Flight Phase Control Strategies for Airborne Wind Energy Systems

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Abstract

Traditional Danish concept wind turbines face many constraints when upscaling in order to access higher wind speeds, such as size, mechanical loading and weight. It is possible that some of these constraints could be circumvented through use of airborne wind energy systems (AWES).

With research into AWES becoming more prominent, the topic of launching and landing the system must be analysed in detail. Currently several concepts are being pursued with differing launch and land technologies. For all systems it is likely that minimising launch and land cycles will be a key objective due to increased energy costs and hardware risk in these phases.

This research focuses on a cross-wind ground-based generation system and discusses the problem of the launch and land policy with regards to the wind speed at operational height. The paper also discusses the use of an airborne powered loiter phase and a grounded waiting phase. A key consideration when analysing this problem is wind speed measurement uncertainty (including the degree of temporal averaging) and how to integrate this uncertainty into any launch & land policy.

The present research concerns cost-benefit analysis with respect to generated and consumed energy cost functions for each flight phase. It is found that for any given AWES there will be an optimum airborne loiter time after which a system should be landed. This avoids landings due to short-duration low wind periods.

This research will be followed up by further analysis of additional cost functions such as reliability and failure aspects associated with each of the above phases. Further research will also consider the impact of short term forecasting of various accuracy levels on the optimal control policy and performance of AWES.

Introduction

Increasing energy demands have led to a sharp increase in the number of renewable energy technologies being utilised worldwide. Wind power is perhaps the most prominent of these.

As the horizontal axis wind turbine installed capacity has grown, the size of these turbines has increased to reduce overall costs and access higher wind speeds at great altitude. Due to lower material usage, airborne wind energy systems, or AWES, could offer further cost reductions and access to still higher wind speeds.

AWES have been a topic of discussion in the field of energy generation for many years. Early studies and research in this area was published as far back as 1980 by Miles Loyd [1] in which the author outlines the concept of wind power generation using kites. Despite this early research it is only recently that airborne wind research has seen investment as a viable means of renewable energy generation.

Early work in the field was carried out by a dedicated team at TU Delft in the Netherlands. The initial focus of this research was into the concept of the Laddermill, a tiered kite-based AWES [2 - 4]. Through this research a number of branches of AWES technology have been investigated such as multiple kite systems, systems with numerous kites connected to one tether and kites connected to branches of the tether [5]. Other research by the team have investigated the control of the tethering system, using inelastic tethers to control the altitude and flight path of the kite [6, 7].

A functional prototype of the system developed by TU Delft took flight in 2010, the 20kW demonstrator is a pumping kite power system with an inflatable wing. This system, like the system used by KPS, is a ground generating AWES [8, 9]. Several research teams and companies have also begun to develop prototypes, such as Makani, a company acquired by Google in 2013, who have successfully constructed a 600kW cross-wind flight demonstrator [10]. The Makani demonstrator utilises generators fixed to the aircraft to generate energy which is transferred down the tether, this is known as “Fly-Gen” AWES as described by Cherubini et al. in their 2015 paper “Airborne Wind Energy Systems: A review of the technologies” [11].

Other technologies are also being investigated such as ground generating cross-wind flight AWES which can take several forms. Generally, a ground generating system operates via the aircraft or kite pulling on a tether which is attached to a generator on the ground [11, 12]. However, this does require a phase in which energy is consumed to recover the tether. This is illustrated in figure 1 in which phase a shows the generation phase and phase b illustrates the recovery phase.

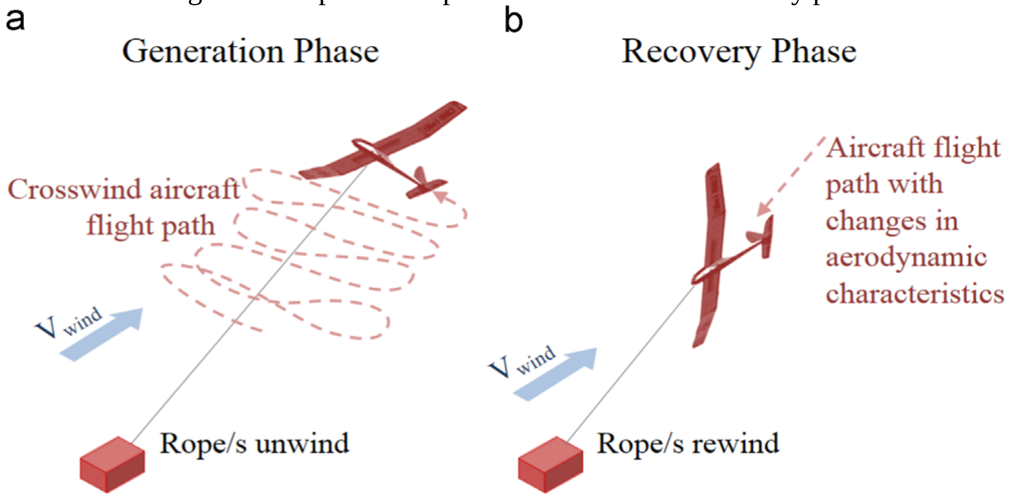

Figure 1: Ground Generating AWES flight pattern [11]

