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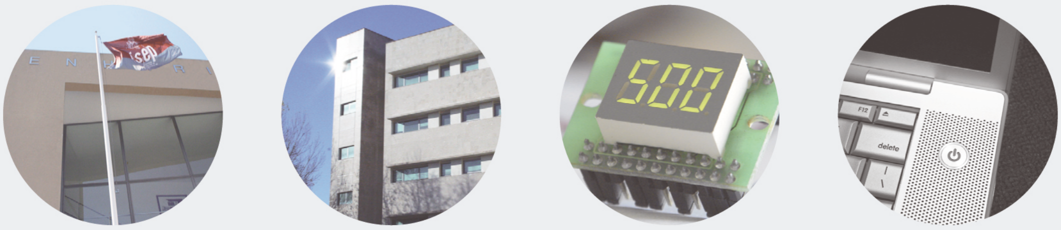
MESTRADO EM ENGENHARIA ELECTROTÉCNICA - SISTEMAS ELÉCTRICOS DE ENERGIA



Emerging renewable energy technologies: Survey, modeling, and simulations

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À minha família

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A small and tiny page proves to be insufficient to recognize those around me.

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Abstract

This thesis approaches recent technologies to produce electric power from wind or water.

The use of tethered kites for harnessing wind or water power and consequently transforming it into electric power is an idea which is starting to take off and with serious on-going developments.

There are two types of major systems: Ground generation and on-board generation. The first one comprises a soaring kite tethered to a ground generator which generates electric power by means of reeling out the tether as the kite rises. This movement is controlled through the manipulation of its surface similar to the control of surfaces an aircraft. As for on-board generation, it is basically an aircraft with mounted generators on its wings, and tethered to the ground by a cable with the double function of securing and tethering the aircraft to the ground, as well as to bring the electric power from the aircraft to the grid. Both systems can be implemented on air and underwater.

In the recent times there were serious developments in these technologies, one of them is the Makani Project powered by Google with a proven concept on-board generator of 600kW. Regarding underwater kite systems, there are several companies like Minesto (Saab spinoff) which also have a proven concept of 500kW.

For these reasons and given the increasing power demand and accountability regarding energy sources, this work offers an overview of these ground-breaking technologies (compared against the conventional technologies) which can and will contribute to the decentralization of the electric energy production. In addition, this work provides a series of simulations and power estimates for kite systems to offer an unbiased view of this new type of electric energy harnessing.

Keywords

Emerging kite power technologies; Airborne wind energy; Underwater kite power systems; Renewable energy.

Resumo

O uso de asas ou kites (vulgo papagaios) para aproveitar a força do vento ou da água e consequentemente transformá-la em energia elétrica é uma ideia que começa a ganhar forma nos últimos tempos e com desenvolvimentos muito significativos, que implicam um olhar mais atento sobre este tipo de tecnologia.

Existem dois grandes grupos de sistemas: Geração no solo e em voo. A primeira consiste numa asa , ancorada a um gerador no solo através de um cabo, em que a energia elétrica é gerada pelo enrolar e desenrolar do cabo que o liga ao solo, à medida que a asa se movimenta ao sabor do vento, com a trajetória controlada através da alteração da superfície da asa de uma forma semelhante ao que acontece numa aeronave comum. Quanto à geração em voo, trata basicamente uma aeronave com geradores montados nas suas asas e ancorada ao solo através de um cabo com a função extra de efetuar a ligação elétrica entre a aeronave e a rede.

Nos últimos tempos têm havido desenvolvimentos muito significativos nestas tecnologias, sendo que um deles chama especial atenção pela espetacularidade das imagens e por se tratar de uma empresa Google X – A Makani Project possui um conceito já provado de geração de 600kW. Da mesma forma e para geração subaquática, existem já diversas empresas entre elas a Minesto (constituída por engenheiros da Saab) com um conceito de 500kW.

Por estas razões e dada a solicitação crescente a nível de energia elétrica e o aumento da responsabilização dos produtores de energia elétrica para o uso de fontes de energia renovável, este trabalho oferece um panorama geral sobre estas tecnologias inovadoras que terão um papel preponderante a desempenhar no futuro da descentralização do sistema elétrico-produtor.

Palavras-Chave

Sistemas suspensos de energia eólica; Kites subaquáticos; Energias renováveis; Tecnologias emergentes;

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List of Acronyms

2D	–	Two dimensional
3D	–	Three dimensional
AEP	–	Annual energy production
APO	–	Average power output
AWE	–	Airborne wind energy
AWES	–	Airborne wind energy systems
BAT	–	Buoyant Airborne Turbine
CF	–	Capacity Factor
DF	–	Demand Factor
EU	–	European Union
LCOE	–	Levelized Cost of Energy
MHK	–	Marine Hydrokinetic turbine
N/A	–	Not applicable
NWTC	–	Northeast Wisconsin Technical College
PV	–	Photovoltaic
TRL	–	Technology readiness level
TUSK	–	Tethered undersea kite

UKPS – Tethered underwater kite energy systems

UPS – Uninterrupted power supply

Nomenclature

Symbol	**Description**	**Unit**
ρ	fluid density (air/water)	$kg\ m^{-3}$
c_D	aerodynamic drag coefficient	-
c_L	aerodynamic lift coefficient	-
$\vec{F}_{aer}$	aerodynamic forces	N
$\vec{F}_{drag}$	aerodynamic drag force	N
$\vec{F}_{lift}$	aerodynamic lift force	N
$\vec{F}_{cent}$	centrifugal force	N
$\vec{F}_{cor}$	Coriolis force	N
$\vec{F}_{inert}$	inertial forces	N
$\vec{F}_{th}$	tether force	N
v_a	apparent fluid velocity	$m\ s^{-1}$
v_w	fluid velocity	$m\ s^{-1}$
v_t	tether reel–out velocity	$m\ s^{-1}$
a_t	tether reel-out acceleration	$m\ s^{-2}$
g	gravitational acceleration	$m\ s^{-2}$
m	mass	$kg\ m^{-3}$
ρ	fluid density	kg
A	surface area	m^2
AR	wing aspect ratio	-
T	tether tension	N
r	tether length	m
s	wingspan	m
u	control vector	-
x	state vector	-
P	Power	W

E	Energy	Ws
C_P	Betz Limit	-
	Angles	
α	angle of attack	rad
Φ	azimuthal angle	rad
β	elevation angle	rad
θ	polar angle	rad
ψ	roll angle	rad

1. INTRODUCTION

The increasing demand for energy and the global conscience to the use of renewable energies forced the uprising of non-conventional methods for producing electric power.

This thesis provides a broad overview of kite technologies which are intended to be used to harvest both water and wind energy, with an extra attention to the wind potentialities.

1.1. Contextualization

The global growing need for energy is translated into an environmental problem which is the result of the increasing of carbon emissions.

Countries all around the world are making a significant effort to reduce carbon emissions, and thus lowering the greenhouse gas emissions. Figure 1.1 reflects that effort, the European Union has come to decrease greenhouse effect gas emissions since 1990, achieving in 2018 79.3% of the emissions recorded in 1990.

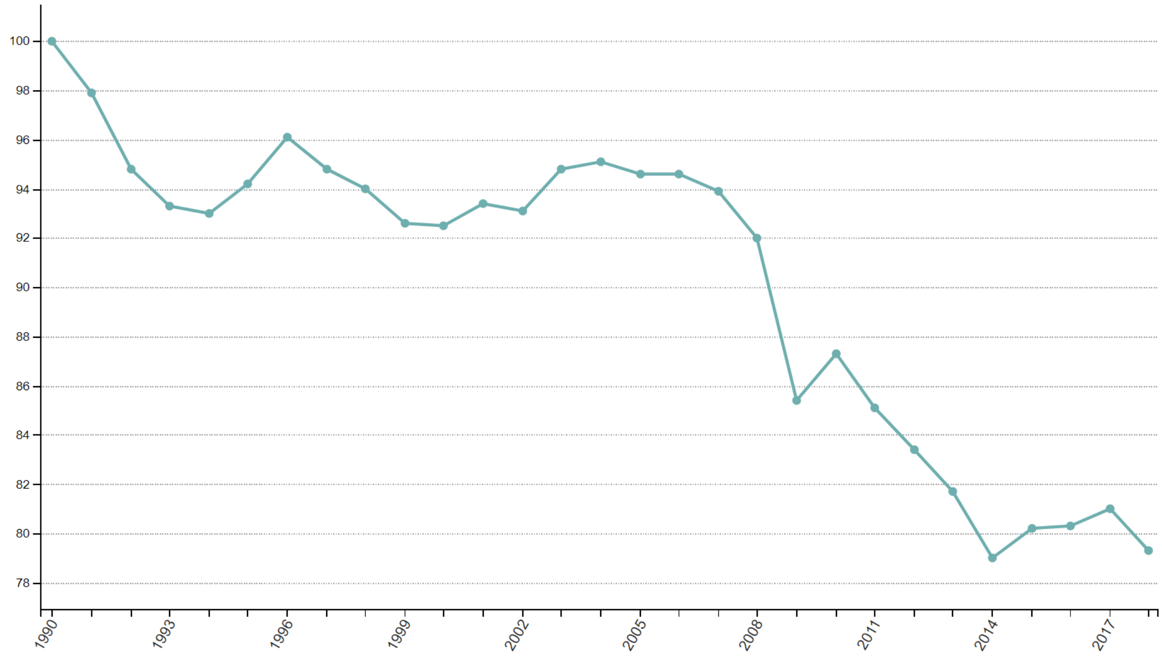


Figure 1.1 - Greenhouse gas emissions in the European Union [31]

Nevertheless, this effort has to grow. Climate changes are an issue that has to be resolved in a short-term basis. One of the biggest contributors to carbon emissions is the energy industry, which in 2017 has represented about 29% of the total carbon emissions, as it can be seen in Figure 1.2.

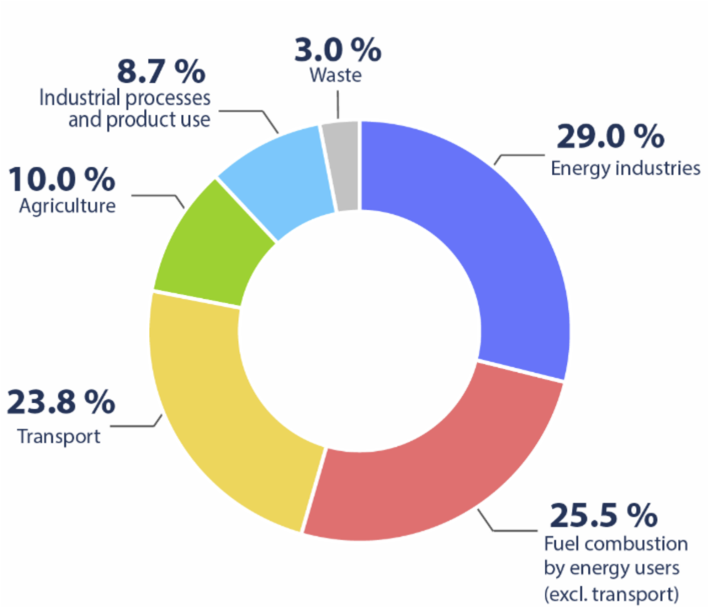


Figure 1.2 - Share of EU greenhouse gas emission by source, 2017 [30]

This means that the electric production industry has to decarbonize, resorting to renewable energy sources. As it can be seen in Figure 1.3, 14% of the EU energy mix still uses solid fossil fuels and 36.4% of petroleum products.

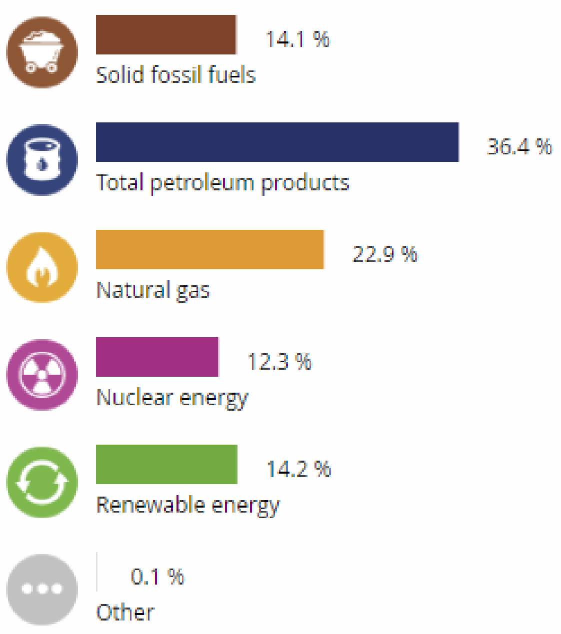


Figure 1.3 - Energy mix in the EU [30]

This is an indicator that there is still much work to be done in order to replace these pollutant energy sources by non-polluting alternatives, such as renewable energy sources. As it can be seen in Figure 1.4, there is a significant investment by the EU countries in order to increase the use of renewable energy sources in their own energy mix, which came to resolve this problem.

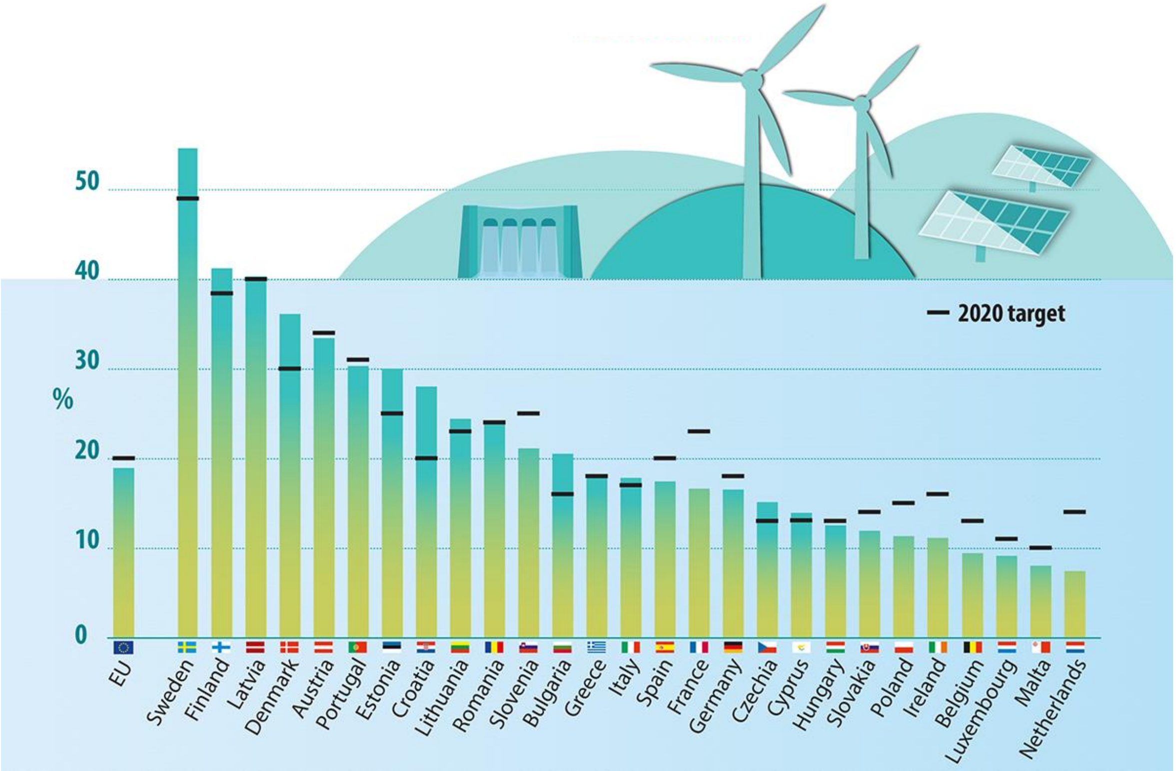


Figure 1.4 - Share of energy from renewable sources in the EU (2018) [30]

There is a present urgency and unavoidable need to increase the use of renewable energy sources and to decarbonize the economies in order to stop climate changes and to preserve the environment.

Traditional electric grids are characterized by a central production paradigm. Consisting of a small number of power plants of which the electric power is transported to intermediate sub stations and then distributed to the consumers. Centralized production comprises the use of thermal plants to serve as the base of the power diagram, using renewable energy sources as a complement to fulfil the needs. The state-of-the-art technology for thermal power production [1] is based on combined cycle gas turbine power plants which resort to the combustion of natural gas.

Nevertheless, there are strong ongoing changes to the centralized production paradigm. Every day, new photovoltaic (PV) power plants and new wind farms are built, thus increasing the use of the available renewable clean primary energy sources. The implementation of these methods started at a large-scale basis (replicating centralized production models), but soon they were developed in order to make them available at a smaller scale, i.e. small regular costumers started to install both PV systems at home and even small wind turbine systems. This started to decentralize the energy production centre contributing to the new paradigm for electric energy power systems – Decentralized production. This new method implies large scale adaptation given that the grid philosophies and protection systems were built on the assumption of a downstream energy movement, creating the necessity of redesigning protection systems and grid architecture. Decentralization is a reality which is already in motion and cannot be stopped.

This thesis will approach different methods of harnessing water power and, especially, wind power. With less visual impact compared against conventional technologies, the use of kite technologies has started to emerge in the last few years.

1.2. MOTIVATION

The approach about kite energy systems, make use of a fluid motion and they can be divided by primary energy source: wind or water.

In this work, the intention is to offer both insights as well as the available technologies and companies, with a special attention to the wind kite technology since it is in a higher TRL[1] (Technology Readiness Level) (between 4 and 7). This because it is believed that in order to start the implementation of a kite system, it is more fruitful to begin by a visible palpable solution instead of an underwater "hidden" solution. The mathematical modelling of a wind kite is more defying given that wind kite systems are modelled at three dimensions (3D), in opposition to the water kite systems which can be modelled at two dimensions (2D).

