# Kite Power

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December 14, 2008

(minor updates added December 20, 2010)

# 1 *Kite power*

A week ago I didn't understand kite power. I didn't understand what were the best ways to turn kites into power-harvesting machines, and I didn't know how to describe the theoretical limit for kite-based power-harvesting.

Then I talked to Saul Griffith of Makani Power, who gave a great talk in Cambridge, and now it makes a lot more sense to me. Although power may be extracted from kites in ways that bear little resemblance to wind turbines, the fundamental limits for kite power are very similar to those of wind turbines. Kites have two advantages over windmills: they require less *stuff* per kilowatt of capacity; and they can suck energy from *higher altitudes*, where the winds are stronger and steadier.

Here's a summary of the conclusions:

1. Appropriately controlled kites can deliver a power per unit *vertical* area that is very similar to the power per unit vertical area of a standard wind turbine with blades sweeping out the same area.

2. A *farm* of kites could in principle deliver a power per unit *land* area that is similar to the power per unit land area of standard wind farm experiencing the same wind-speed. Saul Griffith said he reckons the limit for plausible kite-farms is an average power per unit land area of $6\,\mathrm{W/m^2}$.

## How would it actually work?

How can a high-speed twizzling kite be used to deliver power from the wind? A kite that just twizzles in circles at the end of a tethered string isn't delivering any useful power, even if it is pulling with a large force on the string: a big force and a big velocity aren't useful if they are perpendicular to each other. To get power from a force and a velocity, we need the force and the velocity to be *aligned* with each other – at least, partially aligned – not perpendicular.

To explain some ways in which kite power could work, I'll take an excursion through planes, gliders, and windmills. I'm going to assume that you have already read Technical Chapters B (wind) and C (flight) of *Sustainable Energy – without the hot air*.

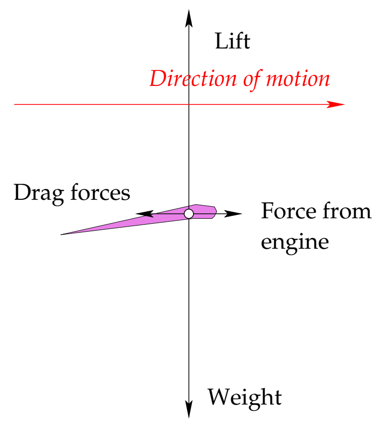


Figure 1.1. The forces on a steadily-flying plane. This figure shows the wing of the plane.

### *Planes*

Let's recap how a plane works. Imagine a plane that is moving along at steady height. It requires energy to keep it going forwards, and to keep it staying up in the air in the way that bricks don't. It gets this energy from its engines, which throw a thread of air backwards extremely hard so as (by Newton's third law) to get in return a forward-directed force on the plane. The wings of the plane throw a big sausage of air down, and in return (by Newton's third law) the plane gets a lift force from the air. The lift force balances the plane's weight. The plane also experiences air resistance, which is a drag force acting backwards on the plane; the reason for this air resistance is that the plane is giving kinetic energy to a plane-sized sausage of swirling air. The useful energy delivered by the engines to the plane is passed on from the plane to the air that it sets in motion: half goes into making lift – into kinetic energy of the big downward-moving sausage thrown down by the wings; and half goes into making drag – into the kinetic energy of the smaller sausage of swirling air behind the plane.

Figure 1.1 shows the forces acting on the plane under steady flight. The arrow labelled "drag forces" shows the sum of both the drag force associated with air resistance, and the lift-associated drag (sometimes called the induced drag). For a typical plane, the lift force (which is equal to the weight) is much bigger than the drag forces. (For example, the weight of a jumbo jet is much bigger than the force exerted by a jumbo jet's engines, which is why jumbo pilot can't do nose-up hovering stunts.)

