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Acoustic impact of airborne wind energy technology on the environment

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Abstract

The number of the renewable energy systems is continually growing as a consequence of the increasing energy deficit. Wind energy is one of the most promising types of the renewable energies, therefore, there is no wonder that many airborne wind energy harvesting systems are available today. The goal of the airborne wind energy systems (AWES) is to harvest energy from the upper-boundary layers thus ensuring more permanent renewable energy source by decreasing the influence of the weather on the working period of the wind technologies. But like all man made devices, AWES also have impacts on our environment which is emphatic regarding the damages additional to the current impacts. The questions are: *what is the environmental footprint of this technology; and what is the specific environmental footprint of the prototypes?*

To answer these questions, firstly a sufficiently well developed prototype is needed to study the effects on the environment. On examining the literature, it is observed that acoustic impact is the most notable impact of the AWES. Due to the lack of data, a set up to acquire the noise emission data from the system and also to compare the acoustic level with the conventional wind turbines and a few house-devices was developed.

In the end, the first results about the acoustic impact of an airborne wind energy system were obtained. The predominant acoustic source proves to be the flying kite, ahead of the generator and the tether. Comparing it with a conventional wind turbine ensures us about the environmental friendly being.

Consequently, the airborne wind energy systems are one step closer for commercial exploitation with my result which prove with numbers that the technology has factually low-environmental acoustic impact.

1. INTRODUCTION

1.1. Historical background

Our energy sector is bigger than ever in our history. In the 21st century, Earth's population is steadily growing which results in the need more and more energy. The energy resources are classified as renewable and non-renewable energy sources. Unfortunately, the energy density of renewables – wind, sun, water, geothermal energy and biomass/biogas – is less than the energy density of non-renewables. So, most of our energy needs are satisfied by coal, oil, nuclear and other non-renewable sources. But the problem with them is that the non-renewables technologies have a lot of additional by-products which damage our environment. Well-known examples of harmful by-products are carbon dioxide (CO2), carbon monoxide(CO), methane (NH4), nitrous oxide (N2O), and several other combustion by-products which primary and constantly cause and raise the greenhouse effect, and through this, the global warming. This led us to rethink how we produce our energy, and we started to invest in the renewable energy sources. [1] [2] [3]

Wind is the natural horizontal movement of the air in the atmosphere of the Earth. We have been using wind as an energy source for thousands of years. There are several technologies and devices with we can transform the movement of the air to energy. Firstly, we built sails to using the power of the wind. Secondly, we created windmills to extract power on the ground from the wind. Windmills were used to lift water or mill the grain in the early ages. We have already had records from the 7th century about the different types of windmills. In the 1700s, there were more than 8000 windmills existed just in Netherlands. We have been using wind as an electric power source since the 20th century. Nowadays, we improved windmills to wind turbines to convert kinetic energy to electrical energy. The share of wind energy in the global energy economy is steadily increasing. However, we encounter physical constraints. The velocity of the wind is not sufficient everywhere. Especially in the midland, wind speed is not enough to operate a wind turbine. For instance in Hungary, using wind as an energy source is economically challenging. Nevertheless, we know that wind velocity generally increases with altitude. In the upper layers, there is nothing which can increase the wind speed, unlike in the lower layers where mountains and buildings diminish the wind velocity. As a result, we should go higher, where wind speed is more constant and stronger. Awareness of this knowledge, we have built more than 200-meter tall wind turbines, but it is still not enough, and the physic does not allow to us to construct larger turbines. It seems like the limit of this technology has been reached so it was the time to figure out how we can harvest the wind of the upper layers. There are several promising technologies under development these days, and their aim is the same. Using wind as a constant and reliable energy source, achieving this with harvesting wind from 300 meters altitude and higher; they are the airborne wind energy systems. [4] [5]

1.2. Objective

The purpose of my dissertation is to explore the environmental impacts of the airborne wind energy system using prototype of Kite Power company. The first aim of this test campaign is to collect information about the total acoustic emissions of the entire AWE system, i.e. generator (ground-station), tether and kite on the ground surface. Thereby, proving that the kite does not have a serious negative environmental impact, so it has the low environmental footprint. Addition to this, the identification of the dominant noise sources of the Kite Power's system and take an evaluation of the acoustic source differences.