Also, it is believed that given the extent of the work done in wind systems, there is the need of the establishment of "proof of concept" before departing to the application of underwater kites. Though the idea of carrying out the work and exploring other subjects such as water kite analysis is considered in order to continue this work.

1.3. OBJECTIVES

The considered objectives are separated in two major groups: primary and secondary. This given the high degree of novelty of kite energy systems.

The primary objective of this work is to gather all the disperse information regarding kite power systems, providing a compiled information regarding the existing technologies, concepts, working principles, manufactures, rated powers, development status, and other information considered relevant to introduce a base knowledge of these systems as well as to provide a technical overview.

The secondary objective in this thesis is to make a deep modelling analysis as well as three case studies to enable a technical analysis of an AWES – Airborne Wind Energy System to

[1] Technology readiness level is a scale from 1 to 9 developed by NASA which indicates the maturity level of a given technology, being 1 – Basic principles observed and reported and 9 – Actual system "flight proven" through successful mission operations.

obtain real power data taking under consideration real weather data. The results of these simulations will assess the feasibility of this technology and they will provide a base of comparison towards conventional technologies and economical studies to be considered in future works related to this thematic.

We expect to contribute to the development of a kite system knowledgebase, by launching the state-of-the-art of both and Underwater Kite Power Systems - UKPS so that these systems can become worldwide known and thus enhancing the spotlight over them in order to be considered in future projects, both academical and prototype, and real-world installations.

1.4. METHODOLOGY

In order to gather the necessary information to achieve the proposed objectives, a series of information sources were considered besides world wide web searches. The University of Strathclyde hosted the "Airborne Wind Energy Conference" in 2019, an event fertile in the presence of manufacturers and researchers on the subject providing an excellent and trustworthy source for AWES.

The work of authors such as Olinger [2]–[5], Diehl [6], Roque and Paiva [7], Paiva and Fontes [8], [9], enabled the modelling and simulation in order to obtain simulated results with a very high degree of reliability.

1.5. CONTRIBUTIONS

We highlight the contributions of this work on several levels.

Firstly, by conducting a thorough research on this subject, exploring, analysing and comparing the different available solutions; summarizing and organizing all the relevant information on several tables, providing for the first time a categorization of all the available technologies, separating them by wing type, generator mounting specifics and tether type.

This categorization will enable future comparisons within similar systems in order to offer a clearer evaluation among apparently equal systems.

An extensive work of gathering power output information and to only include in this work already proven concepts and companies, that are in a mature stage of development and others not so developed, nevertheless with serious funding by some of the biggest renowned companies worldwide.

I have calculated and developed power estimates for this type of systems, (both underwater and wind) so that the total potential of these primary energy sources could be analysed in the simulations that were presented further within the thesis.

Two sections were dedicated to the enlightenment of the advantages and disadvantages of these systems, not withholding any information that could be considered prejudice to the acceptance and knowledge of these type of systems.

I have extensively studied and analysed 2D and 3D modelling of energy harnessing, having concluded that 3D models were more defiant to implement as well as more accurate in terms of the obtained results. This part was of extreme importance to this thesis, since it provided the knowledge-base for the development and adaptation of the simulations for each case-study that was widely computed in MATLAB® software, version R2016b, generating the results intended for further analysis.

The simulation took into account several characteristics of these systems such as: real wind data, extrapolation calculus for high altitude winds, trajectory vs generated power, total available power, retraction during storms, elevation angles, collision prediction and avoidance, as well as the obvious variables such as wing area, generator rated power, tether length, air density, drag coefficient and lift coefficients. This has enabled me to produce data for three different case studies, first with a single commercial kite, second with a kite farm built with the same model as case study 1, and last an off-the-shelf kite, which objective was to provide awareness of the simplicity and availability of the required materials in the market to enable the construction of one small system that could be used for an off-grid application.

I have developed a critical analysis of the obtained results that state the worthiness of these systems as a complement to the existing technologies.

Nonetheless, this work has provided the raising of new questions – which are stated in the section 5.2 - Future Work, as well as the creation of new paths of investigation that surely will contribute in a positive way to the development of these systems

1.6. STRUCTURE

This thesis starts by approaching the state-of-the-art regarding kite systems both airborne and underwater, providing a bibliographical review of studies within this field of work.

The second chapter follows with an approach on emerging technologies, starting by Airborne Wind Energy Systems both with ground and On-Board generation, introducing companies and research groups in a highly advanced development stage of this kind of technology. Underwater kite systems are also mentioned, divided by tethered and buoyant systems, and as per the wind sub-section it is also described the industry main players. It also provides theoretical generical physics concepts that help to understand the differences and implications between water and wind systems. This chapter intends to offer a practical description of the existing and "soon-to-be" technologies in this field, which are being simulated on the fourth chapter.

Third chapter describes the actual modelling for these systems. First, by exploring the 2D concepts and modelling, taking under consideration the external factors that influence the flight path and consequently the energy generation process. Further addressing the problem in a 3D perspective, and thus improving the quality and feasibility of the output data.

In the fourth chapter it is taken under consideration a real product from an AWES manufacturer and a series of simulations are made. Firstly, a stand-alone kite system is analysed to access the power output and generator rate of usage, advancing to a simulation of a group of kites in the same place, i.e. kite farm, and in the last place, a computation is made considering an off-the-shelf kite with a windsurf wing, this intends to offer the size perspective of the system in opposition to its power output. Finally, the chapter is closed after a comparison between the three case studies.

Final conclusions and future work remarks are unveiled in the fifth chapter. With a special emphasis on the future work, given that this thesis opens several lines and paths of research, which are a direct result of the work developed in this dissertation.

2. Renewable energies – Kite power systems

This chapter intends to offer a state-of-the-art review regarding emerging cutting-edge technologies in the field of harnessing wind and waterpower, converting it to electric energy.

The research and development of new ways to harness electrical power from clean energy primary sources has not ended. Worldwide exploration and new companies with new concepts emerge at a staggering speed. This chapter provides an overview of the existing concepts within the scope of this thesis.

2.1. KITE SYSTEM INTRODUCTION

A sunny day with mild wind on the beach, with kites soaring in the sky held by lines at the hands of people of all ages. A small change in the way that the line is held results in a dramatic change in the direction of the kite increasing its speed well above the present windspeed. And the game continues, repeating this type of manoeuvres in order to gain the maximum speed and thus the adrenaline and joy of the person holding it, and the longer the line is, more speed is achieved.

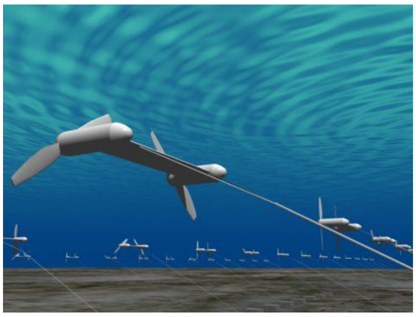
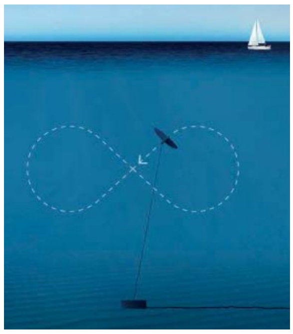
Figure 2.1 – Soaring kite in the air [32]

This is the concept behind the emerging technologies which will be presented and analysed in this thesis – the usage of kites in order to harness wind and water stream power resorting to different kinds of technologies.

The technologies within the range of this work use both water or air as primary energy source. Nevertheless, there is a relation between these two types of systems as they are similar amongst each other, given that the only significant difference resides only in the energy source (air or water).

The major emerging technologies grouping which will be approached in this text is gathered in the Table 2.1, in which is possible to have a glimpse of the similarities between both air and water systems, as well as the positioning of the generator in relation to the whole system.

Table 2.1 - Emerging technologies grouping (Air and water) [2], [10]–[12]

	Airborne Wind Energy Systems (AWES)	**Tethered underwater kite energy systems (UKPS)**
Onboard generator	In-flight Generation 	Sub Generation 
Fixed generator	Ground Generation 	Buoyed Generation Ground Generation 

Besides the obvious distinctions between air and water generator location (fixed or onboard), there are substantial differences between these.

Onboard generator: This type of assembly requires the electric power transmission to a fixed point, thus the tethering which supports the kite, has to contain a double feature, i.e.

the cable has the double function of assuring mechanical tethering, as well as the conductibility of electric power to the fixed point.

Fixed generator: This type of assembly is quite different, given that the generator is fix mounted on the ground and the tether function is to mainly transmit the mechanical power generated by the kite to the fixed generator, however in some cases there is the need of adding control wires to the tether in order to enable communications and providing optimal control to the kite systems so they can maintain an optimum flight/navigation path which assures the best yield and efficiency.

Similarities between wind and water systems: There are obvious visual similarities between AWES and UKPS. As referred earlier, one of the greatest advantages of a water system in opposition to a wind system is the fluid density which results in a greater availability power to harness. The motion of both kites is controlled with the objective of making the kite move across the current/wind placing high tension on the tether reeling it out from the generator. During the retraction phase this tension is reduced allowing the tether to be reeled in by a motor through the use of part of generated power [4].

2.2. State-of-the-art

This section will make a state-of-the-art approach on a set of emerging technologies, known as kite energy systems.

Not only the airborne concept will be addressed, but also a new one and not so explored, The Underwater kites – This new technology for energy harnessing through the use of submerged systems bring a whole new set of ideas as well as the possibility of an out-of-sight installation, thus concealing all the system and maintaining environmental landscape untouched while generating a significant amount of clean electric power.

There is a considerable amount of scientific and practical work developed in this field. The next sub-sections will summarize strictly theoretical main results on this subject, being separated both in wind and water systems.

2.2.1. UKPS - Underwater Kite Power Systems

For decades that the idea of harvesting hydrokinetic energy has occupied minds worldwide. Now that all the hydroelectric plant technology has reached a considerable stage of matureness and development, there are other approaches on the use of hydrokinetic power, whether by the use of fixed mounted generators or by using moving generators in underwater vehicles.

Given the theoretical advantages associated to the fluid density of water, it was just a matter of time before the appearance of the first underwater kite experiences.

In 2007, Magnus Lanberg [15], filled for a patent regarding a submersible plant which has many similarities with an on-board generator kite. Swedish company Minesto AB (spin-off company from SAAB Aircraft) was the assignee for this patent and it has been developing an underwater energy generation system ever since. Lanberg has reached a solid proof of concept solution, which can harvest tidal or a water stream energy, even with very low flow rates (1.2-2.4 m/s), generating up to 500kW.

Not only a practical working concept is already in place, but there is already work in place in order to validate this type of solution through a practical point of view.

Lazakis et al [16] have developed an extensive work in the field of risk assessment for this type of energy generators, concluding a series of proceedings and methodologies to implement this solution. Furthermore, Lazakis et al [17] have continued the work in this field, also analysing the cost structure of a tidal energy array, accounting for equipment and maintenance costs. Various maintenance scenarios are studied, and the achieved conclusions enhance once again the viability and practicability for this type of system from the cost structure point of view.

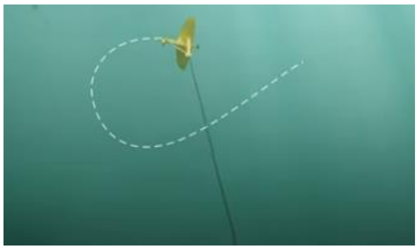
In a further approach, Oliver and Wang have made a deep technical analysis to Underwater energy systems [2], [4], [5] in which was integrated the hydrodynamic modelling of both kite, tether and cavitation studies. These studies allowed the developing of models for the known drawbacks in these technologies, thus proving once again these types of systems viability.

Paiva and Fontes [9] have formulated for the first time an optimal control problem to devise the trajectories and underwater kite controls in order to maximize the total energy produced. The results of this highly nonlinear problem have provided a set of output power values for different design choices and confirmed that electrical energy can be produced by resorting to this type of devices.

Different types of submerged kites and underwater vehicles will be reviewed in this thesis based upon state-of-the-art information and ongoing test results, therefore assessing these technologies.

Table 2.2 catalogues the different underwater technologies as Ground and Sub generation.

Table 2.2 - Market players UKPS (Image sources [18], [19])

	Ground Generation **TUSK**	**Sub generation** **MHK**
Flexible wing	N/A[2]	
Rigid wing	SeaQurrent (Netherlands) 	Minesto – 500kW (Sweden) 

2.2.1.1. TUSK – TETHERED UNDERWATER KITE

The next sub-sections present two examples of UKPS which are in a higher TRL. Nevertheless, there are other systems and manufacturers both in early and late stage of developing, not approached within this work.

SeaQurrent

SeaQurrent is a Dutch company which is currently developing a solution that can be fixed to the seabed (Ground generation). This concept is relatively simple – note Figure 2.2, as it features a fixed generator (4) tethered to a kite (1-2), the electric power is then conducted to

[2] Not applicable to water generation technologies, given that the elevated water density (See Table 2.4) and the associated forces that the wing would be subject to, which constitutes an obstacle to any developments in the field of flexible wing kites.

shore by cable (5). The kites are reeled in and out as per optimum control controlled by the Power Take Off system (3), providing the maximum possible electric power generation.

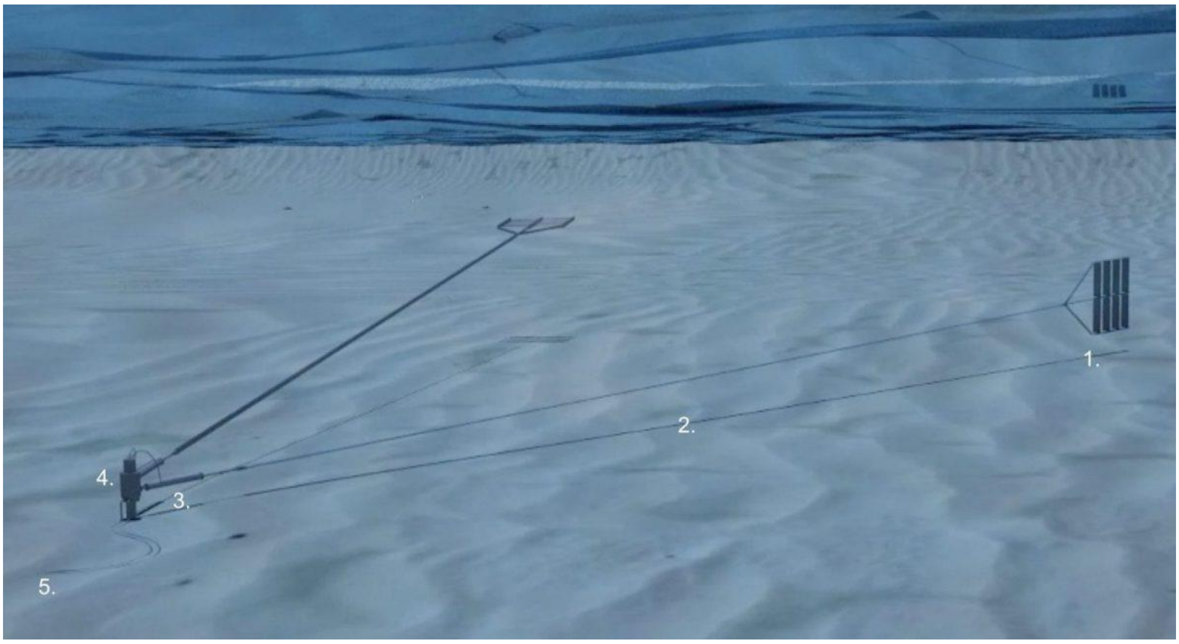


Figure 2.2 - SeaQurrent system diagram [19]

2.2.1.2. MHK – Marine Hydrokinetic Turbine

Minesto

Minesto is a Swedish corporation. A spin-off developing firm from the aerospace company SAAB. This team has know-how imported from high-tech state-of-the-art companies, such as Saab Aircraft, Volvo, and Bofors Missile Systems. The Minesto share is listed on the Nasdaq First North Growth Market in Stockholm [18].

This Marine Hydrokinetic Turbine is anchored to the seabed by means of a mixed mechanic and electric cable, which is used to conduct the generated electric power. Test already took place and the concept is well proven – one single kite is able to generate up to 500kW of electric power and can exploit low-flow streams from 1.2m/s (approx. 4.32km/h).

The working principle behind this system features a kite (see Figure 2.3), which is delicately controlled in order to pursue a given optimal trajectory, designed to obtain the best possible power generation efficiency.

Figure 2.3 - Minesto kite trajectory (On the left); Kite detail (On the right) [18]

2.2.2. AWES – AIRBORNE WIND ENERGY SYSTEMS

Mariam Ahmed, Ahmad Hably and Seddik Bacha approached this subject [13] in which is possible to have a glimpse of a simplified working principle view of some of these systems.

Pumping system – In Figure 2.4 the proposed idea is by having two opposed kites connected to a single cable, controlling them in order to rotate around the cable, generating a lift force that will pull out the cable, and when the maximum height is achieved, they are closed in order to reduce the aerodynamic lift, and then pulled down, so that the cycle can re-begin [13].

Figure 2.4 - Rotokite operation principal [13]

Kite-Based System Structure – As presented in Figure 2.5, a simplified kite-based system involves in a kite attached to a drum by means of a cable. The drum adjusts the traction force produced by the kite into a resistive torque force applied on an electric machine through a gearbox. The machine converts this mechanical power into electric energy [13].