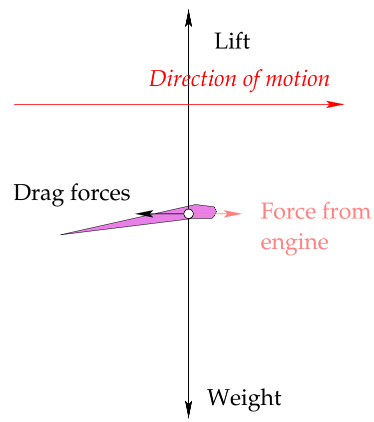


Figure 1.2. The forces on a plane when the engine is suddenly switched off.

## *Glider*

Now imagine that we switch off the engine. The plane is now a glider. Figure 1.2 shows the forces. Without the forward force, the plane will slow down. To keep a glider going at steady speed, we adjust the wing such that the plane's direction of travel is slightly downhill. If we rotate the wing and the direction of travel of the wing by a small angle, the lift force and drag force on the wing will also rotate by the same small angle, as shown in figure 1.3a. Figure 1.3b clarifies how the sum of the rotated drag force and lift force points in the opposite direction to the weight.

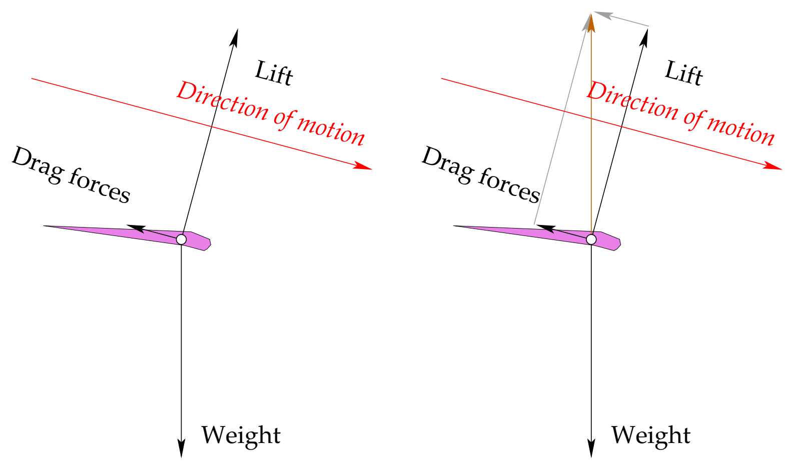


Figure 1.3. The forces on a glider, gliding steadily downhill. The lift and drag forces in panel (a) are obtained by rotating the wing and the direction of travel from figure 1.2 by a small angle. Panel (b) shows the sum of the lift and drag forces, which now points in the opposite direction to the weight.

Why am I talking about gliders? Well, my plan is to do some thought experiments now, to think about *how to get energy from gliders*. Once we understand two ways to get energy from gliders, we'll transfer these ideas to kites.

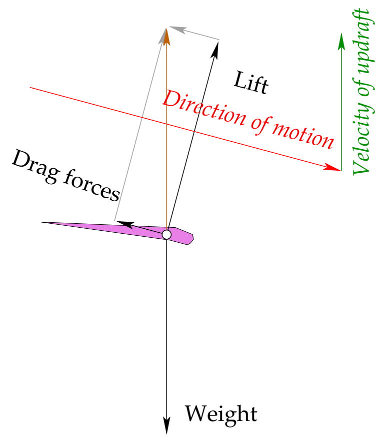


Figure 1.4. Add an updraft.

## *Power from a glider*

Till now, the air through which our glider is sliding has been stationary. Imagine now that there is a region where there is a perpetual updraft. The air is moving upwards at a speed (shown by the green arrow in figure 1.4) that is a little greater than the speed at which the glider's height was falling in figure 1.3. If we insert the glider into this updraft, and keep its orientation pointing downhill, then the glider will move at steady speed relative to the air – moving to the right, and falling as before. Relative to the rest of the world, the glider will be moving to the right and rising. From the point of view of the glider, air that comes near its wings gets thrown down by its wings. From the point of view of an onlooker, air that was rising vertically in the updraft gets slowed a little by the glider; it continues rising, but not so fast. Figure 1.5 shows these two points of view alongside each other.