The co-authors of this paper, KPS, are currently developing a cross-wind ground generating device [13]. The device uses rotors for take-off and landing, and these rotors may also be used for sustained flight in low-wind conditions. The energy requirements of these flight phases, as well as generation phase energy production, have been calculated and are used as indicative values in the following analysis.

Flight Phase Policy

An AWES will exist in one of several flight phases. For this research, they are considered to be Grounded, Launch, Generate, Loiter and Land. The transition between states is visualised in figure 2:

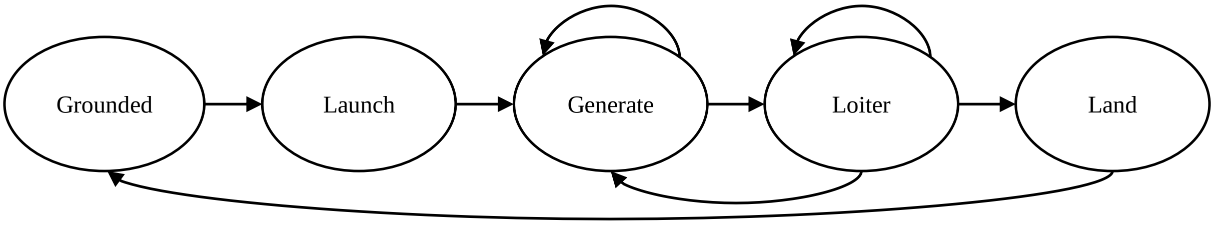

Figure 2: States and Transitions between states of a ground generating airborne wind energy system

The transition between states is dictated by wind speed and time. If a system is grounded it should only transition to a launch state if the wind speed surpasses a predetermined minimum wind speed (cut-in speed). Similarly, if a system is in the generate phase and the wind speed drops below the cut-in speed then it will enter a loiter phase. Launch and land phases will always transition to generate or grounded respectively.

The transition from the loiter phase to either loiter, generate or land is determined by wind speed and time. Landing will be initiated if the system has been in a loiter phase for a predetermined length of time with the wind speed below cut-in. If the wind speed rises above cut-in while the system is loitering, generation will resume.

The loiter phase is utilised to add hysteresis into the launch/land decision, thus avoiding an excessive number of launch and land cycles when the wind speed fluctuates around cut-in wind speed. A loiter time should be established, preferably an optimal loiter time which is discussed later in this paper, that is the maximum duration the system will remain in the loiter phase with wind speed below minimum cut-in speed.

Through review of airborne wind energy literature there appears to be no research in the area of flight phase control policy, so it is difficult to establish whether all the presently considered flight phases are implemented across all ground generating systems.

The following sections consider the specific example of optimising the loiter time of the system. This research aims to establish the utility of airborne loitering of an AWES, and the effect of system parameters on the optimal loitering time.

Loiter Time

In order to optimise the energy output from an AWES using such a policy, the maximum time allocated to loitering must be established. Consider the following:

$$\frac{E_{Land} + E_{Launch}}{E_{Loiter}} = 1 \qquad [1]$$

$$\frac{E_{Land} + E_{Launch}}{P_{Loiter}} = t_{Loiter} \qquad [2]$$

Where *P* is the power and *E* the energy used when landing / launching / loitering and t is the time spent landing / launching / loitering.

However, many AWES will require an intermission between land and launch phases, e.g. for charging batteries or resetting the system. In this scenario it is possible that without a loiter capability a system could risk losing substantial generation time due to a premature landing. This leads to the conclusion that the optimal loiter time must also account for the time lost whilst landing.

Airborne Loiter Policy

The optimum loiter time will depend on the relative energy costs and yields of the flight phases. If an energy-intensive VTOL launch and land method is implemented by KPS, the energy cost of launching and landing the system is significantly higher than the cost of loitering.

Considering only the costs associated with loiter, launch and land – or generally the parasitic costs – would suggest that there would be little benefit to implementing a loiter policy due to the increasing parasitic costs with increased loiter times. However, this does not account for the increased energy yield that could be determined due the implementation of an effective loiter policy.