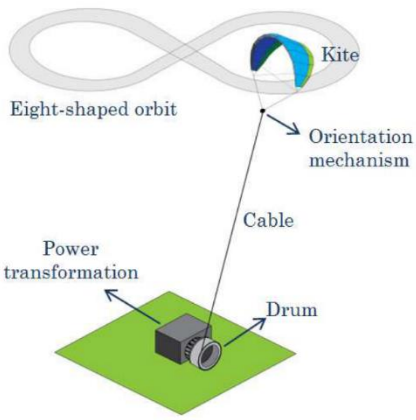


Figure 2.5 - Simplified kite-based system [13]

As per technical and economic viability point of view, E. Lunney, M. Ban, N. Duic, and A. Foley, have developed a work in which are analysed the optimal locations in Northern Ireland having under consideration both high altitude winds and geographical constraints.

Besides presenting the above technology types, there are approached and developed subjects such as wind power density , ground safety issues, airspace safety and infrastructural limitations [14].

This study concludes that there is potential for this system in Northern Ireland, presenting the best possible location with a high degree of feasibility [14]. There are some other findings in this study which are very relevant for analysing: - Present wind power density ranges from 1850 W/m^2 to 2100 W/m^2 (average of 1998 W/m^2 at an altitude of 3000m); Average wind power variations as per graphic in Figure 2.6.

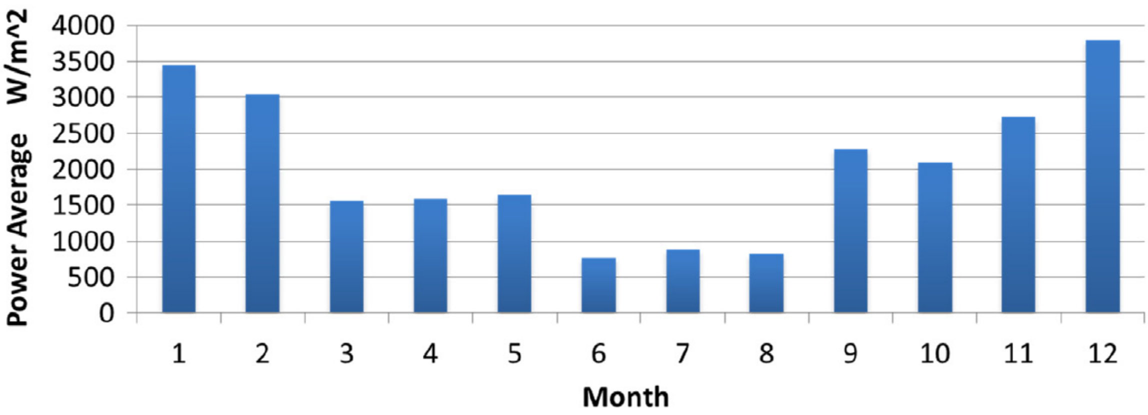


Figure 2.6 - Wind power density average from 2010 to 2013 at 3000m altitude in Northern Ireland [14]

Roque et al [7] have studied the implementation of a kite farm with the objective of the efficient use of a given land area by a set of kite systems, taking under consideration the location of each unit, their mid-air trajectory, tether length and elevation angles. They have developed and implemented a heuristic optimization procedure in order to devise the kite farm layout in order to maximize power generation.

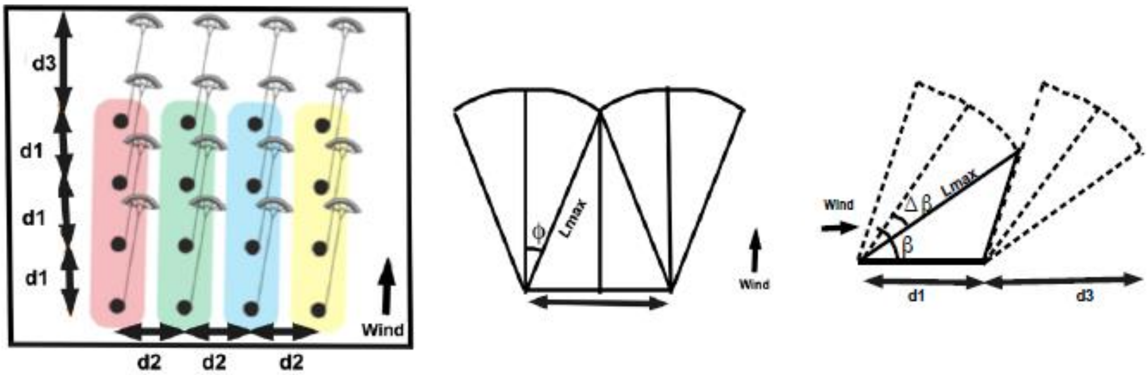


Figure 2.7 - Roque et al layout optimization output considerations [7]

They have also calculated annual energy productions, capacity factor and pumping efficiency in order to obtain the levelized cost of energy (LCOE).

Thus, regarding the technology added value, there is a considerable amount of companies worldwide working on AWES. Some of them are in a mature stage, while others are in the development stage. By analysing Figure 2.8 it is possible to have a glimpse of the work being developed all over the world towards the development of this technology. Important to note that not only start-up companies are in this field, but also a significant amount of gigantic companies are working in this field, such as: Google, Honeywell, NASA, and Alstom. As well as renowned universities: Stanford University, among other prestigious institutions.

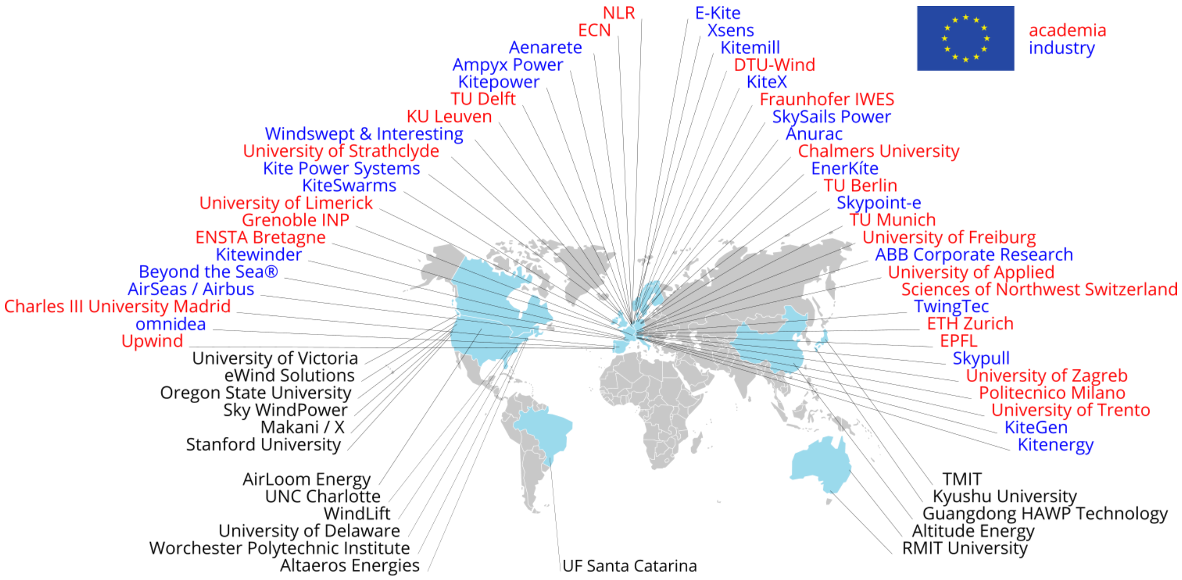


Figure 2.8 - AWES research and development activities by country (2018) [33]

The principle behind AWES it is simple. Like a conventional wind generator, a kite system harvests wind power at greater altitudes in order to achieve greater windspeeds. This method is a deconstruction of the wind turbine in its key components and thus getting a smaller efficient generator as it can be observed in Figure 2.9.

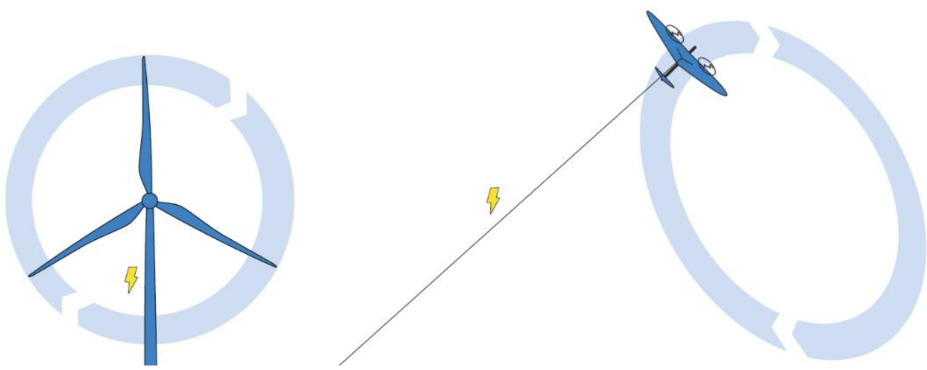


Figure 2.9 - Analogy between conventional wind turbine and a kite system [6]

This is the basic concept behind Airborne Wind Energy Systems (AWES), from this basic principle there are some variations comprehending multiple kite systems as exemplified in Figure 2.10.

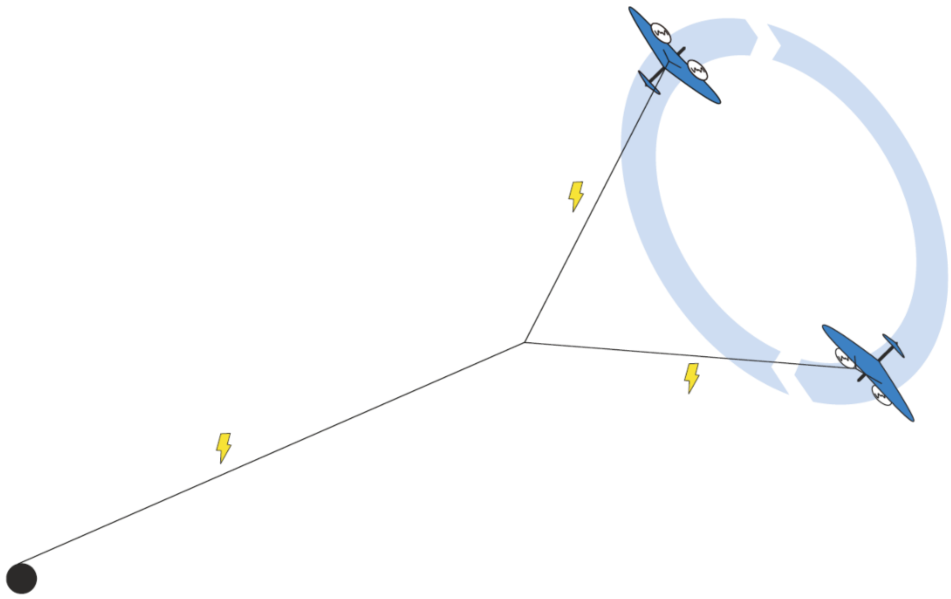
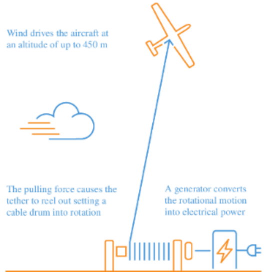
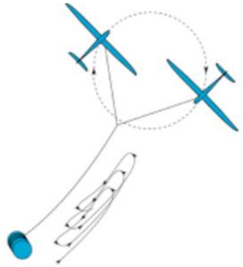


Figure 2.10 - Multiple wing kite system [6]

Analysing different existing emerging technologies for AWES, they can be divided in ground and on-board generation, considering whether the electric power generation takes place on the ground or in mid-air. Furthermore, the generator can be characterized by wing type, thus it can be flexible, rigid, or lighter than air.

Table 2.3 shows a few examples of each generator, as well as each type of wing. Additionally, is provided one specific company example for each type.

Table 2.3 – Market players in AWES (Image sources: [20]–[25])

	Flexible wing		**Rigid wing**		**Multi wing**	**Lighter than air**
Ground generation	Kite Power – 100kW (Netherlands) 	Kite Gen – 40kW (Italy) 	Kitemill – 30kW (Norway) 	Ampyx Power – 150kW (Netherlands) 	Kiteswarms (Germany) 	Omnidea – 30kW (Portugal) 
On-board generation	-	-	Makani Power – 600kW (United States)  		-	Altaeros – 30kW (United States) 

2.2.2.1. AWES – Ground Generation

Ground generation technologies all follow the same principle – The generator is fixed at one given point on the ground, and the energy is harvested by resorting to a kite which is tethered to the generator thus producing energy according to its movement.

There are several types of technologies involving ground generation methods. In order to achieve the best possible yield, there is the need to ensure the trajectory control of the kite. For this purpose, it is interesting to analyse Figure 2.11 as it shows the already existent ways for getting the needed control.

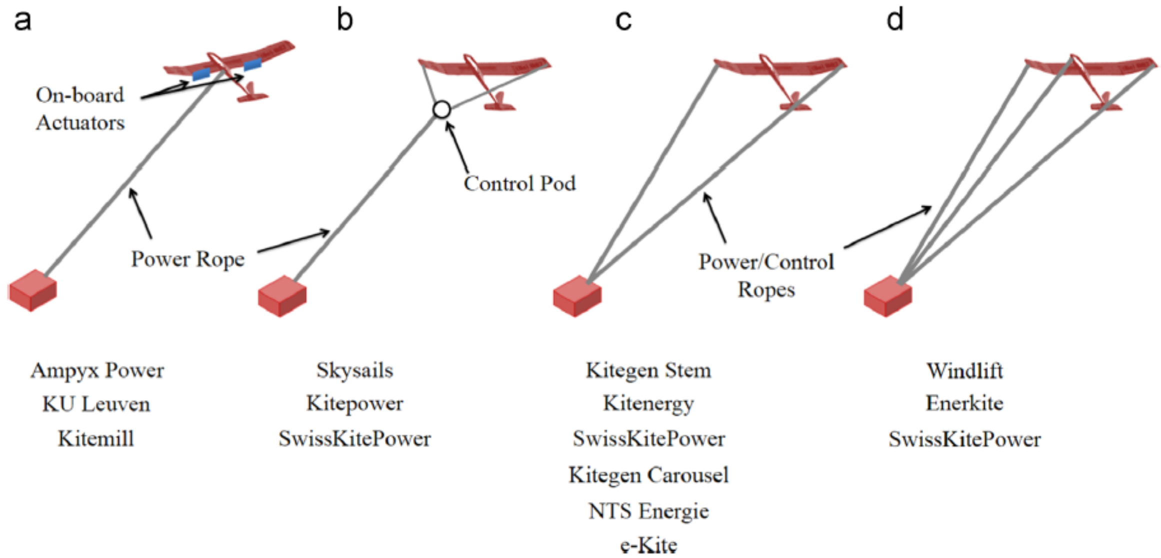


Figure 2.11 - Different ground generation control layouts considering different manufacturers/researchers for rigid wing kite systems [34]

a) This type of control is inspired on traditional aircraft controls. The kite has a series of control surfaces which enables total and complete control over the kite trajectory. In this case the tether functions are to provide control signals to the kite, as well as actuating the ground generator by reeling in and out.

b) Kite is controlled by means of a control pod which rolls the kite to the desired position in order to control its trajectory. The tether functions are the same as the previous type.

c) Control is made through the use of two tether lines which have the double function of transmitting mechanical power to the ground generator and also provide control to the kite.

d) Exactly the same as the previous system, although with three tether lines.

Regarding flexible wing kites, there are different control systems to ensure the proper control and mechanical energy transmission as it can observed in Figure 2.12.

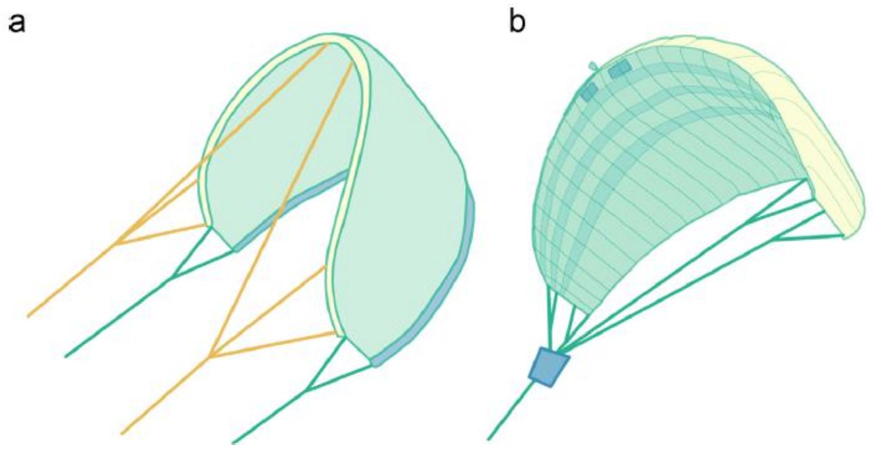


Figure 2.12 - Different ground generation control layouts considering different manufacturers/researchers for flexible wing kite systems [34]

a) This type of kite is controlled through the use of tethers which are also used to transmit mechanical power to the ground generator.

b) In this control layout there is only one tether connected to a control pod which controls four other tethers with the control function

A brief explanation of the working notion of each one of the presented systems regarding particular manufacturers or researchers stated on Table 2.3 is followed.

Kitepower

Kite Power is a Norwegian company with a proven 25 kW concept, which is currently launching a 100kW solution. The main markets are Off-grid clients, Disaster relief, Remote communities, and islands. It consists on a flexible controlled wing tethered to a aground generator which creates electric power by pulling and extending the kite at an optimal pattern as per Figure 2.13 and Figure 2.14.