2. LITERATURE REVIEW

2.1. The formation of the wind

Wind is generated by the effects of air pressure, which is due to the different solar irradiance on the earth surface and the Coriolis force from the Earth's rotation. Close to the Earth's surface, the air is heated by the sun, so the density of this air reduces which causes natural convection (vertical movement of air). However, in the higher altitude, colder air has higher density with higher pressure. The differential pressure wants to equalise, so the cold air gushes with high pressure to the place of warmer air which generates the air to move horizontally. We name this movement as wind. [4]

The Earth's atmosphere consists three permanent, interconnected systems (Figure 1.). Northeast Trade Winds are formed along the Equator in the Hadley cell, where the incoming angle of the sun rays is the highest. These are the cold, dry winds which cause the wet weather along the Equator and the arid one around the Subtropical high-pressure belts. The Westerlies are created by cyclones and anticyclones which are drifted by the Coriolis force. Thus they patrol on a vast area between the Subtropical high-pressure belts and Polar belts, also known as the Ferrel cell. The Polar Easterlies are the most changeable winds on our Earth; there are anti-cyclones which are generated by the pressure differences between the low-pressure equatorial areas and the high-pressure Polar areas. The three wind system are not separated from each other; there is no concrete border of them. They are one entire, permanent and complex system. As we can see in Figure 1, between the idealised and actual global wind pattern, there is little difference. The reason is the surface of the Earth which also influences the air-pressure, thus the air movements. [6] [7]

Along with permanent winds, local and temporary winds can also be considered. These type of winds are environment-dependent, and their strengths cannot be predicted. So they cannot be utilised for energy production. Such as monsoon winds, Sirocco in Sahara or Mistral in France and several others. Beyond the above ones, there are "special" winds, for example, the feverish tornados or the typhoons or hurricanes which also called as the Great Wind. Although their power is significant, there is no elaborated solution to utilise them as an energy source. [6] [7]

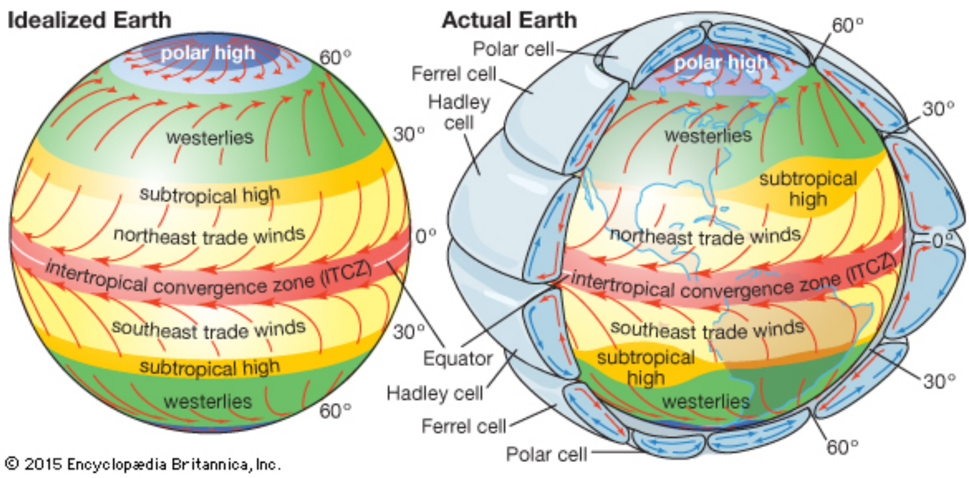

Figure 1: Global wind pattern effects. Source: website of Encyklopeadia Britannica: intertropical convergence zone (ITCZ) | meteorology; https://www.britannica.com/science/intertropical-convergence-zone

Summing up, the wind has several different formations because wind pressure can quickly and easily change by many impacts; for instance current weather, surface, local climate. This causes that we can harvest the wind reliably only in a few area, in turn we know that there is more recoverable energy in the wind.

2.2. Working ability of the wind

The wind is a free and non-polluting energy source and humanity will never run out of it. However, there are three main facts about wind's behaviour which we need to know if we want to utilise it. [8]

Firstly, the working ability of the wind is proportional to the cube of wind speed which leads to the fact that stronger wind means much more power. With Hellmann methods, we can estimate the wind velocity on a given altitude. The wind is unfortunately not steady; therefore we obtain the averages of the measured values in 10 minutes. However, averages wash away the differences between wind gusts and wind lulls, thus estimate the wind speed for a fix duration is hard, but we try to measure it more densely. For more accurate estimates and time coverage, Weibull distribution is most frequently used. With this data, WasP-models were generated– also known as wind atlases. Nowadays in the European Union, the WAsP models are produced by the Danish Risø Laboratory (Figure 2). With this models, the utilisation's value of the wind in a given area can be estimated. According to the model, the basic flow is determined by the obstacles around surface and roughness of the environmental terrain. The actual weather on this areas is also known, so specifying the differences give the value of the base flow. [9] [10]