Any loiter policy would benefit from a reliable wind speed prediction tool being implemented into the system. This could be a physical prediction tool such as a forward scanning LiDAR that would provide wind speed readings to inform decision making. However, the contribution to capital cost of such a system might be detrimental in some markets.

Another method which is being investigated by the authors is the implementation of a prediction model based on historical data. This system could also have some drawbacks due to the reliability of the wind speed data being predicted. The feasibility and impact of such methods are currently being evaluated.

Analysis

Analysis was carried out using the historical wind speed data from two different sites. The wind speed data for these sites was acquired through various means, including LiDAR and met mast data extrapolated to operational heights using wind shear data.

The annual energy yield for each of the sites was calculated for a range of loiter times, 0 -60 minutes, and was offset against the ‘parasitic’ energy (the energy lost to loiter, launch and land.)

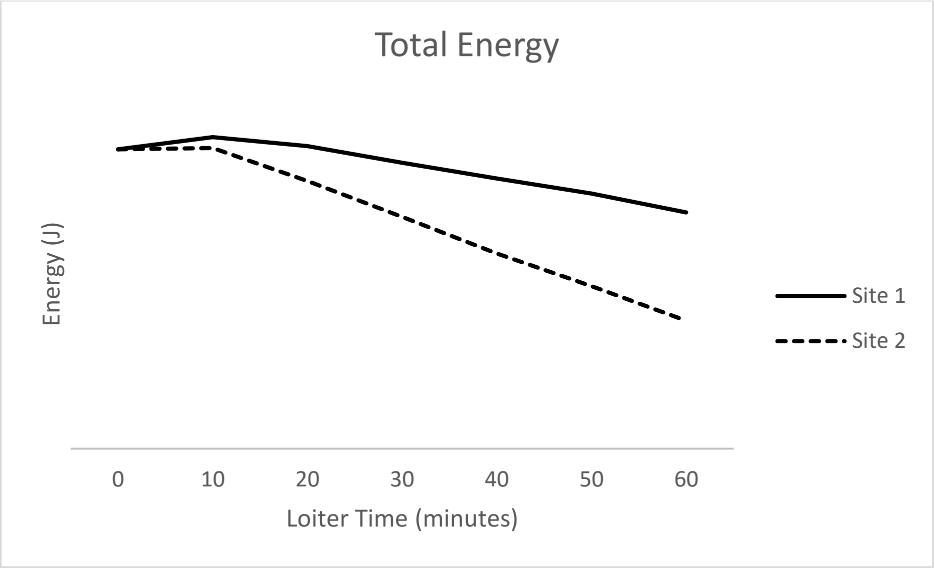

Figure 3: Total Energy Output

Figure 3 shows that given the parameters used in the calculations for both sites 1 and 2 the peak loiter time occurs at 10 minutes after which the total energy output for the system over 12 months diminishes. To further understand the results shown in figure 3 it is important to evaluate both the energy yield and parasitic energy for each of the sites.

The overall energy yield increases with the loiter time. As expected as the loiter time increases less time is spent grounded and more time in the air primed to capture energy as the wind speed exceeds the cut in wind speed. Similarly, for each of the sites the parasitic energy increases as the loiter time increases. This is due to the cost of loiter exceeding the cost of landing the system.

