Chapter 20
Application of an Automated Kite System for Ship Propulsion and Power Generation

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Abstract SkySails develops and markets large automated towing kite systems for the propulsion of ships and for energy generation. Since 2008 pilot customer vessels have been operating propulsion kites in order to reduce fuel costs and emissions. In this contribution the SkySails towing kite technology is introduced and an overview over its core components kite, control pod, towing rope, and launch and retrieval system is provided. Subsequently the principles of force generation and propulsion are summarized. In the following part the system's application to airborne wind energy generation is presented, where the kite forces are used to pull the towing rope off a drum, powering a generator in the process. When the maximum tether length is reached, the kite is reeled back to the starting point using the generator as a motor. A functional model was constructed and successfully tested to prove the positive energy balance of this so-called pumping mode energy generation experimentally. An evaluation of the technology's market potential, particularly for offshore wind farms, concludes the contribution.

20.1 Introduction

Kites have been used for different tasks for many centuries [5]. The possibility to employ kites for commercial shipping was investigated already in the 1980s after the oil crises had clearly shown the economy's dependence on oil [8]. Driven by newly increasing marine fuel oil prices after the year 2000, the company SkySails set out to carry the use of kites into modernity and construct a kite propulsion system that would fulfill the needs of the globalized cargo shipping business. The company was founded in 2001 by graduate industrial engineer Stephan Wrage and shipbuilding engineer Thomas Meyer. Its main office is located in Hamburg, Germany, and it operates a production and testing center in the Baltic Sea port of Wismar, Germany.

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Strategic partnerships with suppliers such as DSM Dyneema, Gleistein Ropes, and North Sails NZ ensure a reliable development of products and materials [6].

The towing kite technology is suitable for ship propulsion and airborne wind energy generation alike. High forces and automated controls are a requirement in both sectors. However, the mechanics for kite launch and recovery have to be re-engineered for the energy production application, since the machinery for the pumping mode energy generation process must be included. As a result, dynamically flown kites grant access to a wind energy level that is beyond the reach of conventional wind turbines [1]. Different approaches to use this technology are being investigated by a number of companies and research groups, as presented in [1] and the references therein.

This article introduces the towing kite technology, its dependencies and the steps taken towards realizing airborne wind energy farms in the future.

20.2 SkySails Towing Kite System

The feasibility of kites as means for propulsion was tested in small scale on various boats and models between 2001 and 2006. After the basic concepts had been established, a full scale prototype was installed on MV "Beaufort" (Fig. 20.1) to be tested in the North and Baltic Sea. The 55 m long vessel was equipped with propulsion kites of up to 160 kN design load.

Fig. 20.1 Research vessel MV "Beaufort" during launch of the towing kite

In 2008 SkySails moved its focus to a small fleet of pilot customer vessels that employ kite propulsion during normal ship operation (Fig. 20.2). At this stage, the kite system's key features and functions were further developed and improved to meet the reality of the offshore environment and the requirement of the cargo shipping market. Among these core technologies are:

- fully automated controls and optimization of the kite's flight pattern,
- a launch and retrieval procedure including its superstructures and mechanics,
- a kite structure capable of transmitting high forces,
- a durable rope with an enveloped electric cable,
- a ship movement compensation mechanism for the main winch to work in accordance with the automated kite control under launch and retrieval,
- robust handling procedures that enable the regular ship's crew to fully operate the system correctly and effectively.

Fig. 20.2 Pilot customer vessel MV "Michael A." with towing kite in operation

The first system to incorporate all these features will be ready for market in 2013. It is designed for a design load of 320 kN and offers an effective thrust of up to 190 kN in optimum wind conditions, which is sufficient to substitute 2000 kW of a ship's main engine power. On a 130 m long multipurpose vessel as shown in Fig. 20.3, this corresponds to 60 – 70 % of the nominal cruise engine power.