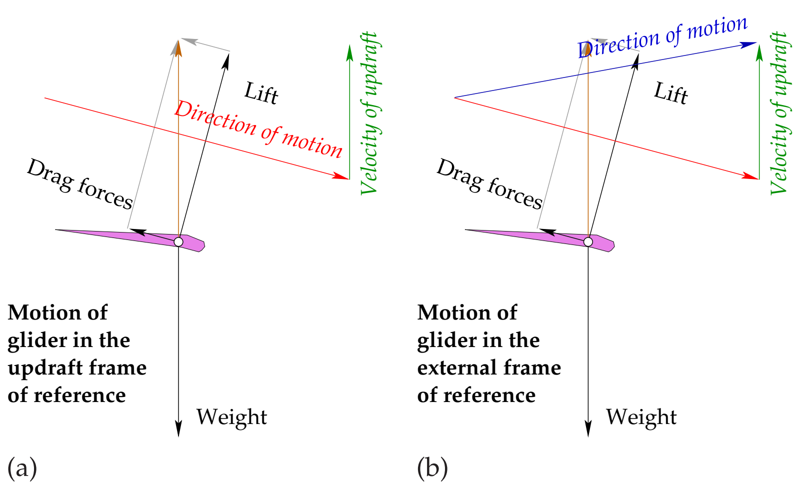


Figure 1.5. A glider, gliding steadily in an updraft. The red arrow shows the velocity of the glider relative to the air in the updraft. The blue arrow shows the velocity relative to an external onlooker.

OK, why did I introduce the updraft? Well, this steadily rising glider presents an opportunity to extract power from the updraft. If the glider circles in the updraft region, how can we get useful work from it? For ease of engineering I'm going to allow us to make use of pieces of magic string. Magic string can be used to pull on the glider in any direction we choose; if the glider extends the magic string then the string generates power.

*Method 1: the extra drag force (drag power production)*

Here's one way to use magic string to get work from the glider. We could attach string and pull horizontally backwards on the glider with a force similar to the drag force. Figure 1.6a shows this extra load in red.

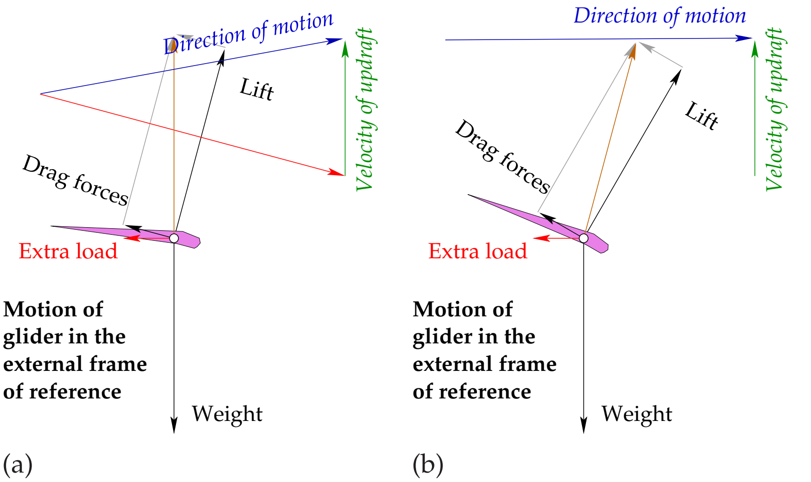


Figure 1.6. Getting work from the glider in an updraft by adding a horizontal force. (a) Force added. (b) Wing and direction of travel rotated so as to keep steady flight.