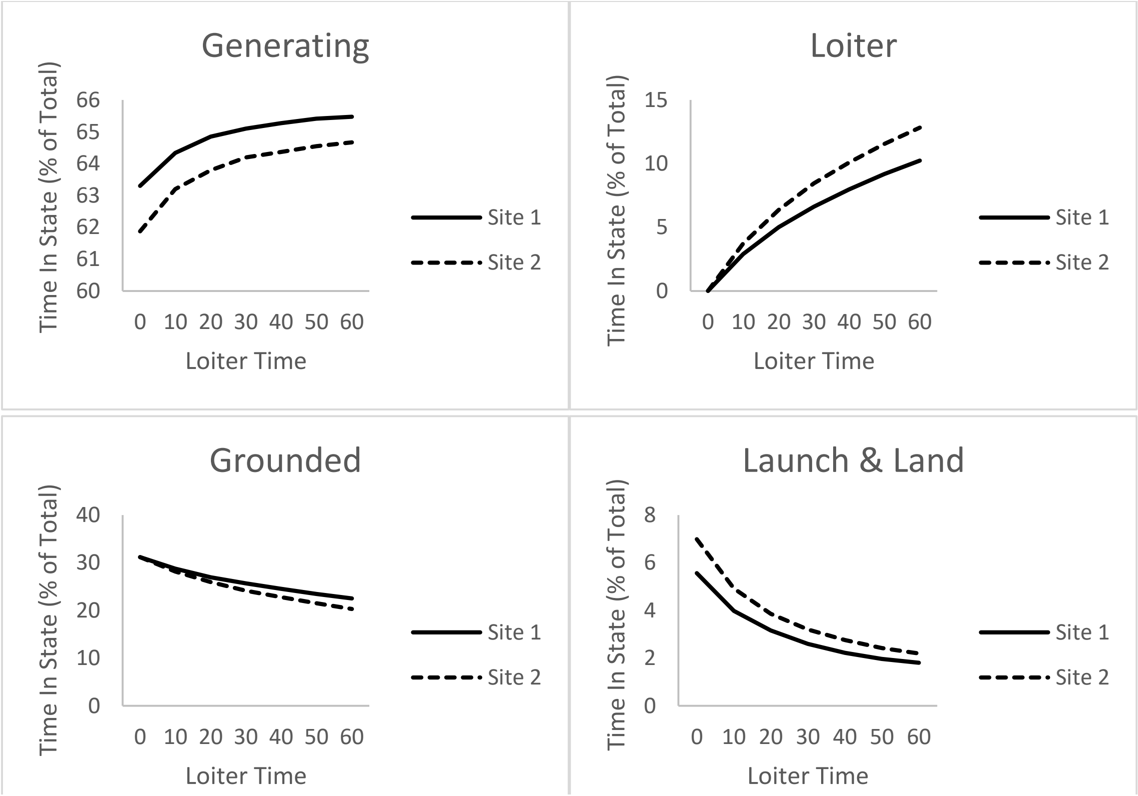

Figure 4: Time in states as % of total time operational

Note also the effect of loiter time on relative time in each of the five states. From figure 4 it can be seen that in each of the sites the predetermined loiter time has a direct impact on the amount of time spent in each of the phases. As expected as the loiter time increases as does the time spent in the air (generate and loiter phases) and the time spent on the ground (grounded, launch and land phases) decreases. This could be essential when considering the relative reliability implications of these conditions.

Discussion

The research presented in figure 3 shows the total energy output by the system in two sites. In this graph it appears that the optimal loiter time for both of the sites is 10 minutes. These results could prove to be specific to the technology being researched throughout this paper and could be altered by several factors, particularly the energy costs of the flight phases and the system power curve.

Perhaps most importantly the results will vary depending on the phase length allocated to the system. This will have a significant impact upon both parasitic energy and energy yield. Currently this research assumes 10 minute phases due to the wide availability of 10-minute datasets.

Currently launch and land phases are allocated a full ten-minute phase to complete, whereas in practice this would take significantly less time. This results in a significant loss in energy yield, as the ten-minute launch phase is lost generation time. Similarly, loiter phases are also allocated ten minute phases.

The information presented in figure 4 highlights that the behaviour of the system is as expected when the loiter time is increased, with the time in the air increasing as loiter time increases and the time on the ground decreasing.

To improve the modelling process, and to further evaluate the utility of airborne loitering, several prediction methods are being investigated and implemented. This is explained further in the future work section of this paper.

Conclusion

This paper has set out to investigate the airborne loiter policy that will be implemented by ground generating airborne wind energy systems. Equations have been presented to theoretically calculate the maximum amount of time that should be spent loitering by an AWES.

Through analysis of historical wind speed data at several sites the flight phase control strategy was evaluated. Whilst an optimal loiter time appeared to have been established the reasons that this may change for other systems in different environments have been highlighted.

Investigation into the behaviour of the system given changes in the predetermined loiter time was conducted. It was confirmed that the system behaves as expected.

To optimise the loiter time of any given ground generating airborne wind energy system weather prediction tools must be implemented to allow the system to make better informed decisions about the time spent loitering or waiting on the ground.

Future Work

As described throughout this paper due to the infancy of this area of research there are a number of areas in which the research is ongoing.

Several parameters of the flight phase policy require investigation, such as the utility of a grounded waiting phase entered above cut-in wind speed before launch is initiated. Estimation of realistic costs other than energy costs, such as load cycles of launch/land components and costs of increased risk during these phases, will be key to determining true optima of policy parameters.

A further key study in advancing this research is that of implementation of a prediction tool into the model. This would allow a number of advancements for decision making compared to the current model, that considers only the current wind speed. There are many methods being investigated in order to implement this tool, autoregression being the primary method being explored currently whereby estimations are extrapolated from reverse autoregressive fits.

In future work, the flight phase policy decision will be formalised in a Markov Decision Chain framework.

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