20.3 Kite, Control Pod, and Towing Rope

The key component of the SkySails system is a computer controlled propulsion kite that is constantly flown in figure-eight flight patterns. The kite itself is a double skin ram air kite with an aerodynamic profile. The canopy is made of two textile skins

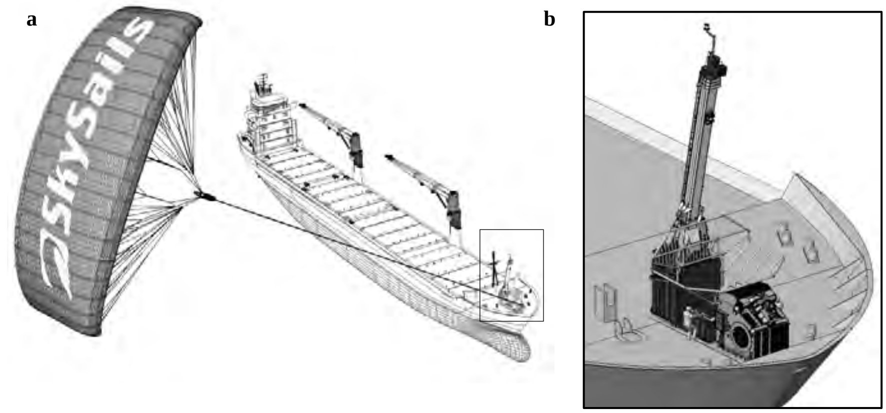

Fig. 20.3 **a** CAD drawing of multipurpose vessel with SkySails system SKS C 320, **b** CAD image of forecastle installation

connected by ribs which define the aerodynamic shape. Air intakes in the leading edge allow the canopy to fill with air.

A line tree connects the canopy to a central control pod (Fig. 20.4). The control pod transmits the kite forces to a single towing rope and controls the kite's flight pattern. Based on a flight pattern algorithm, a computer inside the control pod activates a servo motor to modify the position of a toothed drive belt which is connected to the kite's wingtips. When the steering mechanism is activated, the servo motor retracts one wingtip while releasing the other. A passive pulley system allows the main section of the canopy to follow the movements of the wingtips and maintain a consistent arc throughout the wing.

The towing rope transmits the kite forces to ground level and encloses an electric cable for power supply and data communication to the control pod. It is made of high-modulus polyethylene which is stretched and tempered after the cable is woven in.

The layout of rope, power and data cable, control pod, and kite enables the SkySails system to operate like a multi line controlled kite while being tethered by only one line. The control functions are moved from ground level to the control pod right underneath the line tree. Effecting the wingtips from this position permits an instantaneous transmission of steering commands, which is a more direct approach than controlling several tethers from ground level, where the winches' reactivity and slack in the towing ropes dampens the commands.

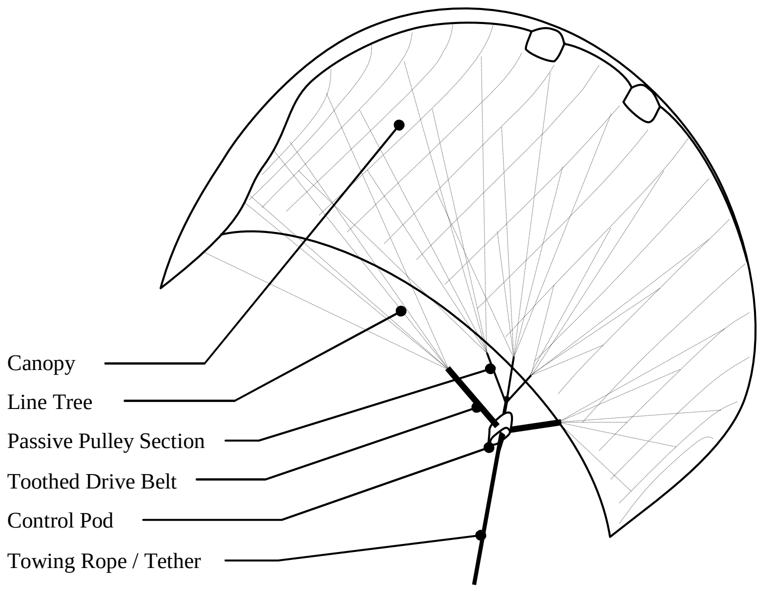

Fig. 20.4 SkySails kite and control pod

20.4 Launch and Retrieval System

The SkySails launch and retrieval system was developed for its marine application. Its purpose is to launch the traction kite from the ship's forecastle deck and to retrieve and safely stow it after use. Figure 20.5 shows the arrangement of the functional launch and retrieval installations of the 320 kN ship propulsion system also pictured in Fig. 20.3.