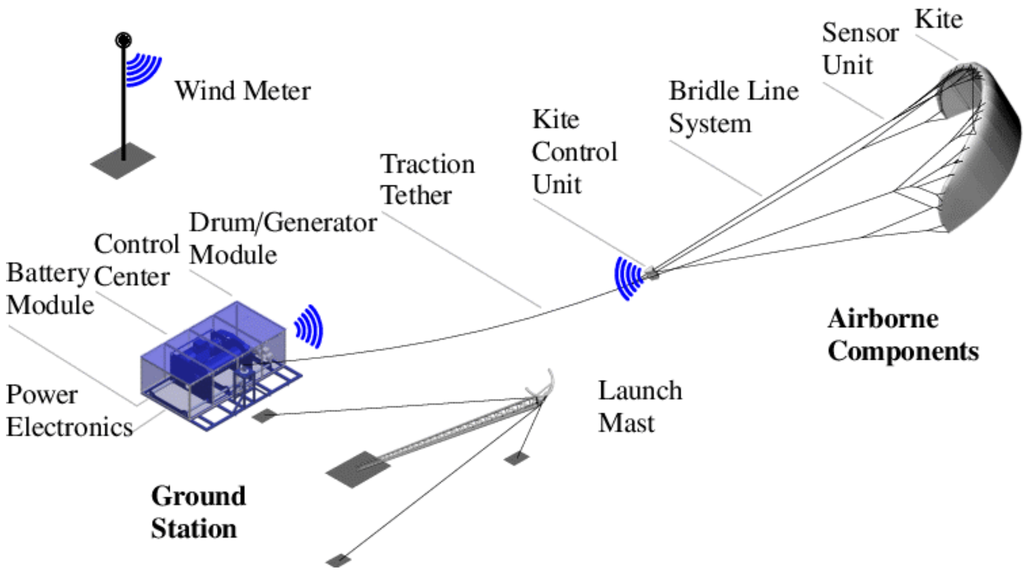


Figure 2.13 - Kitepower system components [35]

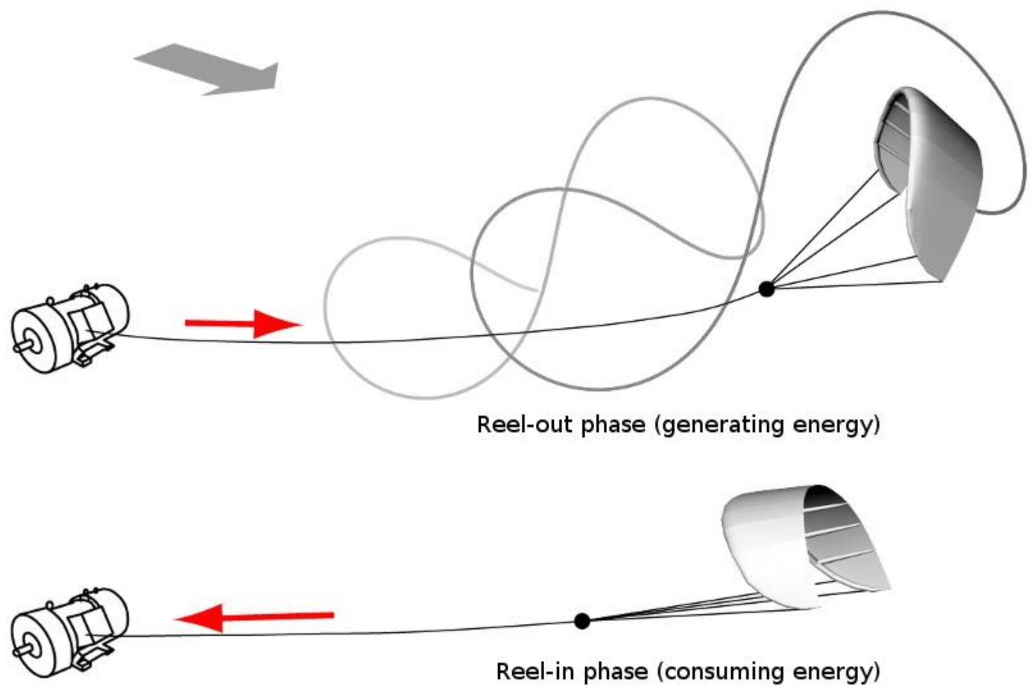


Figure 2.14 - Kitepower working principle diagram [35]

KiteGen

KiteGen is an Italian company which offers a flexible wing solution tethered to a ground generator which can produce 5kW average and 40kW peak, with a wind groundspeed of 4.5 m/s [24]. This kite (as well as the other flexible wing-ground generating examples) can be easily understood by resorting to the Figure 2.16 bellow which clearly demonstrates the deconstruction of a conventional wind generator in order to convert it to a tethered kite enabling wind harvesting at greater altitudes.

Figure 2.15 - KiteGen System in operation [24]

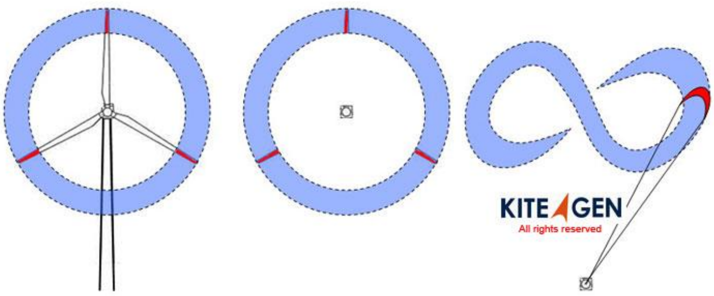


Figure 2.16 – KiteGen's comparison of a traditional wind generator and it's tethered kite system [24]

Kitemill

Kitemill is a Norwegian company which provides a ground generation solution. However, it uses a rigid wing kite with a controllable trajectory in order to obtain the optimum control to generate electric power.

This kite has working principle of unreeling (producing) and reeling (returning) the wing thus completing a production cycle as it can be shown in Figure 2.17.

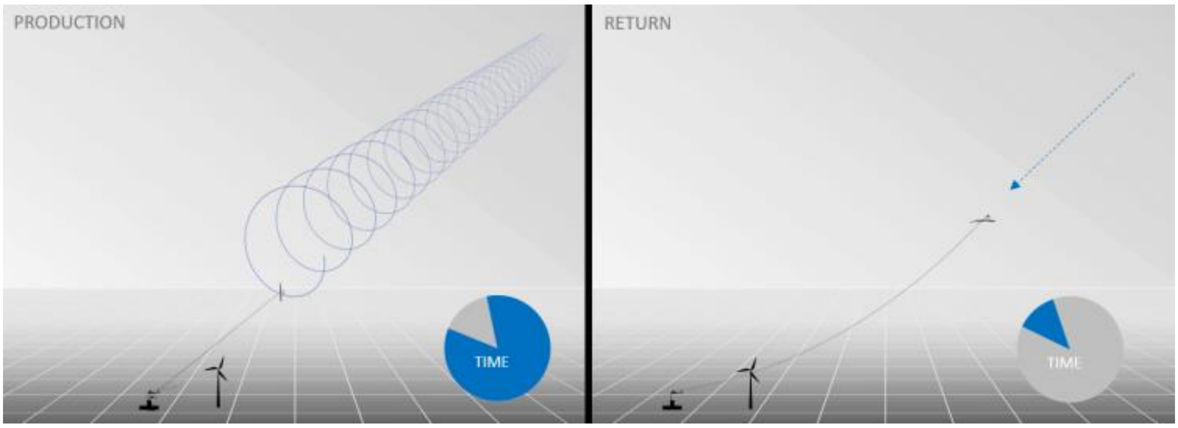


Figure 2.17 - Kitemill working principle [23]

European union (EU) has announced a record allocation of NOK 24 million (aprox EUR 2.25 million) to Kitemill in late summer 2019. The money comes from the EU's prestigious Horizon 2020 program [23]. This award recognizes the potential of this solution enabling the further research and developing of Kitemill solutions.

Ampyx Power

Ampyx Power is a Dutch company which stared AWES research in 2009 it has gained a powerful experience throughout the years, having reached a 150kW ground generation rigid wing kite.

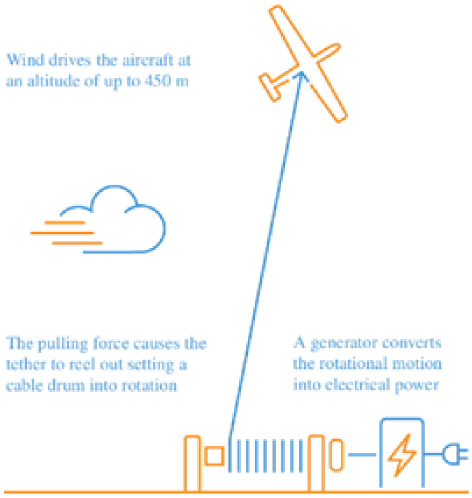


Figure 2.18 - Ampyx power working principle [22]

Kiteswarms

Kiteswarms is a recent German company which is developing this technology with a different approach – the usage of a multi kite system combined in the same tether as it can be witnessed by the picture in Table 2.3 page 25. There is not much more information about this system, as it is a recent player in this market.

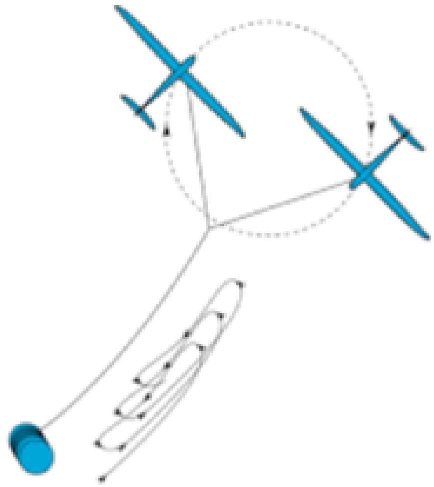


Figure 2.19 - Kiteswarms system [36]

Omnidea

Omnidea is a Portuguese company which uses a lighter than air prototype balloon filled with helium tethered to a ground generator. The balloon is forced to rotate by the Magnus effect (Figure 2.21), and the energy associated to the rotation movement is transferred to the ground generator by the tether This concept has proved its reliability in generating power up to 30kW.

Figure 2.20 - Omnidea balloon [21]

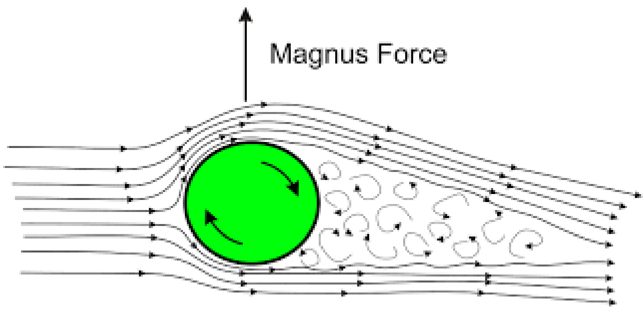


Figure 2.21 - Magnus effect [37]

2.2.2.2. AWES – ON-BOARD GENERATION

Another AWES system is "On board generation". As the name suggests, these systems are characterized by the fact of the generator being airborne. The tether assumes the function of anchoring the system to the ground, as well as to bring the electric power to the ground, so it can be connected to the grid. Figure 2.22 shows different types of on-board generation systems.

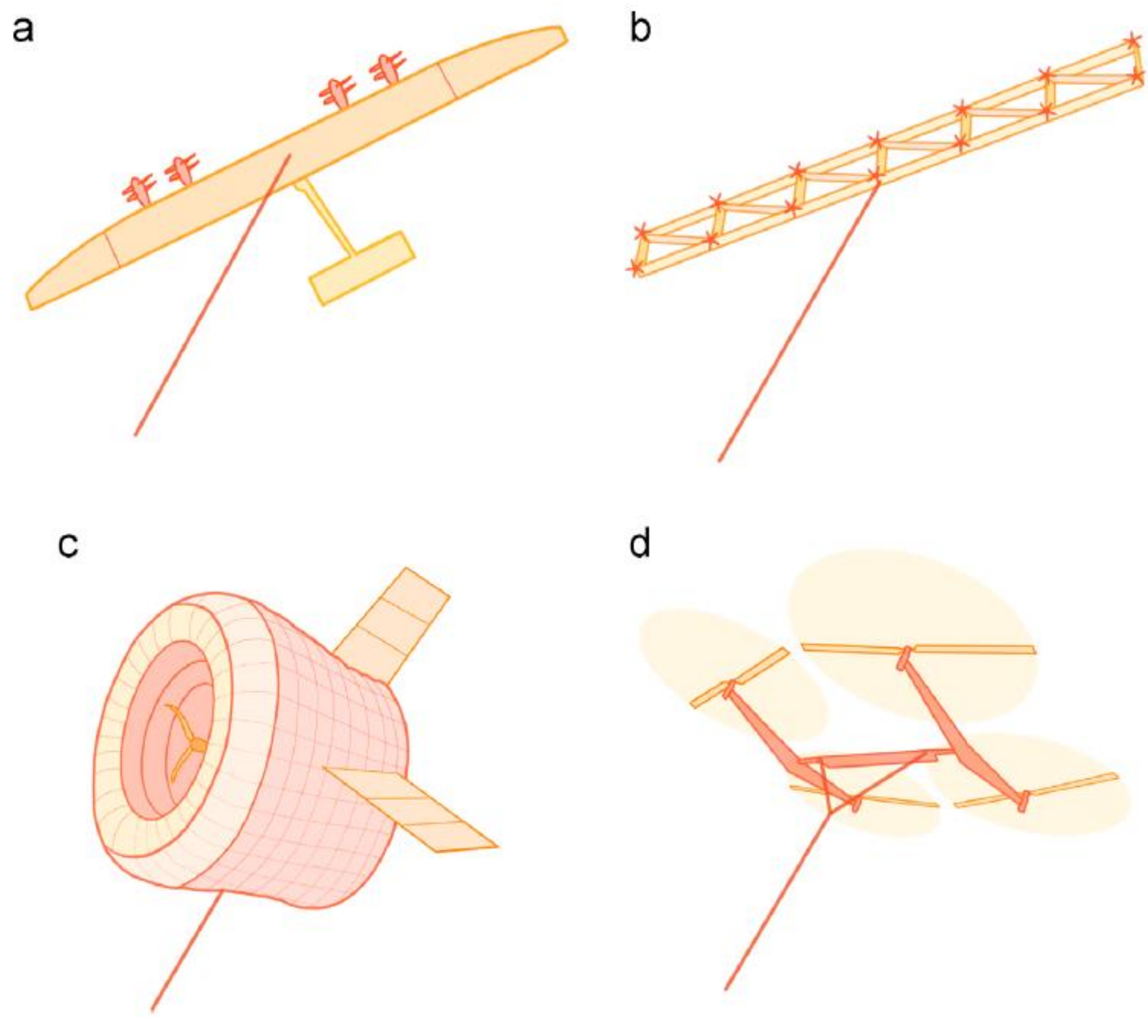


Figure 2.22 - Different On-Board generation layouts in different manufacturers [34]

a) This type of rigid wing kite (Makani) is comparable to a conventional aircraft tethered to the ground. This kite has built in generators which can also work as motors thus enabling more control for take-off, landing and control. Trajectory control is reached through the use of control surfaces similar to conventional aircrafts, enabling perfect and safe operational control. The cable function is both to anchor the kite to the ground, as well as conducting the generated electric power to the ground, as well as the transmission of the necessary control signals and telemetry.

b) Another rigid wing kite (Joby Energy), with double wing mount and the presence of several generators enables control without the resource for control surfaces unlike conventional aircrafts. This kite draws circles alongside its trajectory harvesting wind energy in the process.

c) Lighter than air kite – A tube shaped light wing filled with a light gas enables this system to gain altitude (Altaeros). A generator mounted in the centre of the cylinder generates electric power which is conducted to the ground by means of the tether.

d) Drone-like kite (Sky WindPower) – between a perfectly controlled take-off and landing this kite system is capable of reaching high altitudes in order to harvest wind power in its built-in generators and conducting the power to the ground through the tether.

Makani power

Makani Power is an American company, owned by Alphabet Inc. (Google owner). This company has developed a 600kW solution which consists on an airborne airplane with six mounted generators tethered to the ground through a cable. This concept is well proven for both sea and land operations, it can be fix mounted for electric power generation in almost any place on earth proving instant clean energy.

Figure 2.23 - Makani test facilities (on the left). Off shore tests (on the right) [20]

Figure 2.24 - Makani kite comissioning [20]

Altaeros

Altaeros is an American company with a simple concept – a lighter than air balloon with a mounted generator. This simple assembly, enables a mobile and quick deployment of the system, generating 30kW of power.

Figure 2.25 - Altaeros BAT - Buoyant Airborne Turbine [38]

2.3. POWER ESTIMATES

Given the possibility of the usage of kite systems both in air or water, it is interesting to analyse the amount of available power given the environment in which the system is inserted.

Wind power can be calculated by the following formula:

$$P_{Wind} = Cp \frac{1}{2} \rho_{air} \, A \, u^3 \quad (2.1)$$

In which $Cp = \frac{16}{27}$ (assuming the ideal Betz limit) ρ is the air density, A is the plane section in which the measurement is performed (e.g. total area swept by a conventional wind generator) and u the wind speed [26].

Considering water power harnessing in a similar way, by gathering the water energy in a stream in opposition to a fall (like conventional dams) the formula would be exactly the same:

$$P_{Water} = Cp \frac{1}{2} \rho_{water} \, A \, u^3 \quad (2.2)$$

The significant difference between air and water energy harvesting resides on the density ρ of the given fluid. Air density can vary between 1.423 and 1.127 kg/m^3 given the temperature variation as per Table 2.4.

