellers to lift the system in hovering flight, electrical cable-based hovering power sources as alternative to an energy storage, like lithium-type batteries, were explored. Since an onboard energy storage or electrical cables are only needed during launch and retrieval but add significant mass to the airborne parts, the idea emerged to use standard electrical cables which are connected only for launch and retrieval, and moved by a carriage along the tether. To gain a high efficiency during kite power generation, also the whole multicopter could be separated from the control pod or from the rigid kite in a similar way.

Static and dynamic feasibility analyses were carried out. The results for considered example systems similar to a paraglider for a soft kite and to a hang glider for a rigid kite are feasible. However, energy-storage-powered solutions are prone to high airborne masses, whereas cables-powered solutions are less sensitive. Compared to other launching and landing concepts for lift power kites, the main advantages can be summarized as follows: (i) The ground station is simple as it primarily consists only of one winch and tether guides. Hence, the overall system complexity could be lower compared to other launching and landing concepts (e.g. rotating arm launching and landing), although the airborne part is more complex. (ii) It is possible to launch and land the system also without wind near the ground, (iii) with relatively simple and proven flight maneuvers in the case of rigid kites.

The investigations also revealed the weaknesses of such concepts which are (i) a high airborne mass due to propellers and particularly due to an energy storage (if such a solution is considered), (ii) higher drag (if the propellers/multicopter cannot be detached), (iii) and/or, in the case of detachable cables or detachable multicopter solutions, a then again increased complexity. Moreover, the soft kite concept has the disadvantage that the kite generates a lift force opposite to the propeller thrust. Subject to further research in this area would be the reduction of this force during the hovering phases. Further studies would focus on more detailed dynamic simulations, the design of a system or carriage with which an external electrical cable can be attached and detached and also economical efficiency analyses. A more elaborate comparison between the multicopter-based lift power rigid kite concept (vertical takeoff and landing, VTOL) with short takeoff and landing concepts (STOL), and with the drag power rigid kite concept are of particular interest.

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