When the kite is to be launched, a telescopic mast lifts the folded kite out of the stowage compartment from under deck. When the mast is fully extended, air intakes in the kite's leading edge allow the wind to inflate the canopy and unfold the line tree. During the inflation, a set of reefing lines spreads out inside the canopy as a preparation for the reversed reefing process after the flight. When the kite is fully inflated and puts sufficient tension on the towing rope, it is docked off the mast and starts its ascend to flight altitude. At this stage, the heaving motions of the ship's bow are actively compensated by the towing winch in order to stabilize the kite in the air. After reaching its operational altitude, the kite starts its dynamic flight patterns. During flight, the telescopic mast is retracted and the stowing hatch is closed to seal off the stowing compartment against spray and sea water. A thin, secondary line keeps a connection between the mast top and the bundle of reefing lines which exits the canopy in the middle of the leading edge.

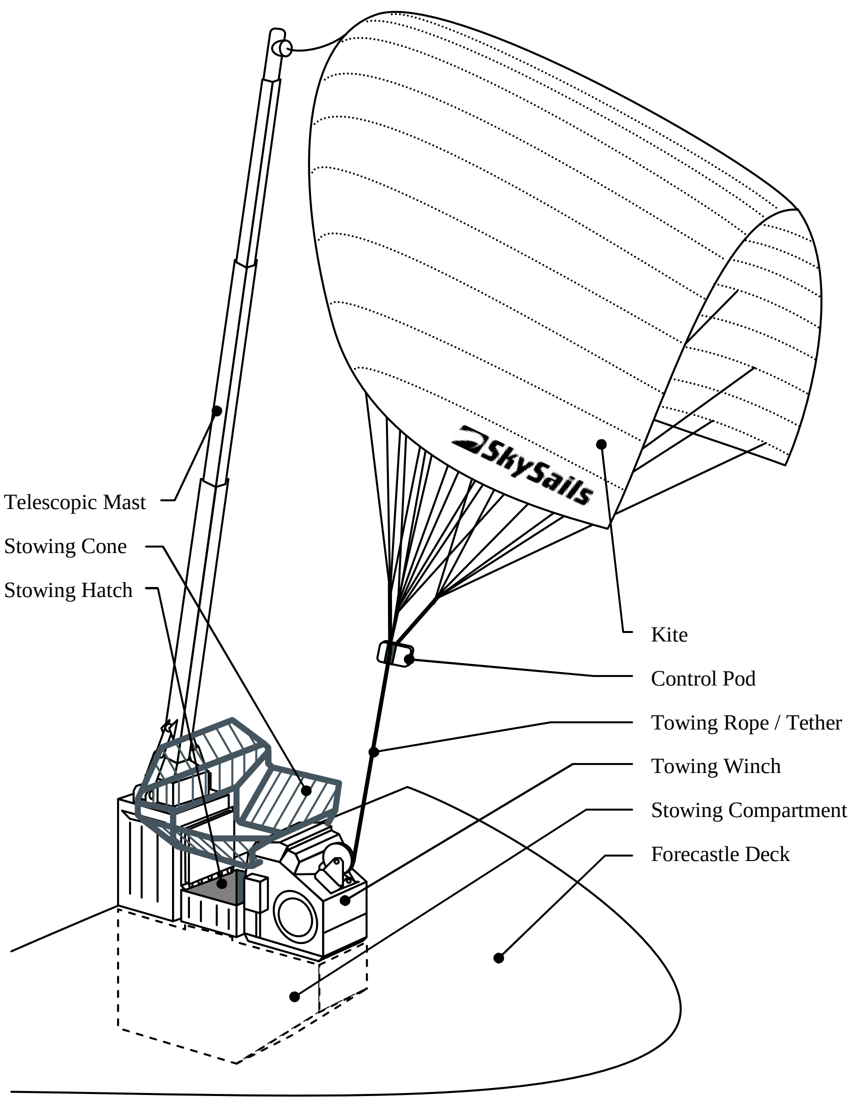

Fig. 20.5 SkySails Marine Launch and Retrieval System

To start the landing procedure, the kite is flown to a static position above the ship where its forces are at a minimum. The towing winch reels the kite back to the ship. A smaller, secondary winch located in the mast foundation retracts the secondary guiding line to reconnect the kite's leading edge to the mast top. When the kite is safely docked to the mast, the bundle of reefing lines is pulled into the mast by the secondary winch. The openings in the leading edge work as air outlets during reefing. By lowering the telescopic mast, the kite and control pod are brought back to deck level. A stowing cone centers the reefed kite right above the stowing hatch to ensure reliable handling procedures during stowing. When the kite is stowed in its compartment, the towing rope is disconnected from the control pod and the stowing hatch is closed. Further details on kite handling during launch and retrieval are given in Chapter 32.