Table 2.4 - Air density at normal atmospheric pressure [26]

Temperature (^0C)	Density ρ (kg/m^3)	Variation
-25	1.423	116%
-20	1.395	114%
-15	1.368	112%
-10	1.342	110%
-5	1.317	108%
0	1.292	105%
5	1.269	104%
10	1.247	102%
15	**1.225**	**100%**
20	1.204	98%
25	1.184	97%
30	1.165	95%
35	1.146	94%
40	1.127	92%

Analysing water density Table 2.5 [27], it is possible to conclude that this fluid is approximately 1000 times denser than air.

Table 2.5 - Water density with temperatures at normal atmospheric pressure

Temperature (^0C)	Density ρ (kg/m^3)	Variation
0.1	999,9	100%
1	999,9	100%
4	1000,0	100%
10	**999,7**	**100%**
15	999,1	100%
20	998,2	0%
25	997,1	0%
30	995,7	0%
35	994,0	99%
40	992,2	99%

This data suggests the possibility of harnessing water stream energy in a similar way of actual wind power plants, with roughly 1000 times more available energy.

Adjusting equation 3.2 considering Loyd's [28] theoretical limit, the maximum theoretical power that can harvested from a water stream is given by:

$$P_{WaterKite} = \frac{2}{27}\rho_{water}\, A\, u^3\, c_L \left(\frac{C_L}{C_D}\right)^2 \quad (2.3)$$

In which ρ is the water density, u the current speed, A the kite area, c_L the lift coefficient, $\frac{C_L}{C_D}$ the lift-to-drag ratio.

Calculating the following example: In which $\rho = 1025\, kg/m^3$, $u = 2m/s$, $A = 35m^2$,$c_L = 1$ and, $\frac{C_L}{C_D} = 7$;

$$P_{WaterKite} = 1.04MW$$

Considering this example [4], and subtracting the estimated losses accounted for reeling in operation, control systems and general system inefficiencies, it is possible to achieve about 40% electric power yield [6], thus resulting in a 400kW power generation output.

2.4. ADVANTAGES TOWARDS CONVENTIONAL SYSTEMS

Airborne Wind Energy Systems (AWES) are very similar to Tethered underwater kite energy systems (UKPS), as their operation principle is exactly the same. So, they share the same virtues, like being a cost-effective alternative to conventional technologies. UKPS have the advantage of benefiting of the earlier development of AWES and the main advantage which is the higher fluid density of water in comparison to air, thus increasing very significantly the amount of available power to harvest through these systems [4].

These types of technologies have certain advantages in opposition to the conventional ones. Which deserve a reflexion at the moment of choosing the right technology for a given project:

-Low environmental impact

-Easy material procurement

-Investment costs compared to conventional technologies

-Better use of the installation site in comparison to a conventional air or water generator given the possibility of driving the kites to a desired altitude/depth in order to acquire maximum power from the primary energy source (wind/water) as it can be shown in Figure 2.26 and Figure 2.27 bellow.

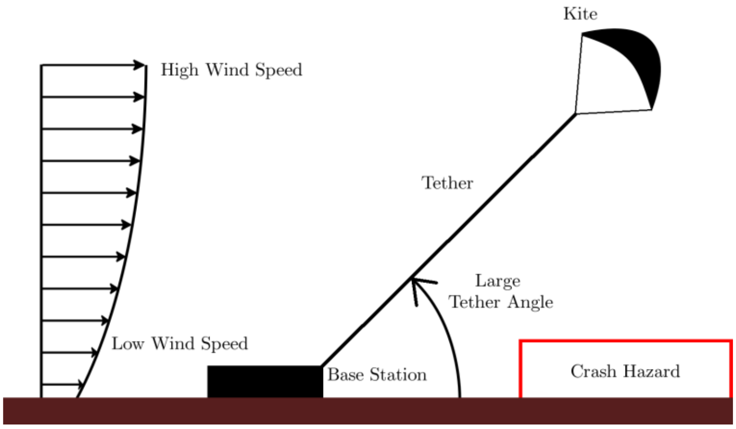


Figure 2.26 - Comparison between windspeeds at different altitude levels [39]

This is one of the main advantages that can catapult these technologies to the front line of the renewable's energy mix. The possibility of harnessing wind or water currents at different altitudes and depths, increases the available energy at one given point by comparison to traditional energy harvesting technologies, such as conventional wind generators.

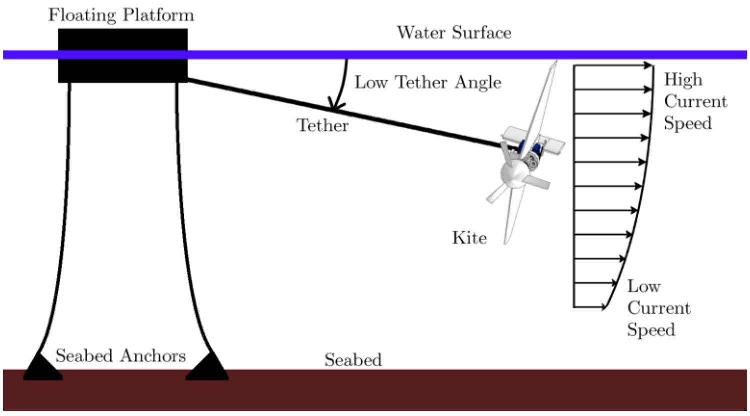


Figure 2.27 - Comparison between water current speeds at different depths [39]

AWE Systems intend to achieve high wind speeds at high altitudes, often exceeding 500m, doing this while minimizing the tether length and thus its weight, it is highly recommended to use a high tether angle (referenced as per Figure 2.26). Nevertheless, the maximum power generation is achieved when the kite is aligned with the horizontal wind direction, i.e. with a small tether angle [4]. The advantage of harnessing high altitude windspeed energy creates a problem which can be a potential drawback, this is called the “cosine effect [6]”

In opposition, UKPS achieves the higher ocean current or tidal flow speeds closer to the surface (Figure 2.27), which makes it easier to minimize the “cosine effect losses [6]”, especially in small depth streams facilitating installation while minimizing tether length and maximizing power output [4].

2.5. DRAWBACKS

There are some drawbacks associated to these technologies.

The requirement for complex and advanced control systems in order to ensure optimal motion, thus ensuring the best performance given the current/wind. The instability of the wind flow, which is a result from phenomena's like gusts, wind shear or burst effects, increase the demand over these systems. Their capability to handle these events determine the service time of an AWES thus minimizing the reeling in necessity while withstanding a storm (for example).

The choice of materials is a critical part of AWES and UKPS designing, as lighter and stronger materials are needed in order to assure minimum maintenance, maximum power generation minimizing losses due to material drag and excessive weight.

Turbulence conditions are an important part of the design and location choice for these systems, as they can influence directly in the kite system overall performance or even contribute to a catastrophic loss.

Cavitation is also an important part to be assessed in Underwater kites, as it can be an important variable in power generation and motion control. The high speeds achieved by these kites, can create cavitation phenomenon which have to be studied and assessed in order to have it considered within the framework of optimum control.

These systems have to be compatible with air and naval traffic, and take into account their environmental impact [4].

3. MODEL DESCRIPTION

This chapter departs from the work basis developed by Luís Paiva and Fernando Fontes [8] which established kite modelling, simulation, control and optimization.

The model approach will be divided in two sub-sections, separating 2D and 3D modelling of a kite system – both airborne (using wind as primary energy source) and underwater (using water as primary energy source).

3.1. 2D KITE ENERGY SYSTEMS

For establishing the basic coordinate systems for the 2D problem analysis, Luís Paiva and Fernando Fontes [8] defined:

Global G: Cartesian coordinate system (x, y) where $x$is aligned according to wind direction $\mathrm{v}_w = (v_w, 0)$ – basis $(\vec{e}_x, \vec{e}_z)$

Local L: Polar coordinate system (r, β) centred at the kite position – basis $(\vec{e}_r, \vec{e}_\beta)$

Considering the position **p**,

$$\mathbf{p} = \begin{bmatrix} r\cos(\beta) \\ r\sin(\beta) \end{bmatrix}$$

We get

$$\vec{e}_r = \frac{\frac{\partial p}{\partial r}}{\left|\frac{\partial p}{\partial r}\right|} = \begin{bmatrix} \cos(\beta) \\ \sin(\beta) \end{bmatrix},$$

$$\vec{e}_\beta = \frac{\frac{\partial p}{\partial \beta}}{\left|\frac{\partial p}{\partial \beta}\right|} = \begin{bmatrix} -\sin(\beta) \\ \cos(\beta) \end{bmatrix}.$$

Rotation matrix from L coordinate system to G

$$R_{LG} = [\vec{e}_r \quad \vec{e}_\beta] = \begin{bmatrix} \cos(\beta) & -\sin(\beta) \\ \sin(\beta) & \cos(\beta) \end{bmatrix}$$

Rotation matrix from G coordinate system to L

$$R_{LG} = R_{LG}^{-1} = R_{LG}^{T} = \begin{bmatrix} \cos(\beta) & \sin(\beta) \\ -\sin(\beta) & \cos(\beta) \end{bmatrix}$$

3.1.1. AIRBORNE KITE ENERGY SYSTEMS

Luís Paiva and Fernando Fontes [8] work regarding airborne kite energy systems, considers the kite's position (**p**), its mass (m)and the resulting force acting on it (F), Newton's law reads:

$$m\ddot{p} = F \tag{3.4}$$

Now, decomposing the resulting force F in (4.4),

$$F = \vec{F}^{th} + \vec{F}^{grav} + \vec{F}^{aer}(\alpha).$$

In which the tether and gravitational forces are given by:

$$\vec{F}^{th} = -T\,\vec{e}_r = \begin{bmatrix} -T \\ 0 \end{bmatrix}_L$$

$$\vec{F}^{grav} = -mg\,\vec{e}_z = \begin{bmatrix} 0 \\ -mg \end{bmatrix}_G$$

$$= R_{GL}\begin{bmatrix} 0 \\ -mg \end{bmatrix}_G = \begin{bmatrix} -mg\sin(\beta) \\ -mg\cos(\beta) \end{bmatrix}_L$$

3.1.1.1. AERODYNAMIC FORCES – FORCE DIRECTIONS DEFINED BY THE APPARENT WIND

Now it has been considered [8] the true case in which the drag force is aligned with the apparent wind velocity and the lift force has its upward normal direction as per Figure 3.1.

$$\vec{F}_L^{aer}(\alpha) = \vec{F}^{lift}(\alpha) + \vec{F}^{drag}(\alpha)$$

Where

$$\vec{F}^{drag}(\alpha) = \frac{1}{2}\,\rho\,A\,c_D(\alpha)\|\mathrm{v}_a\|\mathrm{v}_a$$

$$\vec{F}^{lift}(\alpha) = \frac{1}{2}\,\rho\,A\,c_L(\alpha)\|\mathrm{v}_a\|R_{90}\,\mathrm{v}_a$$

Where $R_{90}$is 90º anticlockwise rotation matrix. Thus,

$$\vec{F}_L^{aer}(\alpha) = \frac{1}{2}\,\rho\,A\,\|\mathrm{v}_a\|\,(c_D(\alpha)\mathrm{v}_a + c_L(\alpha)R_{90}\,\mathrm{v}_a).$$

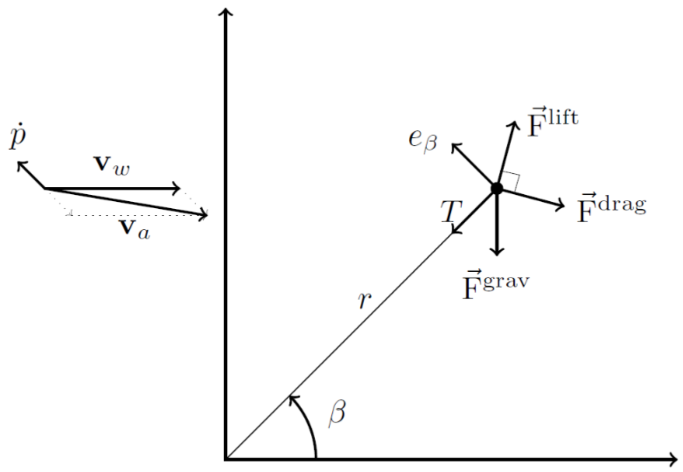


Figure 3.1 - Acting forces on the kite [8]

3.1.1.2. KITE MODEL

In a polar coordinate system,

Considering the aerodynamic force directions defined by the apparent wind,

$$m\begin{bmatrix}\ddot{r}\\ r\ddot{\beta}\end{bmatrix} = \vec{F}^{th} + \vec{F}^{grav} + \vec{F}^{aer} + \vec{F}^{inert}$$

Where $\vec{F}^{inert}$represents the inertial forces.

$$\vec{F}^{inert} = m\begin{bmatrix}r\dot{\beta}^2\\ 2\dot{r}\dot{\beta}\end{bmatrix}_L$$

Considering the aerodynamic force directions defined by the apparent wind (Case 3),

$$m\begin{bmatrix}\ddot{r}\\ r\ddot{\beta}\end{bmatrix}=\vec{F}^{th}+\vec{F}^{grav}+\vec{F}^{aer}+\vec{F}^{inert}$$

$$=\begin{bmatrix}-T\\ 0\end{bmatrix}-mg\begin{bmatrix}\sin(\beta)\\ \cos(\beta)\end{bmatrix}+\begin{bmatrix}F_r^{aer}(\alpha)\\ F_\beta^{aer}(\alpha)\end{bmatrix}+m\begin{bmatrix}r\dot{\beta}^2\\ -2\dot{r}\dot{\beta}\end{bmatrix}$$

Therefore,

$$\begin{bmatrix}\ddot{r}\\ \ddot{\beta}\end{bmatrix}=\frac{1}{m}\begin{bmatrix}-T-gm\sin(\beta)+F_r^{aer}(\alpha)+mr\dot{\beta}^2\\ \frac{1}{r}\left(-gm\cos(\beta)+F_\beta^{aer}(\alpha)-2m\dot{r}\dot{\beta}\right)\end{bmatrix}$$

And

$$\vec{F}^{aer}(\alpha)=\begin{bmatrix}F_r^{aer}(\alpha)\\ F_\beta^{aer}(\alpha)\end{bmatrix}=\frac{1}{2}\,\rho\,A\,\|\mathrm{v}_a\|\,(c_D(\alpha)\mathrm{v}_a+c_L(\alpha)R_{90}\,\mathrm{v}_a)=\cdots$$

Considering $\dot{r}=v_t\in\mathbb{R}$, we have $\ddot{r}=0$ and therefore we can define the state $\mathrm{x}=\left(r,\beta,\dot{\beta}\right)$, the control $\mathrm{u}=(v_t,\alpha)$, the dynamic equation

$$\dot{\mathrm{x}}=\frac{\mathrm{d}}{\mathrm{dt}}\begin{bmatrix}r\\ \beta\\ \dot{\beta}\end{bmatrix}=\begin{bmatrix}v_t\\ \dot{\beta}\\ \frac{1}{m\,r}\left(-gm\cos(\beta)+F_\beta^{aer}(\alpha)-2m\dot{r}\dot{\beta}\right)\end{bmatrix}:=\mathrm{f}(\mathrm{x},\mathrm{u})$$

And the output $y=(x,z,T,v_a^2)$ as

$$y=\begin{bmatrix}r\cos(\beta)\\ r\sin(\beta)\\ -gm\ \sin(\beta)+\ F_r^{aer}(\alpha)+mr\dot{\beta}^2\\ (v_w\cos(\beta)-\dot{r})^2+\left(v_w\ \sin(\beta)+r\dot{\beta}\right)^2\end{bmatrix}$$

3.1.2. TETHERED UNDERWATER KITE ENERGY SYSTEMS – BRIEF APPROACH

Underwater kite systems take advantage of the water's higher fluid density in order to produce more power maintaining the method and concept used for airborne kites.

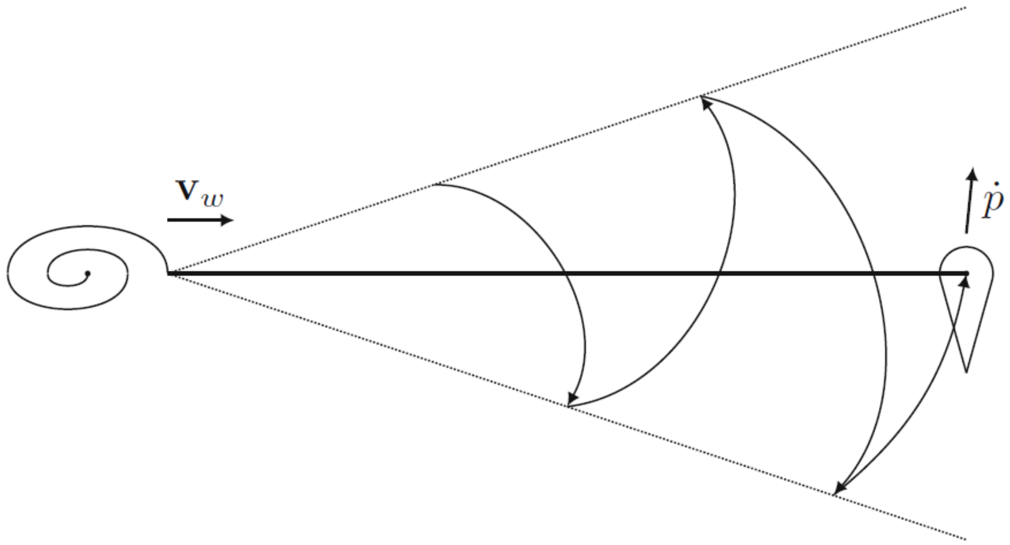


Figure 3.2 - Underwater kite energy system - Top view (2D) [9]

As it can be seen on Figure 3.3, the underwater kite is not influenced by the gravitational forces which is on more virtue to take into account in the comparison to the wind kite.