If we simply added this load force to the glider, it would slow down; just as when we switched the plane's engine off, the way to maintain steady motion of the glider is to further rotate its wing and its direction of motion. Figure 1.6b shows the wing and the drag and lift forces appropriately rotated, so that the total force on the glider is approximately zero, and the glider flies level, while pulling on the magic string.

The red force and the velocity of the wing are in opposite directions, so the moving wing does work against the string's force. Figure 1.7 shows how the rotated lift and drag forces, when added to the extra load in red, sum up to a force that's approximately opposite to the weight.

Now, this picture is useful, because it clarifies how wind turbines work. Figure 1.7 showed the side view of a glider sliding sideways across an updraft. Now think of it a different way: figure 1.8 shows the *top* view of a wind turbine; the wind is moving up the page; one blade of the wind turbine is flying across the page from left to right. The extra load in red is exerted by the generator in the hub of the turbine. The force formerly known as the weight of the glider is now the force keeping the blade perpendicular to the wind.

We'll describe in a moment how this energy extraction method could apply to kites.

But first let's describe another way of getting power from the glider in the updraft.

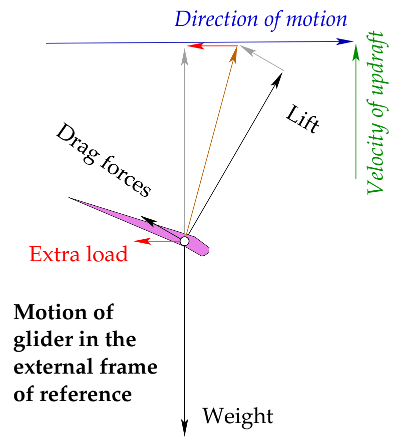


Figure 1.7. How the forces on the glider add up.

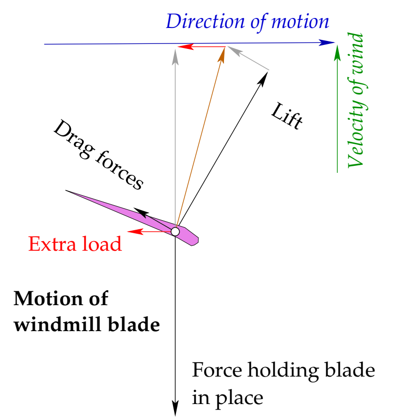


Figure 1.8. Top view of a wind turbine's blade.

*Method 2: getting lift to do work (lift power production)*

We rewind to figure 1.5b. What this figure shows is a glider in an updraft, steadily rising because the speed of the updraft is larger than the vertical speed at which the glider would naturally fall (in the absence of the updraft). Let's allow ourselves an additional piece of magic: let's imagine that gravity is switched off in the vicinity of the updraft, so the glider's weight is abolished. But quickly, before anything untoward happens, let's replace the glider's weight by a force exerted by a magic vertical piece of string, pulling *down* on the glider, exactly as its weight used to pull down on it. Figure 1.10 shows the forces on the glider after this quick substitution, and the velocities, which are unchanged. This figure emphasizes (by the cyan arrow) that the glider is still gaining height, so as it rises, it must be doing work against the magic string's force (the force formerly known as the weight).

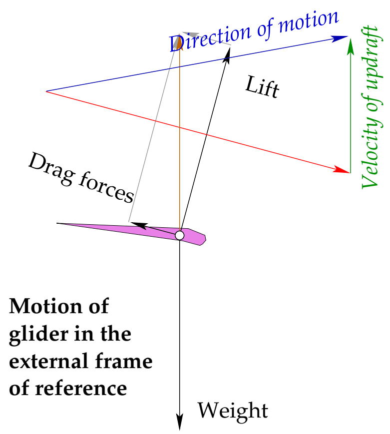


Figure 1.9. A recap of the glider in the updraft, from figure 1.5b.