Regarding the energy generation application, the requirements differ. For the pumping mode energy production process, the winch and motor/generator unit increases in complexity. On the other hand, the stowing system is less limited in its design when the whole facility is constructed exclusively for kite operation and not as an auxiliary propulsion device on a cargo ship, where space is scarce and heavy sea wash is expected.

20.5 Basic Principle of Kite Force Generation

The maneuverability of the kite is an important factor for its force generation. The generated tether force F_t is a vector addition of the airfoil's lift force F_L and drag force F_D (Fig. 20.6). It is determined by the airflow speed v_a, the air density ρ, the kite's surface area A, and its reaction coefficient C_R [4] as shown in Eq. (20.1).

$$F_t = v_a^2 \frac{\rho}{2} A C_R \tag{20.1}$$

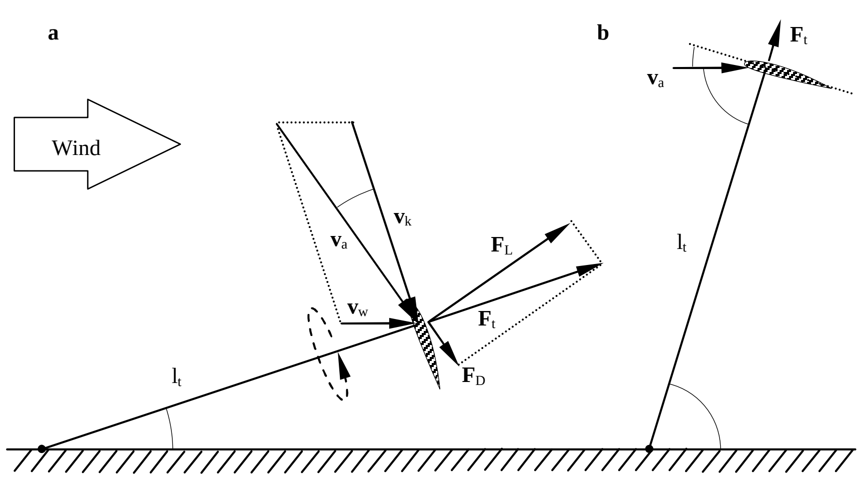

Fig. 20.6 **a** Force and velocity vectors at a kite in a continuous loop, **b** kite in a static position

Since the force is proportional to the square of the airspeed around the aerodynamic profile, a dynamically flown kite produces significantly higher forces than a similar one flown in a static position. As a simple approximation, the airspeed v_a is determined by the wind speed v_w at kite flight altitude, the kite's glide angle ε, and its position in the wind window, represented only by its elevation angle β in the simplified two dimensional model in Eq. (20.2) and Fig. 20.6a.

$$v_a = v_w \frac{\cos\beta}{\sin\varepsilon} \tag{20.2}$$

A tethered kite's motion is limited to a spherical surface around the fixation point of the tether, with the tether length l_t being the radius of the sphere. If the kite's glide angle ε is not altered during flight and a constant wind speed is assumed, the kite's position in the wind window determines its speed and force. It will assume its own kite speed v_k as long as it is not in a position where the sum of glide angle ε and elevation angle β is 90°, where the wind speed vector v_w and the airspeed vector v_a are equal (Fig. 20.6b).

20.6 Propulsion on the Horizontal Plane

When applying a kite for the propulsion of an object on the horizontal plane, e.g. a ship at sea or a trolley moving along a track, the trajectory of the fixation point itself becomes an important factor. Continuing the simplified model, where the elevation angle represents the position in the wind window, the fixation point of the tether moves along the ship's or trolley's course parallel to the true wind while the kite follows its designated flight pattern at its own speed above, as shown in Fig. 20.7.