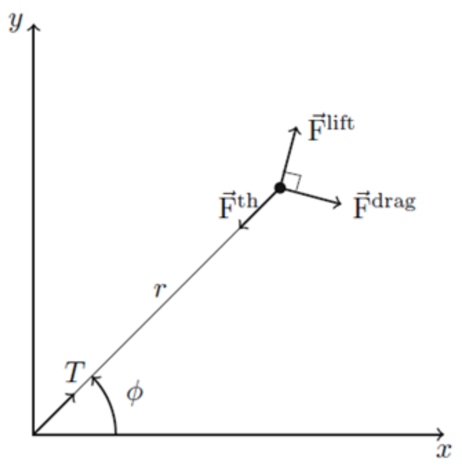


Figure 3.3 Acting forces on the underwater kite [9]

3.2. 3D KITE ENERGY SYSTEMS

For establishing the basic coordinate systems for the 3D problem analysis, Luís Paiva and Fernando Fontes [8] defined:

Global G: Cartesian coordinate system (x, y, z) where $x$is aligned according to wind direction $v_w = (v_w, 0,0)$ – basis $(\vec{e}_x, \vec{e}_y, \vec{e}_z)$.

Local L: Spherical coordinate system (r, Φ, β) – basis $(\vec{e}_r, \vec{e}_\Phi, \vec{e}_\beta)$.

Body B: Coordinate system attached to the kite's body – basis $(\vec{e}_1, \vec{e}_2, \vec{e}_3)$. With $\vec{e}_1$coinciding with the kite longitudinal axis pointing forward, $\vec{e}_2$ in the kite transversal axis pointing to the left wing tip, and $\vec{e}_3$in the kite vertical axis pointing upwards.

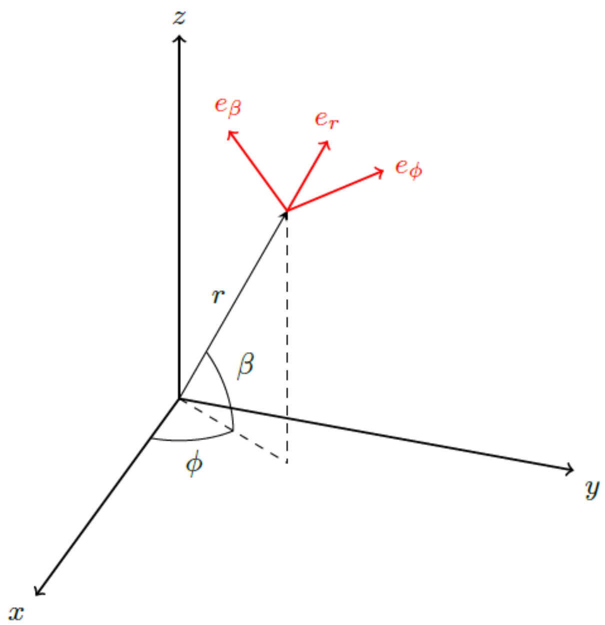


Figure 3.4 - Global/Local coordinate system [8]

It has been considered [8] that the kite's position is given by a point **p** with coordinates (x, y, z).

Given the polar angle θ and the elevation angle β known connection

$$\theta = \frac{\pi}{2} - \beta \Leftrightarrow \beta = \frac{\pi}{2} - \theta$$

And considering the position **p**:

$$\mathbf{p} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} r\ \sin(\theta)\cos(\Phi) \\ r\ \sin(\theta)\sin(\Phi) \\ r\cos(\theta) \end{bmatrix} = \begin{bmatrix} r\ \cos(\beta)\cos(\Phi) \\ r\ \cos(\beta)\sin(\Phi) \\ r\sin(\beta) \end{bmatrix}$$

We get

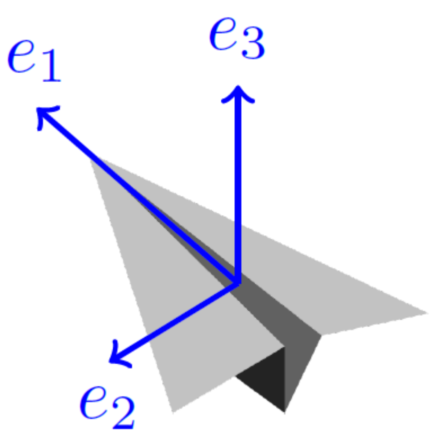


Figure 3.5 - Body coordinate system [8]

$$\vec{e}_r = \frac{\frac{\partial \mathbf{p}}{\partial r}}{\left|\frac{\partial \mathbf{p}}{\partial r}\right|} = \begin{bmatrix} \cos(\beta)\cos(\Phi) \\ \cos(\beta)\sin(\Phi) \\ \sin(\beta) \end{bmatrix},$$

$$\vec{e}_\Phi = \frac{\frac{\partial \mathbf{p}}{\partial \Phi}}{\left|\frac{\partial \mathbf{p}}{\partial \Phi}\right|} = \frac{1}{r\cos(\beta)} = \begin{bmatrix} -r\ \cos(\beta)\sin(\Phi) \\ \cos(\beta)\cos(\Phi) \\ 0 \end{bmatrix} = \begin{bmatrix} -\sin(\theta) \\ \cos(\Phi) \\ 0 \end{bmatrix},$$

$$\vec{e}_\beta = \frac{\frac{\partial \mathbf{p}}{\partial \beta}}{\left|\frac{\partial \mathbf{p}}{\partial \beta}\right|} = \frac{1}{r} = \begin{bmatrix} -\sin(\beta)\cos(\Phi) \\ -\sin(\beta)\sin(\Phi) \\ \cos(\beta) \end{bmatrix}$$

Rotation matrix from L coordinate system to G

$$R_{LG} = \begin{bmatrix} \vec{e}_r & \vec{e}_\Phi & \vec{e}_\beta \end{bmatrix} = \begin{bmatrix} \cos(\beta)\cos(\Phi) & -\sin(\theta) & -\sin(\beta)\cos(\Phi) \\ \cos(\beta)\sin(\Phi) & \cos(\Phi) & -\sin(\beta)\sin(\Phi) \\ \sin(\beta) & 0 & \cos(\beta) \end{bmatrix}$$

Rotation matrix from G coordinate system to L

$$R_{GL} = R_{LG}^{-1} = R_{LG}^{T} = \begin{bmatrix} \vec{e}_r^{\,T} \\ \vec{e}_\Phi^{\,T} \\ \vec{e}_\beta^{\,T} \end{bmatrix} = \begin{bmatrix} \cos(\beta)\cos(\Phi) & \cos(\beta)\sin(\Phi) & \sin(\beta) \\ -\sin(\theta) & \cos(\Phi) & 0 \\ -\sin(\beta)\cos(\Phi) & -\sin(\beta)\sin(\Phi) & \cos(\beta) \end{bmatrix}$$

Considering the apparent wind velocity

$$\mathrm{v}_a = \mathrm{v}_w - \dot{\mathbf{p}}$$

Assuming that the kite's body is at all times positioned in a way that its longitudinal axis is aligned with the apparent wind velocity,

$$\vec{e}_1 = \frac{-\mathrm{v}_a}{\|\mathrm{v}_a\|}$$

Considering ψ the roll angle which measures the rotation around the $\vec{e}_1$ axis. Assuming that $\vec{e}_2$ is initially in the τ plane (for $\psi = 0$), tangent to a sphere centred at the origin, containing the axis $\vec{e}_\Phi$ and $\vec{e}_\beta$. It can be said that:

$$\vec{e}_1 \perp \vec{e}_r, \text{ and } \vec{e}_2 \perp \vec{e}_1$$

So, it is possible to define

$$\vec{e}_2 = \frac{\vec{e}_r \times \vec{e}_1}{\|\vec{e}_r \times \vec{e}_1\|}$$

ethr forming a right-handed coordinate system

$$\vec{e}_3 = \vec{e}_1 \times \vec{e}_2$$

It is now possible to consider that the kite's body has an counter-clockwise rotation of ψ around the $\vec{e}_1$ axis, i.e. roll – see Figure 3.5.

In this demonstration, Luís Paiva and Fernando Fontes [8] assumed that the roll angle ψ can be controlled directly, exemplifying a two line kite where d is the distance between the anchor points and Δr is the relative difference between the lengths of each line, having:

$$\sin\psi = \frac{\Delta r}{d}$$

Thus, in the L framework, the body axis can be calculated as

$$\vec{e}_{1,L} = \frac{-\mathrm{v}_{a,L}}{\|\mathrm{v}_a\|},$$

being the unrotated axis

$$f_2 = \frac{\vec{e}_{r,L} \times \vec{e}_{1,L}}{\|\vec{e}_{r,L} \times \vec{e}_{1,L}\|},$$

with

$$\vec{e}_{r,L} = R_{GL}\begin{bmatrix}0\\0\\1\end{bmatrix}.$$

Applying Rodrigues formula to rotate f_2 by ψ around $\vec{e}_1$, they [8] have obtained $\vec{e}_2$

$$\vec{e}_{2,L} = f_2\cos\psi + (\vec{e}_1 \times f_2)\ \sin\psi + \vec{e}_1(\vec{e}_1 \cdot f_2)(1-\cos\psi)$$

and

$$\vec{e}_{3,L} = \vec{e}_{1,L} \times \vec{e}_{2,L}$$

AIRBORNE WIND ENERGY SYSTEMS – AERODYNAMIC FORCES

Taking the kite's position (**p**) under consideration, as well as its mass (m) and the resultant total force acting on it, decomposed as follows

$$m\ddot{\mathbf{p}} = \vec{F}^{th} + \vec{F}^{grav} + \vec{F}^{aer}(\alpha)$$

where

$$\vec{F}^{th} = -T\vec{e}_r = \begin{bmatrix} -T \\ 0 \\ 0 \end{bmatrix}_T$$

$$\vec{F}^{grav} = -mg\ \vec{e}_z = \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix}_G$$

$$\Rightarrow = R_{GL} \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix}_G = \begin{bmatrix} -mg\sin\beta \\ 0 \\ -mg\cos\beta \end{bmatrix}_L$$

$$\vec{F}^{aer}(\alpha) = \vec{F}^{lift}(\alpha) + \vec{F}^{drag}(\alpha)$$

and

$$\vec{F}^{drag}(\alpha) = \frac{1}{2}\ \rho\ A\ c_D(\alpha)\|\mathrm{v}_a\|^2\vec{e}_1$$

$$\vec{F}^{lift}(\alpha) = \frac{1}{2}\ \rho\ A\ c_L(\alpha)\|\mathrm{v}_a\|^2\vec{e}_3$$

Thus

$$\vec{F}^{aer}(\alpha) = \frac{1}{2}\ \rho\ A\|\mathrm{v}_a\|^2(c_L(\alpha)\vec{e}_3 - c_D(\alpha)\vec{e}_1).$$

In the spherical coordinate system

$$\dot{\mathbf{p}} = \frac{d\mathbf{p}}{dt} = \begin{bmatrix} \cos(\beta)\cos(\Phi) \\ \cos(\beta)\sin(\Phi) \\ \sin(\beta) \end{bmatrix}\dot{r} + \begin{bmatrix} -r\ \cos(\beta)\sin(\Phi) \\ r\ \cos(\beta)\cos(\Phi) \\ 0 \end{bmatrix}\dot{\Phi} + \begin{bmatrix} -r\ \sin(\beta)\cos(\Phi) \\ -r\ \sin(\beta)\sin(\Phi) \\ r\ \cos(\beta) \end{bmatrix}\dot{\beta}$$

$= \dot{r}\vec{e}_r + r\dot{\Phi}\cos(\beta)\,\vec{e}_\Phi + r\dot{\beta}\vec{e}_\beta$

$$\begin{bmatrix} \dot{r} \\ r\,\dot{\Phi}\,\cos(\beta) \\ r\,\dot{\beta} \end{bmatrix}_L$$

and

$$\ddot{\mathbf{p}} = \frac{d^2\mathbf{p}}{dt^2} = \begin{bmatrix} \ddot{r} \\ r\,\ddot{\Phi}\cos(\beta) \\ r\,\ddot{\beta} \end{bmatrix}_L + \underbrace{\begin{bmatrix} -r\dot{\beta}^2 - r\dot{\Phi}^2\cos^2(\beta) \\ 2\dot{r}\dot{\Phi}\cos(\beta) - 2r\dot{\Phi}\dot{\beta}\sin(\beta) \\ 2\dot{r}\dot{\beta} + r\dot{\Phi}^2\cos(\beta)\sin(\beta) \end{bmatrix}_L}_{-\frac{1}{m}\vec{F}^{inert}}$$

Where $\vec{F}^{inert}$ represents the inertial forces which can be decomposed as the sum of the centrifugal force ($\vec{F}^{cent}$), and the Coriolis force ($\vec{F}^{cor}$).

$\vec{F}^{inert} = \vec{F}^{cent} + \vec{F}^{cor})$

$$= m\begin{bmatrix} r\dot{\beta}^2 + r\dot{\Phi}^2\cos^2(\beta) \\ 0 \\ -r\dot{\Phi}^2\cos(\beta)\sin(\beta) \end{bmatrix}_L + m\begin{bmatrix} 0 \\ 2r\dot{\Phi}\dot{\beta}\sin(\beta) - 2\dot{r}\dot{\Phi}\cos(\beta) \\ -2\dot{r}\dot{\beta} \end{bmatrix}_L$$

Evaluating $\mathrm{v}_a = \mathrm{v}_w - \dot{\mathbf{p}}$

$$\mathrm{v}_a = \begin{bmatrix} v_w\cos(\beta)\cos(\Phi) - \dot{r} \\ -v_w\sin(\Phi) - r\,\cos(\beta)\,\dot{\Phi} \\ -v_w\sin(\beta)\cos(\Phi) - r\dot{\beta} \end{bmatrix}_L$$

$$\|\mathrm{v}_a\| = \sqrt{(v_w\cos(\beta)\cos(\Phi) - \dot{r}\,)^2 + \left(r\dot{\beta} + v_w\sin(\beta)\cos^2(\Phi)\right)^2 + \left(r\,\cos(\beta)\,\dot{\Phi} + v_w\sin(\Phi)\right)^2}$$

Enabling the writing of,

$$m\begin{bmatrix}\ddot{r}\\ r\ddot{\Phi}\cos(\beta)\\ r\ddot{\beta}\end{bmatrix}=\vec{F}^{th}+\vec{F}^{grav}+\vec{F}^{aer}+\vec{F}^{inert}$$

$$=\left(\begin{bmatrix}-T\\0\\0\end{bmatrix}+m\begin{bmatrix}-gsin(\beta)\\0\\-gcos(\beta)\end{bmatrix}+\begin{bmatrix}F_r^{aer}(\alpha)\\F_\Phi^{aer}(\alpha)\\F_\beta^{aer}(\alpha)\end{bmatrix}+m\begin{bmatrix}r\dot{\beta}^2+r\dot{\Phi}^2\cos^2(\beta)\\0\\-r\dot{\Phi}^2\cos(\beta)\sin(\beta)\end{bmatrix}\right.$$
$$\left.+m\begin{bmatrix}0\\2r\dot{\Phi}\dot{\beta}\sin(\beta)-2\dot{r}\dot{\Phi}\cos(\beta)\\-2\dot{r}\dot{\beta}\end{bmatrix}\right)$$

consequently,

$$\begin{bmatrix}\ddot{r}\\ \ddot{\Phi}\\ \ddot{\beta}\end{bmatrix}=\frac{1}{m}\begin{bmatrix}-T-gm\ \sin(\beta)+F_r^{aer}(\alpha)+m(r\dot{\beta}^2+r\dot{\Phi}^2\cos^2(\beta))\\ \frac{1}{r\ \cos(\beta)}\left(F_\Phi^{aer}(\alpha)+m\left(2r\dot{\Phi}\dot{\beta}\sin(\beta)-2\dot{r}\dot{\Phi}\cos(\beta)\right)\right)\\ \frac{1}{r}\left(-gm\ cos(\beta)+F_\beta^{aer}(\alpha)-mr\dot{\Phi}^2\cos(\beta)\sin(\beta)-2m\dot{r}\dot{\beta}\right)\end{bmatrix}$$

Luís Paiva and Fernando Fontes [8] assumed that the tether acceleration $\ddot{r}$ can be controlled directly by a_t:

$$m\ddot{r}=ma_t=-T-gm\ \sin(\beta)+F_r^{aer}(\alpha)+m(r\dot{\beta}^2+r\dot{\Phi}^2\cos^2(\beta))$$

Thus, resulting in the tether tension:

$$T=-ma_t-gm\sin(\beta)+F_r^{aer}(\alpha)+m(r\dot{\beta}^2+r\dot{\Phi}^2\cos^2(\beta))$$

4. SIMULATION AND RESULTS

This chapter provides feasible data regarding electric power and energy outputs of an AWES by use of real data and through the analysis of several given cases in order to deliver results for further comparison.

A total of 3 cases are studied:

-Case 1 – Kitepower equipment

-Case 2 – Kite farm with Kitepower energy system

-Case 3 – A “Off-the-shelf kite”, using a kitesurf wing and a standard generator

4.1. PROBLEM FORMULATION AND DATA SOURCING

Resorting to the formulation published by Roque et al in [7], which comprises as entry variables the kite area A, the air density ρ, the maximum traction force F_{max}, the maximum tether length L_{max}, the generator rated power P_N, the kite drag coefficient C_D, the maximum and minimum lift coefficients C_{Lmax} and $C_{Lmin}$for the traction and retraction stages respectively.