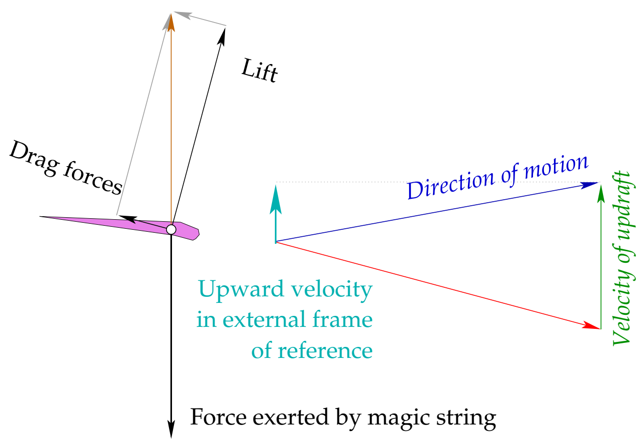


Figure 1.10. A weightless glider in an updraft

So work can be obtained from magic weightless gliders in updrafts by having the glider ascend while pulling hard on a magic string with a generator attached. Eventually the glider will have climbed high enough that we will ask it to come back down and start exploiting a fresh piece of updraft. Because it is a magic glider, this is easy to achieve. The glider can simply package itself nice and small and post itself down a wormhole back to its starting level. Notice that in this method, there is no force extracting useful work from the lateral motion of the glider.

How does this method relate to wind machines? Well, I've never seen a windmill that works in this way, but you could imagine a wind machine that is mounted on a railway cart on a track that runs upwind-downwind; the blades of the wind machine turn; when they turn fast, a substantial lift force is generated, pointing roughly down-wind; this force could be used to force the railway cart down the track, and generators in the railway cart could be used to deliver energy from this motion. Once the wind machine reaches the end of its track, it could be shrunk to the size of a mouse and whisked upwind again to repeat its performance.

A pretty bizarre wind machine to imagine... but a kite power generator could easily work in this way, simply by gradually letting out the strings tethering the kite.

*Kites and method 2*

Let's make clear how everything is oriented: the wing of the kite would circle round rather like one blade of a standard windmill, in a circle that's face-on to the wind. Figure 1.11 shows a side view, when the kite has just passed 12 o'clock. I haven't discussed the details of how to reel a real kite back in. In practice, the trajectory followed by the kite would not have to be circular.

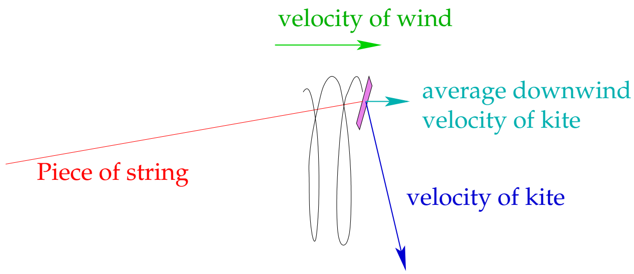


Figure 1.11. Method 2: Side view of a kite extracting power by pulling on a string while twizzling gradually downwind.

*Kites and method 1*

There is another way of extracting power from a kite, analogous to the *horizontal* load on the glider in the updraft. In a standard wind turbine, this load, which acts in a direction opposite to the wing's velocity, is supplied by torque from the generator in the hub of the wind turbine. In the case of a kite, a load opposite to the wing's velocity could be supplied by attaching to the wing a little wind turbine that generates power from the large apparent wind generated by the rapid motion of the kite through the air. Figure 1.12 shows a side view, when the kite has just passed 12 o'clock.

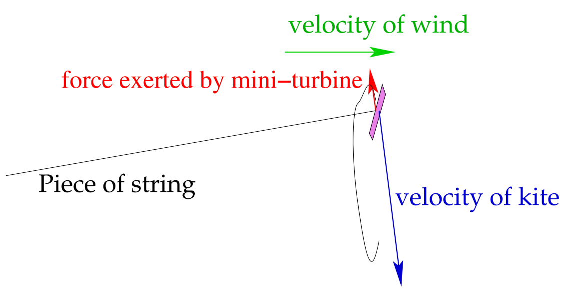


Figure 1.12. Method 1: Side view of a kite extracting power by twizzling in a circle, and generating power with an on-board mini-turbine.