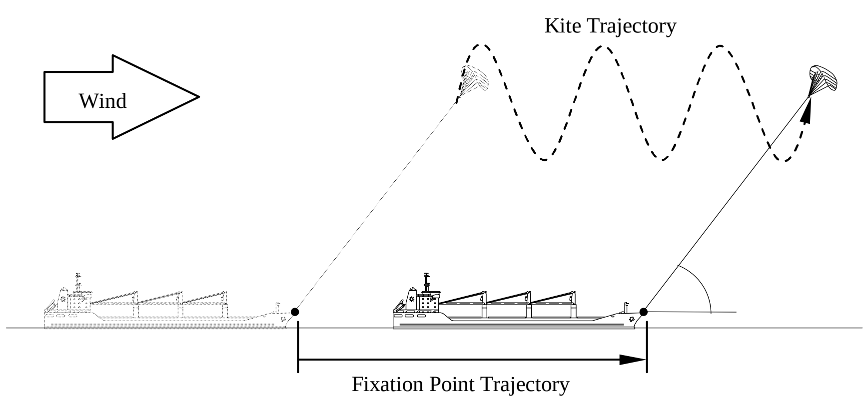

Fig. 20.7 Kite and fixation point trajectories in the ship propulsion application

The advance speed of the fixation or ground point v_g and the equally aligned component of the tether force F_t determine the power output P Eq. (20.3).

$$P = v_g F_t \cos\beta \tag{20.3}$$

Inserting Eqns. (20.1) and (20.2) into Eq. (20.3) returns Eq. (20.4).

$$P = v_g \left[v_w \frac{\cos\beta}{\sin\varepsilon} \right]^2 \frac{\rho}{2} A C_R \cos\beta \tag{20.4}$$

However, the wind speed v_w experienced by the kite is reduced by the fixation point speed v_g when the fixation point moves in the direction of the true wind speed v_{tw} defined by Eq. (20.5).

$$v_w = v_{tw} - v_g \tag{20.5}$$

$$P = v_g \left[(v_{tw} - v_g) \frac{\cos\beta}{\sin\varepsilon} \right]^2 \frac{\rho}{2} A C_R \cos\beta \tag{20.6}$$

By setting the fixation point speed v_g in a ratio to the true wind speed v_{tw}, the maximum power output can be identified as described by Loyd [4] and shown in Fig. 20.8.

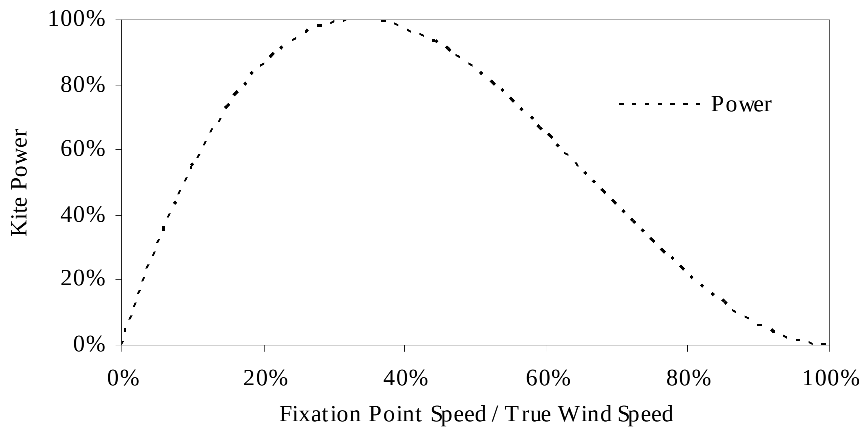

Fig. 20.8 Normalized kite power output dependent on the ratio of fixation point speed and true wind speed

The simplified theoretical approach shows that the maximum power output is reached where the ground point speed v_g is 33 % of the true wind speed v_{tw} at kite flight altitude. However, in any practical application, a maximum stress limit of the mechanical components has to be considered. If the tether force F_t in Eq. (20.1) can no longer be increased in stronger winds, enhancing the fixation point speed v_g

beyond the point of maximum efficiency may be beneficial to obtain a higher power output while staying within the predefined mechanical stress limits.

In the propulsion application on a horizontal plane (ship propulsion, trolley on track or giant hub electrical energy generation), a low elevation angle of the tether is desirable. According to Eq. (20.6) the kite achieves the highest forces when it is flown closer to the center of the wind window (disregarding higher wind speeds at higher altitudes in this simplified model). In addition, a higher fraction of the tether force is also directed in the usable direction of the ground point movement. The aim is to maximize the usable force, as long as the kite has sufficient room to maneuver and keeps a required minimum distance to the surface of land or sea. The automatic flight controls of the SkySails system are designed to approach this optimum within a set of predefined stress and clearance limits.