Resulting in the maximum mechanical power in the traction stage [7]:

$$P = \frac{1}{2}\rho\, v_w^3\, A\, \frac{4}{27}\, \frac{C_L^3}{C_D^2} \tag{4.1}$$

Using real wind data collected throughout the year 2008 with measures taken every 5 minutes, derived from instruments on an 82m meteorological tower located[3] at the western edge of the Flatirons campus (formerly NWTC - Northeast Wisconsin Technical College), Colorado.

This data was imported to MATLAB® software, version R2016b, and given the fact that AWE systems achieve higher altitudes than the available 82 meters altitude, the windspeeds at greater flight levels was achieved through the use of an extrapolation method developed by Prandtl [29] and also used by Roque and Paiva et al [7]. This enables a more feasible calculation of the available power at higher elevations.

The next series of figures represent the data used for the simulations (partial raw data also available on Appendix A).

[3] National Wind Technology - National Renewable Energy Laboratory (M2 Tower coordinates N39º54' 38.34" W105º 14' 5.28"; Elevation:1855meters above mean sea level.

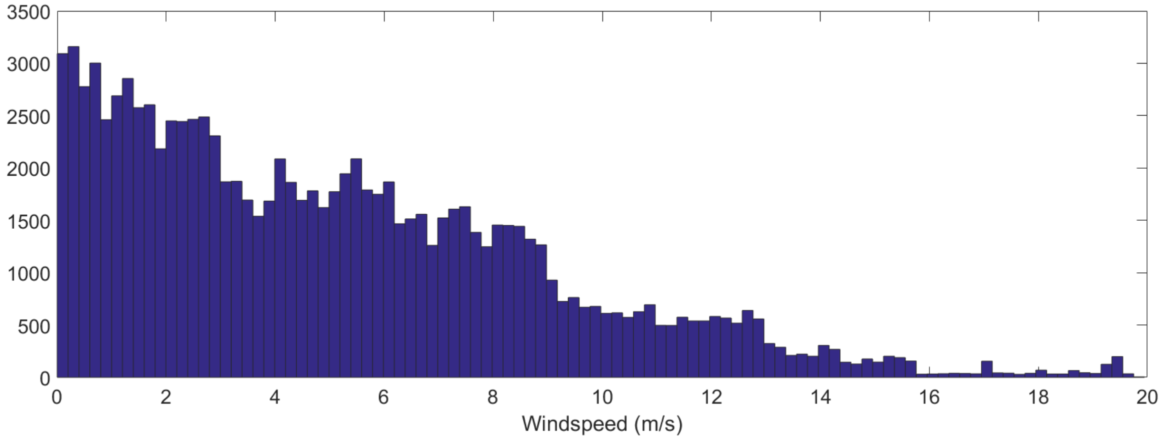


Figure 4.1 - Yearly windspeed histogram

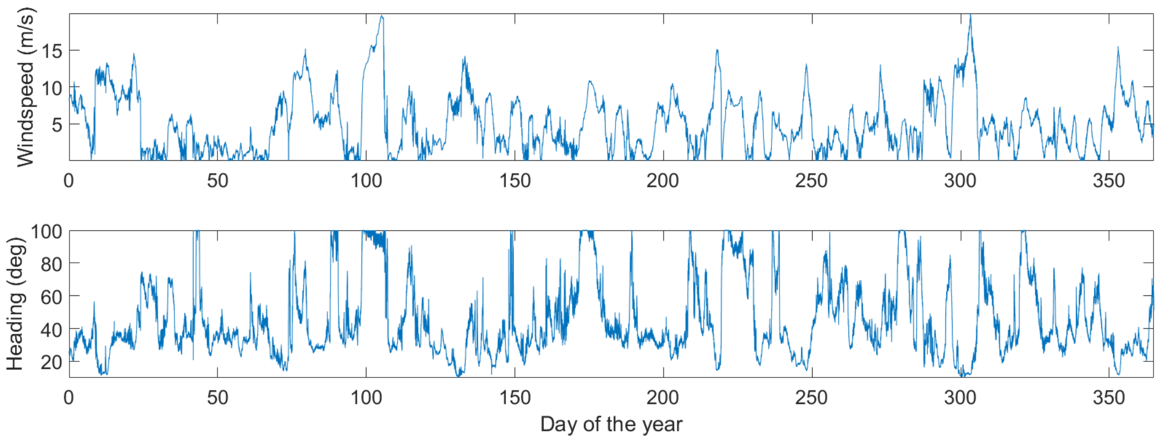


Figure 4.2 - Windspeed and heading throughout the year

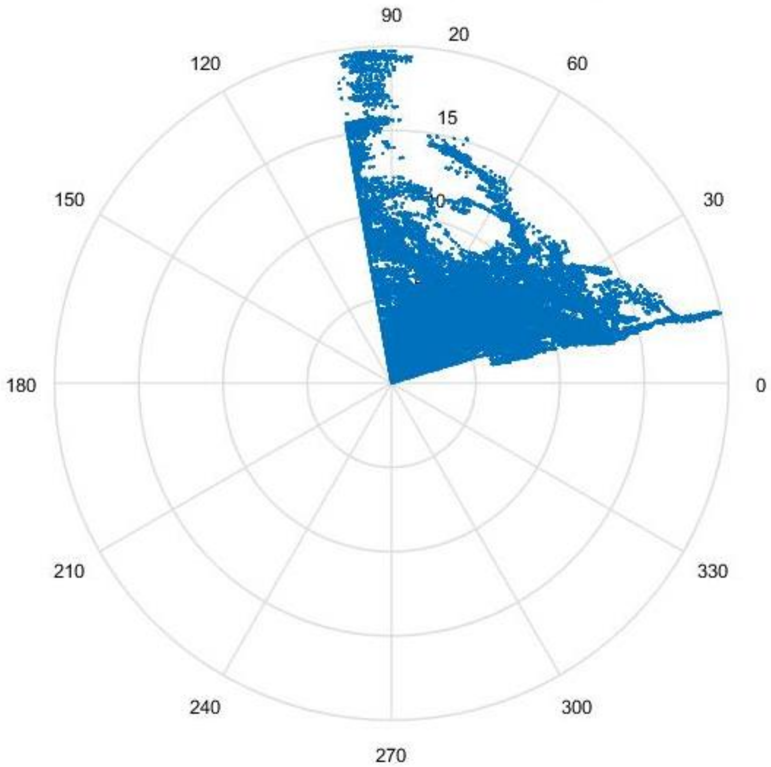


Figure 4.3 - Windspeed and heading (Radar view)

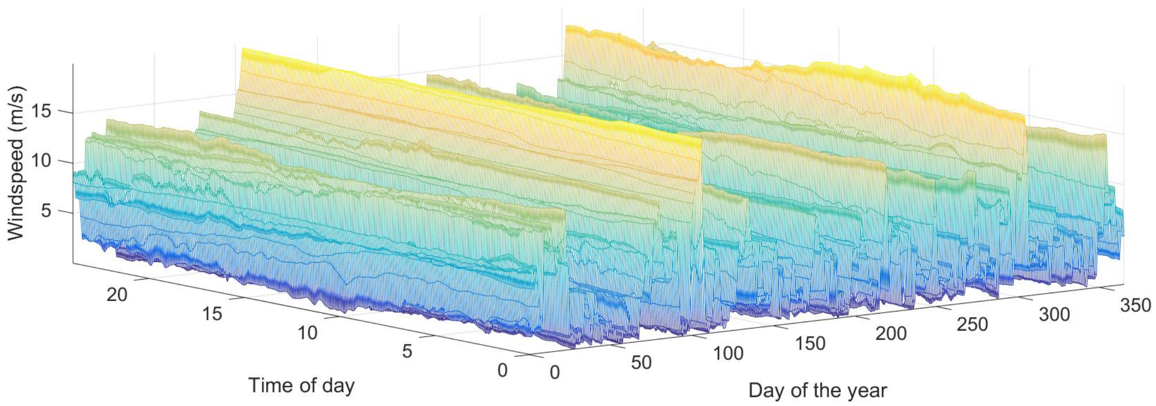


Figure 4.4 - Windspeed throughout the year and time of day

For the subsequent simulations, the required entry variables are A-Kite area; P_N- Generator rated power and L_{max}tether length.

The desired results for further analysis are:

Capacity Factor - It is defined as the ratio of the power actually produced by a wind turbine to the power that could have been produced if the machine ran at its rated power.

$$CF = \frac{P_N}{P}$$

Demand Factor - It is defined as the ratio of the maximum load in a given time period to the maximum possible load limited by the wind.

$$DF = \frac{P_{MaxHarnessed}}{P_{MaxWind}}$$

Annual energy production: simulated energy production for the give values of windspeed

Average power output: simulated average power production for the given values of windspeed

4.2. CASE STUDY 1: KITEPOWER

Considering KitePower manufacturer (already approached in **Error! Reference source not found. Error! Reference source not found.**), and taking into to account the available data regarding this kite the following entry variables are contemplated: Kite area $A = 50m^2$; Generator nominal power $P_N = 20\ kW$; Tether maximum length $L_{max} = 400m$; Air density $\rho = 1.225$; Drag coefficient $c_D = 0.15$; Minimum lift coefficient $c_{Lmin} = 0.1$; Maximum lift coefficient $c_{Lmin} = 1$;

Table 4.1 - Simulation parameters for case study 1

Variable	Value
Kite area	$A = 50m^2$
Generator nominal power	$P_N = 20\ kW$
Tether maximum length	$L_{max} = 400m$
Air density	$\rho = 1.225$
Drag coefficient	$c_D = 0.15$
Minimum lift coefficient	$c_{Lmin} = 0.1$
Maximum lift coefficient	$c_{LMax} = 1$

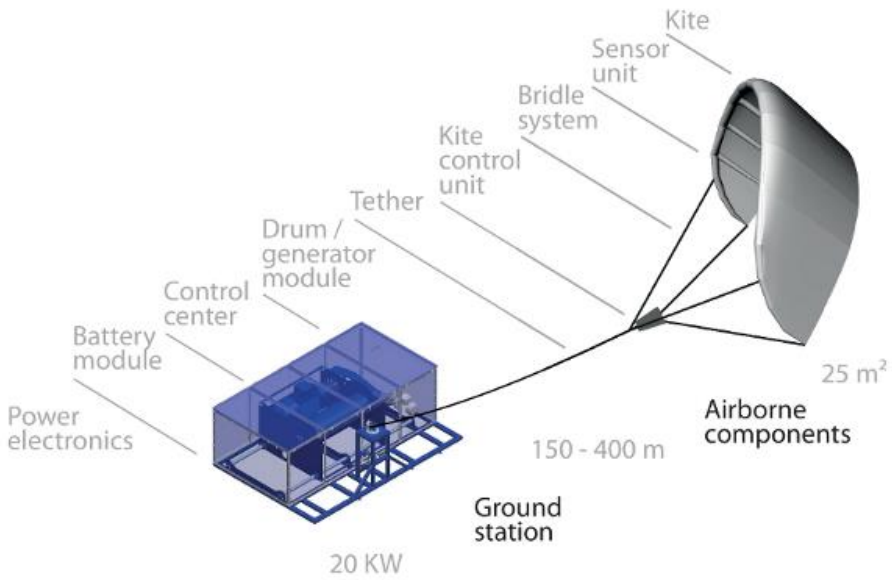


Figure 4.5 - KitePower concept [25]

These variables result in the power output curves represented in Figure 4.6 (also available in Appendix B in full size) which translate the electric power output at different elevation angles of the kite.

Simulation results:

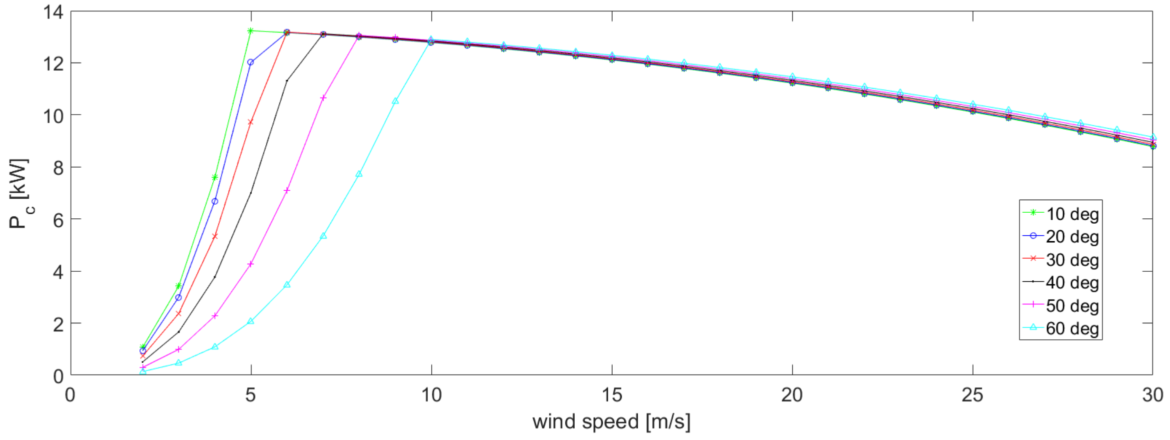


Figure 4.6 – Case 1 simulation – Power output at different kite elevation angles

Capacity factor:

$$CF = 0.8543$$

Demand factor:

$$DF = 0.6616$$

Annual energy production:

$$AEP = 76\,897\ kWh = 210.68\ kWh/day$$

Average power output:

$$P = 8.78\ kW$$

4.3. CASE STUDY 2: KITE FARM

Considering a kite farm installation, with the same make and model described in 4.2 Case study 1: KitePower.

Table 4.2 - Simulation parameters for case study 2

Variable	Value
Kite area	$A = 38 \times 25m^2$
Generator nominal power	$P_N = 38 \times 20\ kW$
Tether maximum length	$L_{max} = 400m$
Air density	$\rho = 1.225$
Drag coefficient	$c_D = 0.15$
Minimum lift coefficient	$c_{Lmin} = 0.1$
Maximum lift coefficient	$c_{LMax} = 1$
Kite Farm area	$KiteFarm_{Area} = 1200m \times 1600m = 1\ 920\ 000m^2$
Number of kites in the farm	38

The optimal kite disposition would be as per Figure 4.7 with values.

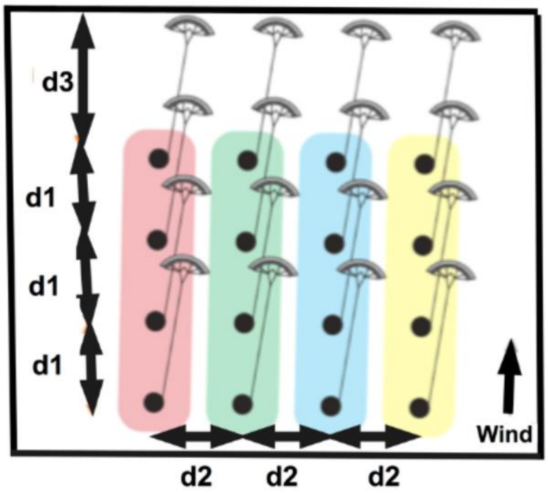


Figure 4.7 - Kite farm disposition example [7]

Simulation results:

Table 4.3 - Distances between kites to be considered

Kite elevation angle (deg)	10	20	30	40	50	60
d1 (m)	176,2	100,7	72,1	57,4	49,0	43,9
d2 (m)	66,9	66,9	66,9	66,9	66,9	66,9
d3 (m)	396,8	382,1	355,8	318,6	271,8	216,7

Capacity factor (is constant up to the 11^{th} decimal case, regardless of the number of kites considered):

$$CF = 0.8484$$

Demand factor

$$DF = 0.6616$$

Annual energy production:

Table 4.4 - Kite farm yearly energy production by kite farm size

Number of kites	**1**	**2**	**3**	**4**	**5**
Annual energy (kWh)	75 838,53	151 677,1	227 515,6	303 354,1	379 192,6
	6	**7**	**8**	**9**	**10**
	455 031,2	530 869,7	606 708,2	682 546,8	758 385,3
	11	**12**	**13**	**14**	**15**
	834 223,8	910 062,3	985 900,9	1 061 739	1 137 578
	16	**17**	**18**	**19**	**20**
	1 213 416	1 289 255	1 365 094	1 440 932	1 516 771
	21	**22**	**23**	**24**	**25**
	1 592 609	1 668 448	1 744 286	1 820 125	1 895 963
	26	**27**	**28**	**29**	**30**
	1 971 802	2 047 640	2 123 479	2 199 317	2 275 156
	31	**32**	**33**	**34**	**35**
	2 350 994	2 426 833	2 502 671	2 578 510	2 654 349
	36	**37**	**38**		
	2 730 187	2 806 026	2 881 864		

Considering the annual energy production for a kite farm with 38 kites:

$$AEP = 2\ 806\ 026\ kWh = 7\ 688\ kWh/day$$

Average power output:

$$P = 320\ kW$$

4.4. CASE STUDY 3: "OFF-THE-SHELF KITE"

In this section, in order to provide the understanding of the scale factor of a simple AWES, a simulation is produced using a small sports kite, which can be easily acquired.

Table 4.5 - Simulation parameters for case study 3

Variable	Value
Kite area	$A = 12m^2$
Generator nominal power	$P_N = 7.5\ kW$
Tether maximum length	$L_{max} = 600m$
Air density	$\rho = 1.225$
Drag coefficient	$c_D = 0.15$
Minimum lift coefficient	$c_{Lmin} = 0.1$
Maximum lift coefficient	$c_{LMax} = 1$

Considering a kitesurf wing (Figure 4.8) with a 600m tether connected to a generator.