The kite now perpetually moves in a circle. The miniturbine mounted on

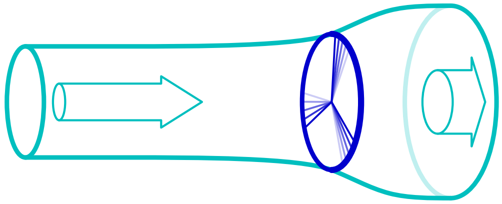

Figure 1.13. Flow of air past a windmill. The air is slowed down and splayed out by the windmill.

the kite does not need to be super-big. The speed of the kite is perhaps ten times the windspeed, and power of a turbine scales as speed cubed times area, so the frontal area of the miniturbine can be one thousand times smaller than that of an equivalent standard wind turbine; as a ballpark figure, the diameter of the miniturbine might be about one thirtieth of the kite's length.

## *Summary*

Whichever of these two power-extraction methods is used, the flow of air past the region where the kite twizzles will be similar to the flow of air past a traditional windmill, as depicted in figure 1.13.

I haven't quantified this cartoon of how kite power could work. The aim of this qualitative description is to give a feel for the kite power options, so that it becomes plausible that the power-extraction limits for kite power are much the same as the limits for standard wind turbines. Loyd (1980) describes an idealized model under which both kite power methods – drag power production and lift power production – produce, when optimized, the same power from a kite with a given lift-to-drag ratio. The power from a single kite increases as the square of the lift-to-drag ratio. Under this idealized model, "a kite the size of the C-5Aa [an enormous military transport plane] with a wing area of 576 $m^2$ . . . would produce 22 MW in a 10-m/s wind" Loyd (1980).

A quantitative discussion for method 1 would have to describe how the weight of realistic on-board miniturbines is supported; and would account for the efficiency of those miniturbines, which presumably dissipate in turbulence some of the energy harvested by the kite.

A quantitative discussion for method 2 would work out the optimum speed for the kite to move downwind (Loyd (1980) says it's $v_{\rm wind}/3$); and would specify in more detail how the kite is reeled back in.

For both methods, a quantitative discussion would need to keep an eye on the drag force associated with the rapid motion of the piece of string through the air.

Loyd (1980) describes results from a detailed realistic model of drag power production. A kite the size of the C-5A, on a 400 m tether, would produce 6.7 MW in a 10 m/s wind. The tension in the tether would be up to 3.2 MN.

## Other applications

### *Tide*

Saul pointed out that the same kite-power methods could be applied to tidal power also, using underwater kites. With method 2, the whole power generation part of the system could be located in the dry, on board an anchored barge.

### *Lifting*

Moving back through our thought experiments, think again of a lightweight plane powered by a small engine, ascending in a gradual helix in stationary air. If a long rope is hung from this plane, the free end of the rope will hover almost stationary, and loads could be suspended from it and raised. The plane would work rather like a very large single-bladed helicopter, but without the helicopter.

Reader Mark Ayliffe points out this is how at least one jungle pilot used to send and receive messages and small packages from jungle clearings in the 1950's. (Nate Saint `http://jmm.aaa.net.au/articles/4670.htm` paragraph 5).

## Frequently asked questions

***I don't understand why the method-2 kite has to "circle", is it somehow more efficient than an otherwise stationary kite being let out at* $1/3$ *of the wind velocity?***

A circling kite has a much bigger tension in its string than a stationary kite, so you have a bigger force and thus more work done. The stationary kite could work on the same principle, but it would have an output similar to a much smaller wind turbine – one with frontal area just the size of the kite itself; and not a very efficient turbine at that.

# *Bibliography*

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