20.7 Pumping Mode Power Generation

In contrast to the ship propulsion application, a kite system used for electrical power generation on a specific site must work in a closed loop. The fixation point needs to return to its starting point with the kite in tow. One way to construct an airborne wind energy facility is the pumping mode energy kite (Fig. 20.9).

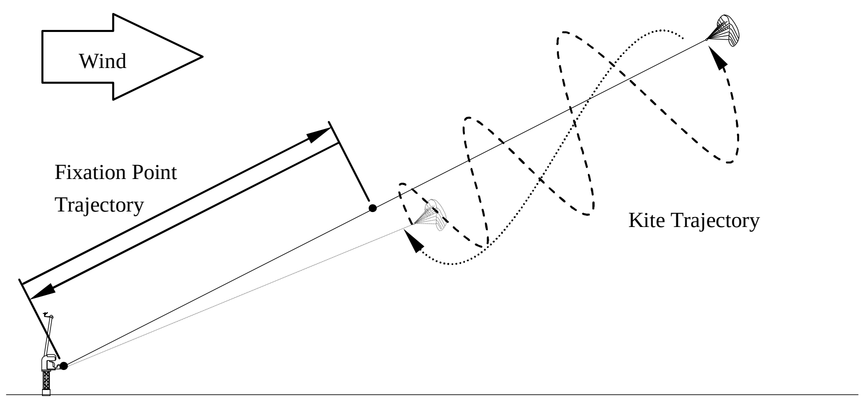

Fig. 20.9 Kite and fixation point trajectories for the pumping mode energy kite

The rope drum is connected to a motor/generator unit which converts the mechanical kite power to electrical energy. The kite is flown in patterns to pull the rope off the drum until the maximum tether length is reached, followed by a return phase where it is reeled back to its starting position.

The facility produces energy during reel-out out and consumes energy while the kite is returned to the starting point against the wind. Adding a time margin for switching from one mode to the other, the average cycle power can be expressed as in Eq. (20.7).

$$P_{\mathrm{c}} = \frac{P_{\mathrm{o}} t_{\mathrm{o}} - P_{\mathrm{i}} t_{\mathrm{i}}}{t_{\mathrm{o}} + t_{\mathrm{i}} + t_{\mathrm{T}}} \tag{20.7}$$

An idealized cycle power profile is shown in Fig. 20.10. In order to obtain the best average cycle power output P_{c}, the productive reel-out power P_{o} and the productive reel-out time t_{o} must be maximized, while the reel-in power P_{i}, the reel-in time t_{i}, and the transit time t_{T}, where the facility neither produces nor consumes power, are to be minimized.

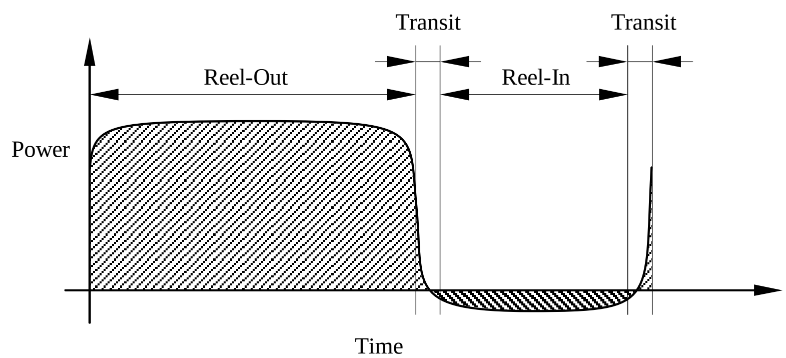

Fig. 20.10 Idealized power profile for one pumping mode cycle

Regarding the factors determining the power in Eq. (20.6), the true wind speed v_{tw} and the air density ρ are external conditions that cannot be influenced. Kite area A, reaction coefficient C_{R}, and glide angle ε can be altered if the kite is constructed accordingly, while the flight pattern position β is a variable if the kite's flight pattern is controllable. The ground point speed v_{g} depends on the mechanical control capabilities of the ground level unit. Shortening the reel-in time ti may increase the reel-in power P_{i} in an unfavorable way and thereby contradict the goal to maximize the cycle power P_{c}. In order to overcome this conflict, the development focuses on improving the factors that can be influenced by construction or design, namely the reaction coefficient C_{R} and glide angle ε of the kite and its control system's ability to conduct optimum flight patterns at all times.