Figure 4.8 - Kitesurf wing $A = 12m^2$

Simulation results:

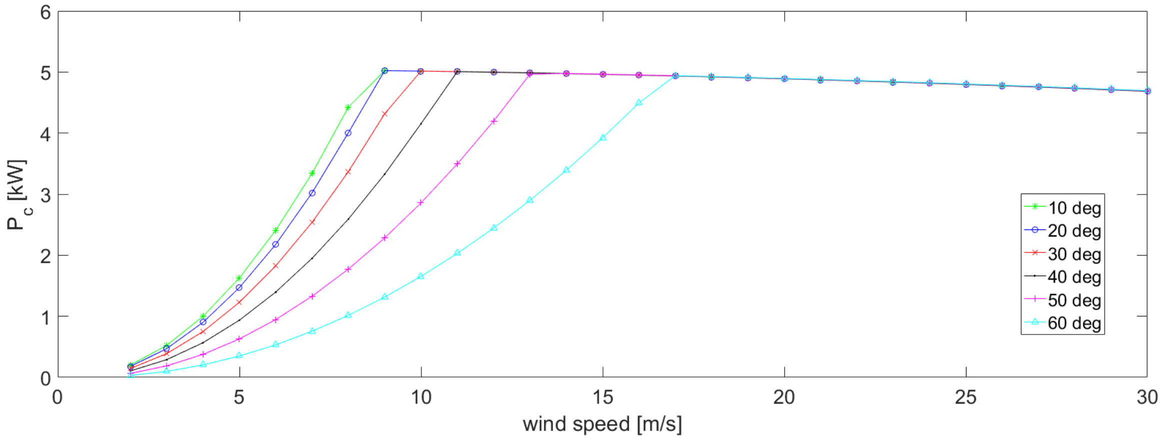


Figure 4.9 – Case 3 simulation – Power output at different kite elevation angles

Capacity factor

$$CF = 0.7796$$

Demand factor

$$DF = 0.6697$$

Annual energy production:

$$AEP = 24\ 015\ kWh = 65.79\ kWh/day$$

Average power output:

$$P = 2.74\ kW$$

4.5. ANALYSIS

Table 4.6 comprises the three case studies taken under consideration in this thesis. Analysing the data, it is evident the linear relation between Case Study 1 and Case Study 2, i.e. the greater the number of installed kites, the greater amount of energy produced.

Also Case study 3 signals the scale of this system, given that a small kite can provide an average power output of $2.74kW$ which is a considerable value considering the size of the wing ($12m^2$).

Table 4.6 - Case studies comparison table

	Case Study 1 (KitePower)	**Case Study 2 (Kite Farm 38 kites)**	**Case Study 3 (Off-the-shelf Kite)**
Kite wing area (m^2)	25	38 x 25	12
Generator rated power (kW)	20	38 x 20	7,5
Tether length (m)	400	400	600
Capacity Factor[4]	0.8543	0.8484	0.7796
Demand Factor[5]	0.6616	0.6616	0.6697
Annual energy production (kWh)	76 897 kWh	2 806 026 kWh	24 015 kWh
Average daily energy production (kWh)	211 kWh	7 687 kWh	66 kWh
Average power output (kW)	8.78 kW	320 kW	2.74 kW

[4] Capacity Factor - It is defined as the ratio of the energy actually produced by a wind turbine to the energy that could have been produced if the machine ran at its rated power.

[5] Demand Factor - It is defined as the ratio of the maximum load in a given time period to the maximum possible load limited by the wind.

Capacity and demand factors analysis:

Demand factor stays virtually unchanged in all 3 cases at 0.66, this indicates that the systems are able to harness a stable fraction of the wind power, regardless of its scale. The capacity factor is the same for case 1 and case 2 (0.85) and lower for case 3 (0.78). This means that AWE systems are well above the CF of the conventional technologies (typical 0.2-Photovoltaic or 0.35 conventional wind turbine).

Energy and power analysis:

The annual energy output is a very important indicator because it is directly related to the monetary yield of a power plant. Nevertheless, from the technical point of view, the average power output is a fast way to understand the potential of AWES, i.e. a relative small generator which is easy to deploy as well as to connect to the grid can easily provide approximately half its rated power (on average). This combined with the fact that high altitude winds are always present, are indicators that this system is quite feasible for ongoing operation. Nevertheless, there is always the possibility to enhance the uninterruptibility by connecting it to a UPS (Uninterrupted power supply) in order to guarantee a stable source of electric energy.

5. CONCLUSIONS AND FUTURE WORK

This chapter provides the work conclusions, as well as the future work to be carried out. Given the nature of this subject and its novelty character, it is of most importance to continue this work and achieve future conclusions in this field.

5.1. CONCLUSIONS

This work started by providing a state-of-the-art analysis regarding existing kite technologies as well as the previous work carried out by reputable authors in this subject. Hereafter, the renewable energy conventional technologies were presented in order establish a comparison base in terms of size and generated power. Followed by the characterization of both wind and water technologies organizing them by primary energy source and generator location with the inclusion of examples from the main players in this growing market. It has been made an approach to the modelling of kite systems both in 2D as in 3D, and the work was finalized with a generated power simulation based in real data for different case scenarios.

The importance of this work is notorious given the growth of decentralized electric energy production, combined with the growing need to resorting to clean renewable primary energy sources in order to respond to the increasing energy demands caused by factors such as the expansion of the world population and the penetration of the electric vehicle. This thesis compilates a series of loose information not yet available, which summarizes the state-of-the-art for kite power systems. Thus, enabling future work regarding this subject in order to facilitate and accelerate the development.

One of the most important conclusions drawn out of this work it is the number of companies which are in a late stage of development, and even in a commercial stage off promoting their products. Almost every company approached in this work, have created strategies to launch their products in the market - This was a conclusion extracted out of this work, that was not expected. Another conclusion, is that is possible to control a kite in mid-air with optimal control algorithms, thus enabling the best yield in terms of power output. It was also concluded that AWES decent capacity and demand factor, which is a very important indicator, when the economic analysis takes place.

We also intend to leave some review observations concerning this work – The decision of a single approach on AWES leaving UKPS on the side was taken under consideration because it would broaden the spectrum of the work and leaving it unwieldy. Nevertheless, it is a subject which has to be addressed in future work given the wide range of applications in which can be applied (See below 5.2.4 - Application of UKPS in hydroelectric plants).

Regarding this thesis proposed objectives, they were all achieved and exceeded. The goal of gathering all the disperse information concerning the existing concepts, working principles and other interest points were approached and even complemented with extra information which was a contribution to a better knowledge and understanding of the technology. As for the target of modelling an AWES and simulating real power outputs based on real data, this too was exceeded providing an extensive modelling of the system as well as three case studies in terms of power output simulation.

In my opinion this is an exciting subject which has tremendous potential for researchers, industries, utilities, and consumers. There is no doubt the systems work and are possible to implement, however there is much work to be done so that it can pass from the prototype perspective to the mainstream usage. To help further research and to summarize the work to be done, the next sub section summarizes the most issues with most priority to be considered in future work.

5.2. Future Work

Given the early stage of both wind and water kite technologies, there is plenty work to fulfil in order to ensure the materialization of these concepts. Based on the assumption that the mathematic model is feasible enough given its reduced margin of error when compared to real-world experiments. There are some subjects which should be studied in order to continue the validation of these systems as a common source of clean electric power.

Given that this thesis mainly approaches the Airborne kite energy systems, it would be interesting to develop the Tethered underwater kite energy systems in order to apply this technology not only at an oceanic level, but also in water streams making use of the existing dams and water reservoirs with less visual impact than a wind kite.

There are two major groups of analysis to perform which would be an important contribution to the development of kite systems.

5.2.1. Financial and economic analysis

Budgeting: All projects must have detailed budgets specially the ones which incorporate new concepts and state-of-the-art technologies. The imponderable costs, the unaccounted items, and a poor cost structure contributes negatively to a viable economic analysis and are susceptible of ending a research and development project even before it starts.

It would be fruitful to produce a detailed budget, with a reliable cost structure in order to advance to the next item in the future work list.

Levelized Cost of Energy (LCOE): Obtaining all the costs required to the implementation of a kite system and using the yearly energy output data it would be very interesting to have a trustworthy work in which is possible to compare energy costs of different solutions in order to evaluate kite systems position facing conventional technologies.

Economic viability study: Using the above data, an economic viability study should be produced in order to assess the quality of this investment, enabling thus its scaling into the energy market and its mass usage. It would be of most importance the significance of maintenance and operational costs to this system, to fully predict the financial costs of this type of structure.

Besides this analysis, it would be of most interest to establish a cost/benefit comparison work between a solar photovoltaic (PV) system occupying the same area, in order to evaluate the feasibility of this solution as an alternative to a PV power plant.

5.2.2. BASE AND DETAIL DESIGN ANALYSIS

Base design: Regardless of the wind energy potential to produce electric power, there are some technical issues that should be carefully addressed in order to maximize the system global efficiency in order to provide the best possible structure.

The electric machine (Generator), there are several options to implement a generator in a kite power plant. However, the reel-in and reel-out particularities (among others), require a very detailed evaluation of the machine type to be used so that the best yield can be achieved.

Tether, wing, and control surfaces, given their specific functions should be evaluated in terms of material considerations to maximize efficiency and reliability.

Reliability studies: Electric power systems are known to be resistant to change. One of the main reasons for this, it's the proven reliability of the existing technologies and systems, therefore it would be of the greatest importance the creation of reliability analysis targeting electric power systems.

5.2.3. WATER MODELLING AND SIMULATION

It is of most importance the behaviour analysis of a UKPS – Tethered underwater kite energy system. This system shows a high potential of energy harvesting, and the application of UKPS should be deeply analysed and simulated for both sea and river applications based on real data.

5.2.4. APPLICATION OF UKPS IN HYDROELECTRIC PLANTS

The existing hydroelectric plants harness the water kinetic energy returning it to the stream still with relative speed and energy. This energy can be used to power up an underwater kite energy system, with the advantage of being close to the electric energy injection point. Thus, significantly increasing the yield of a hydroelectric plant of both types - reservoir and run-of-river.

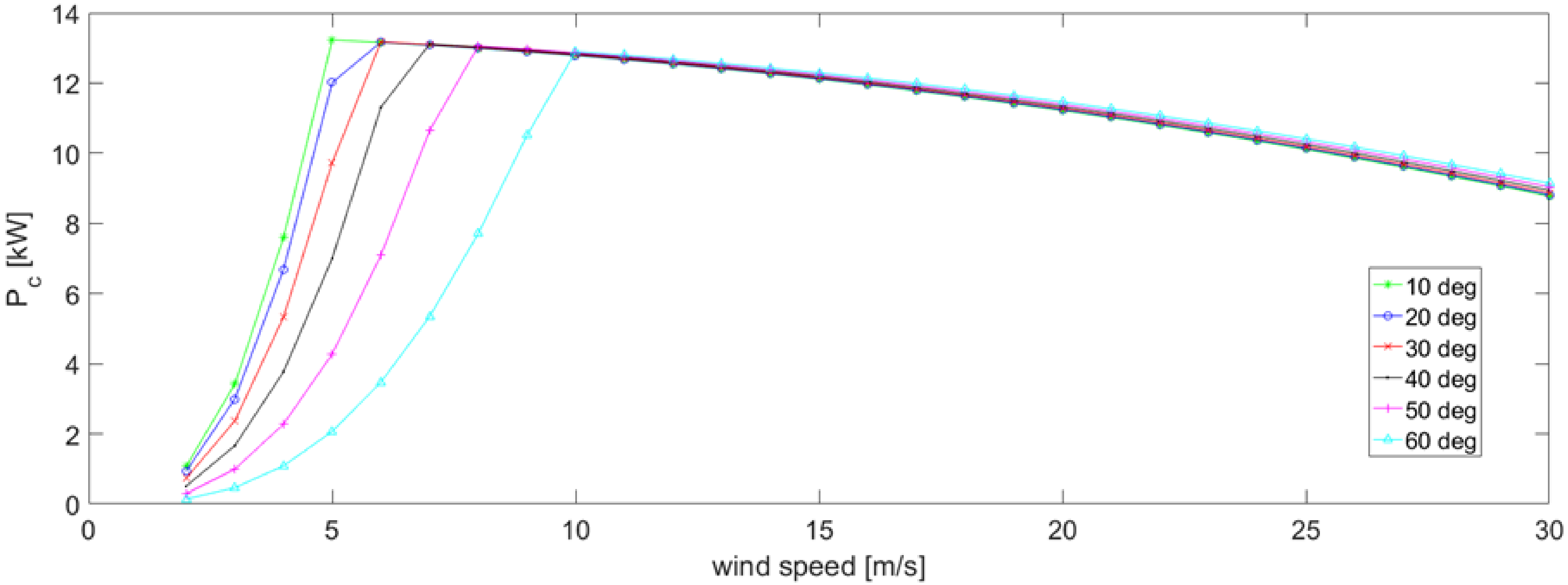
6. APPENDIXES

Appendix A. Wind data (partial) considered in the simulations

Period (minutes)	Temperature @ 80m [deg C]	Relative Humidity [%]	Height (m)	Avg Wind Speed @ 80m [m/s]	abs-Avg Wind Speed @ 80m [m/s]	Avg Wind Direction @ 80m [deg]
5	13,5150	282,3400	80,0000	-8,3643	8,3643	26,130
10	12,3100	268,5000	80,0000	-8,3549	8,3549	26,290
15	12,3240	288,2600	80,0000	-8,3213	8,3213	25,924
20	10,9590	282,2400	80,0000	-8,3750	8,3750	25,429
25	12,3210	295,1600	80,0000	-8,4477	8,4477	25,036
30	13,7700	284,1100	80,0000	-8,4352	8,4352	24,716
35	16,9240	291,7600	80,0000	-8,4455	8,4455	25,161
40	15,7870	292,0300	80,0000	-8,3015	8,3015	24,882
45	15,8960	277,5600	80,0000	-8,2350	8,2350	24,527
50	12,7860	285,9600	80,0000	-8,2147	8,2147	24,724
55	14,9620	280,1600	80,0000	-8,2883	8,2883	24,884
60	14,2350	281,4700	80,0000	-8,2778	8,2778	24,814
65	15,4830	289,5900	80,0000	-8,2239	8,2239	24,576
70	15,5730	280,1400	80,0000	-8,1889	8,1889	24,635
75	12,6410	286,8300	80,0000	-8,1468	8,1468	24,334
80	14,7990	287,1500	80,0000	-8,0924	8,0924	24,266
…	…	…	…	…	…	…
525600	9.5622	276,0700	80,0000	5,0578	5,0578	53,036

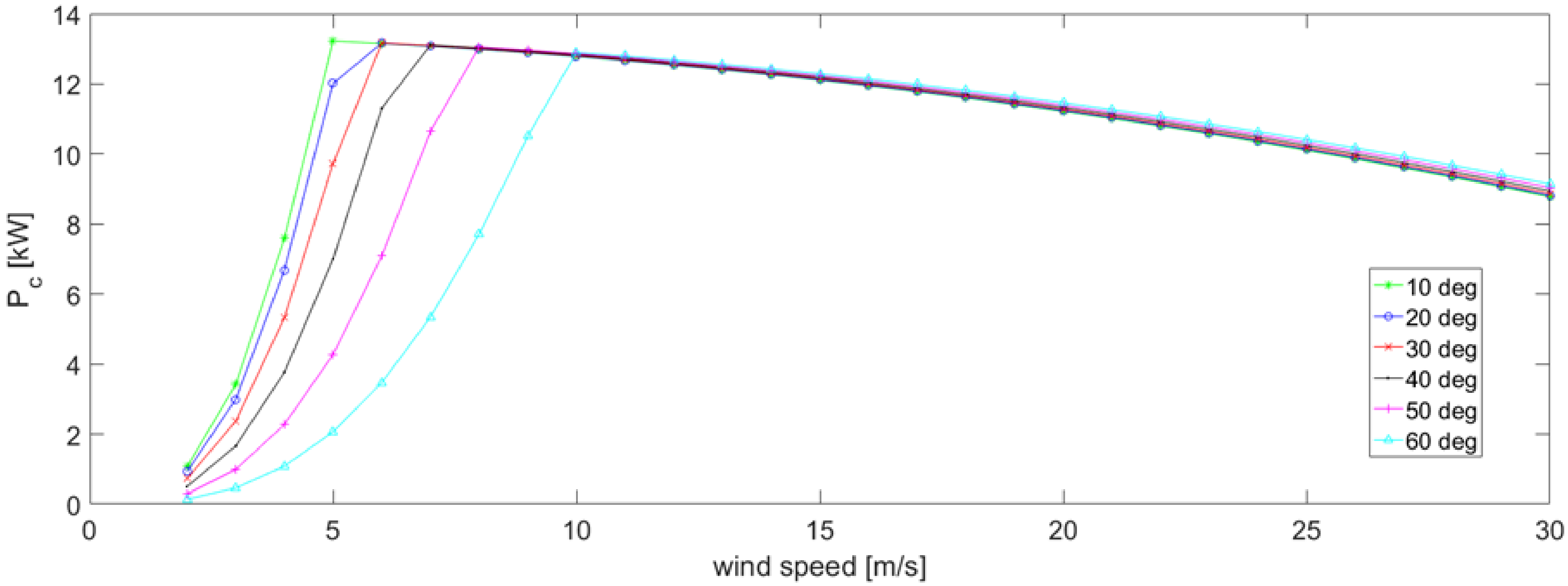
Appendix B. Kitepower simulation – Power output curves at different kite angles

(Figure 4.6 – Case 1 simulation – Power output at different kite elevation angles)



Appendix C. Kitesurf wing simulation – Power output curves at different kite angles.

(Figure 4.9 – Case 3 simulation – Power output at different kite elevation angles)



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