20.8 SkySails Functional Model

A functional model for the pumping mode energy kite was constructed in 2011. It features a 55 kW generator which is powered by a kite with 20 kN design load at a maximum reel-out speed of 5 m/s. All the machinery including a winch for a maximum towing rope length of 350 m, the generator, a switchboard and a 7.5 m long telescopic mast used to unfold the kite is installed in a trailer for easy transportation (Fig. 20.11) [7].

Fig. 20.11 SkySails Power functional model

During flight tests, the positive energy balance of the pumping mode principle could be proven. Fig. 20.12a shows an exemplary curve of the mechanical power output and input during four complete cycles. During the energy production phase peaks of up to 30 kW were generated. The energy consumed during the return phase was only a small fraction of the energy produced, so that the overall balance was positive. Fig. 20.12b shows the corresponding energy production profile.

The kite force was controlled by the winch dynamics and the flight pattern position only. Alterations of the kite's properties, e.g. its surface area, glide angle or reaction coefficient, were not implemented during the flight shown in Fig. 20.12. Future developments in the kite's aerodynamic variability will minimize the return time while keeping the required return power low.

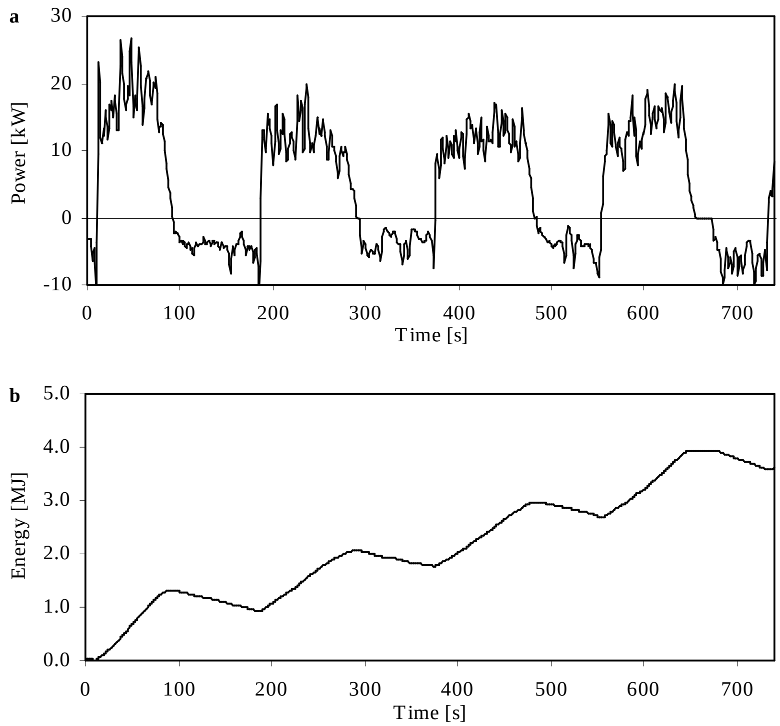

Fig. 20.12 **a** Power profile recorded during four cycles of the functional model, **b** corresponding energy profile

20.9 Airborne Wind Energy Farms

A major future goal of airborne wind energy concepts is the construction of wind farms deploying a larger number of kites. The aim is not only to access altitudes beyond the reach of conventional wind turbines, but also to establish wind power in regions that have previously been unsuitable for wind energy production. The major advantage of the pumping mode device is its easy installation. There is no need for a large tower structure and the machine house covers only a small footprint area.

The highest market potential is expected offshore [2]. The installation advantage and its low structural requirements make the pumping mode technology optimally suited for floating platforms operating in greater water depths than conventionally founded offshore wind farms (Fig. 20.13).

According to [2], the newly installed wind farm capacity that is already projected decreases after year 2020 while the demand for wind energy will still be growing. The gap that may result leaves a market potential for wind energy facilities that are designed to withstand the movements of a floating platform. While the technological challenges increase when moving offshore, the regulatory conditions may

Fig. 20.13 SkySails vision of an offshore wind farm installation (computer rendering)

improve. The competition for both airspace and surface area is smaller outside the states' territorial seas, which extend 12 nautical miles from shore [3]. Especially in countries with a stable and strong political support for renewable energy, airborne wind energy technologies meet a market in a potentially good status [2].

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