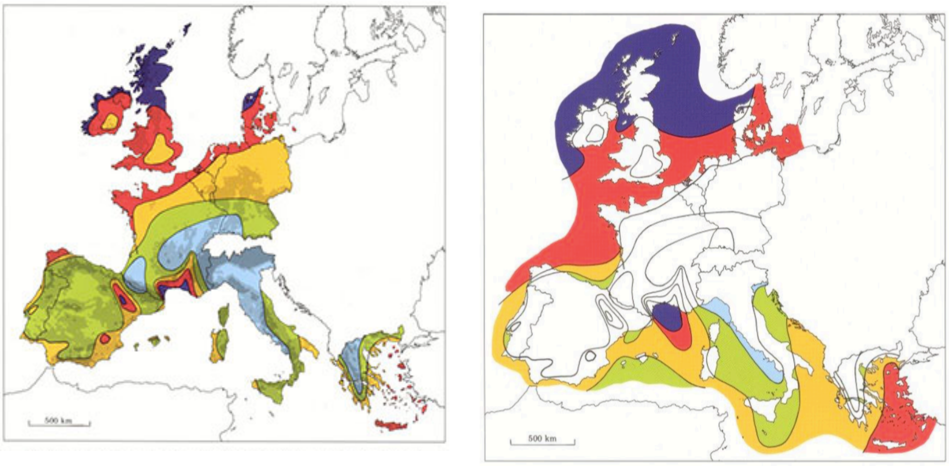

Figure 2: left: on-shore WasP, right: off-shore WasP – Source: European Wind Atlas. [10]

Secondly, on WasP models, the problem of the roughness is also appeared spectacularly. In the middle of the land, the wind speed is lesser than on the off-shore areas where the wind can blow without limitation; there is no obstacle which can decrease the wind velocity. On the contrary, the wind is obstructed by many barriers while flowing towards midlands (Figure 3 and 4). Causing that wind speed is much slower in this areas and harder to utilise it. As a consequence of roughness of the surface, producing electricity from the wind is more efficiently possible on the edge of the land, closer to the sea. On Figure 3 and 4, it is outlined that the power potential of the wind decreases due to the obstacles on the land and the roughness of the surface, while we are passing inside of the land. It is clear that wind is more steady higher up in the atmosphere. We call this as the constant flux, planetary, boundary layer, where the wind is closely stable. [9] [11] [13]

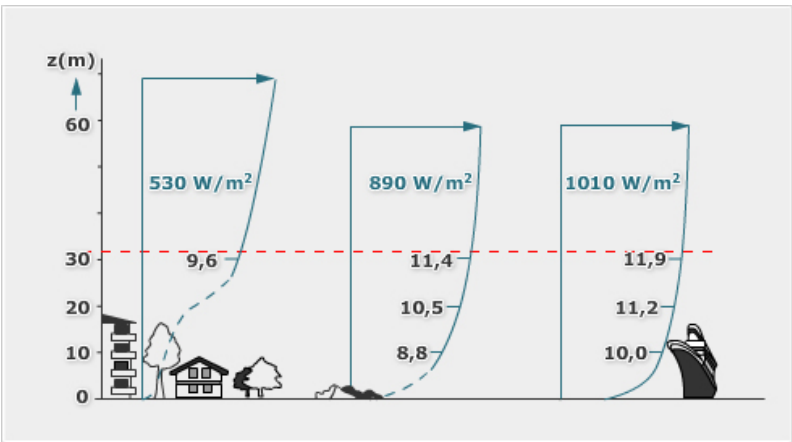

Figure 3: Windprofil. Source: EWEA 2006

Figure 4: Global wind power potential. Source: Dr.Tóth László – Dr.Horváth Gábor: Alternatív Energia, ISBN 963 9553 03 4

Thirdly, the theoretical power of the wind is directly proportional to the density of the moving air mass, perpendicular to the direction of travel ("scrubbed") and the third power of its velocity. However, the velocity of the wind on the two sides of the rotor can not be zero. Thus we can not convert this theoretical performance 100%. The law of Betz in 1926 stated that our wind power plants could only transform 16/27 of the kinetic energy (about 59%) of wind into mechanical energy. This is the ideal "performance value". In practice, this further reduces the loss of additional machine components. [8] [9]

To sum up, using the wind as an energy source is not as easy as it seems. It is hard to predict it in a fixed area. It is not permanent. However, we can evaluate of the wind speed which already is enough to deploy the windmills efficiently. It is known that above 400 meters the wind velocity becomes more permanent, so the aim is simple – going higher. [8] [9]

2.3. Technologies to utilise the wind as energy source in nowadays

According to Albert Betz the theoretical maximum electric power of the wind power plant (P_{max}) equals with the multiplied of the the third power of the wind velocity (v), the surface which is swept by the rotor of the wind turbine (S) and the air density (ϱ); which is multiplied by ½ and 16/27 (Cp_{max}). Betz wrote the next context:

$$P_{\max} = \frac{16}{27} \cdot \frac{1}{2} \cdot \rho \cdot S \cdot v_1^3$$

where:

- P_{max}= maximum electric power of the wind power plant [W]
- 16/27= maximum value of the 'power coefficient' =Cp_{max}
- ϱ= air density [kg/m^3]
- S= swept ares of the wind turbine's rotor [m^2]
- v= wind velocity [m/s]

Higher wind speed means more electric power. George Gustav Hellman found that the wind speed increases with altitude. Therefore, it is logical that we want to go higher and harvest the high altitude wind in the constant flux layer. However, the size of the wind turbine including the blades should be increased because according to Betz's equation, bigger surfaces increase the power produced. In the end, higher altitude with a bigger wind turbine means stronger wind speed, more power and also more stress[1] on the structure. The higher stress levels limit the height of the wind turbine to 220 meters[2]; the lifetime of these turbines significantly reduce. The force on the elements of the turbine will be too high, and there is no structure and material which can survive the effect of the natural forces. In this case, we can say that height of the wind turbines cannot be increased more statically. The physical laws limit their size; therefore using wind energy as a renewable power source is also limited. [5] [9]

It is apt to mention vertical axis wind mills here. They got their name due to the vertical position of their axes of rotation. We use this type for small scale electric power production. Their structure does not allow them to be built bigger because with vertical axis the structure becomes unstable which increases proportionally with the size of the system. However, they have some significant advantages; they don't have to be turned to match the wind direction, and with magnets, we can decrease their starter speed. Thus they are perfect to fulfil smaller energy needs (about 3-5 kW), or simply they can help to reduce our electricity bill. And it is also necessary to have a few words about the control and service system which is based on the ground, so it is easier to manage it. But unfortunately, the fact about their low efficiency cannot make it possible to use them in the same way, as the horizontal wind turbines. [12]

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[1] For example, the surface of the turbine eroded faster, the centrifugal force increases which cause more force on the structure, it is necessary to use a stronger braking system, but it has got limit too, etc.

[2] The world biggest horizontal wind turbine is 220 meters (722 ft), and its blades are 80 meters long (263 ft) which was built by MHI Vestas Offshore Wind company. Source: website of the Wind Power monthly – The ten biggest turbines, http://www.windpowermonthly.com/10-biggest-turbines

2.4. Opportunities in wind

In spite of reaching the physical limits of the wind turbines, we are still extremely interested in the wind as an energy source. Incidentally, the wind is one of the clearest power source. During the utilisation, there is no extra produced waste and also necessary to mention that there is no need for the use of cooling water. Unlike nuclear energy, where maintaining the system requires a lot of cooling water, which also becomes sewage and requires treatment, plus handling of the polluted radioactive waste is still unsolvable. [13]

The wind is also free; continuously and quickly renewable which decreases the costs significantly. Installing a system is the most expensive part of the utilisation of the wind. However, after installation, the operation costs are quite low (in comparison to other power sources). In addition, the wind turbines require smaller area than any other renewable or non-renewable facilities. [13]

Although the wind has several advantages, the only disadvantage is that under 300 meters, wind is not constant. The rapid change in the direction or the strength of the wind, a powerful gust and how these changes affect the power production should be considered. Thus it is hard to connect to the electrical network. And also due to the geographical location, it is not available everywhere for everyone. It is also difficult to predict the power output from the wind accurately. [13]

The wind is the clearest and cheapest energy source what we have on the Earth, but it is also the most capricious and unpredictable natural resource. The next table sums up the advantages and disadvantages of the wind as energy source (Table 1).

Table 1: The advatages and this advantes of utilise wind as an energy source

The wind energy	
Advantages	**Disadvantages**
— The wind is free — No further energy source; only wind — No waste is produced during the operation — No pollutant emmision during the operation — The sturctures leave a smaller carbon footprint. — The operation costs of the wind turbines is low	— The wind is not constant and reliable. Consequences: — It is not available everywhere — Hard to connect to the electrical network — Hard to predict

However, above 300 meters, the behaviours of the wind changes. It becomes more consistent and predictable. Additionally, the wind speed increases too; and as mentioned above, higher wind speed means more power. The average wind power density is four times more at 50-150 meters above the ground, and more or less 40 times higher at 10,000 meters. In Figure 5, the differences between average power density of the wind at 120 meters and 600 meters can be observed. Unfortunately, the upper layers of atmosphere cannot be accessed with wind turbines. [14] [15]

It gave the first push to overthink the utilisation of the wind. And in the end, it led us to create the airborne wind energy systems.

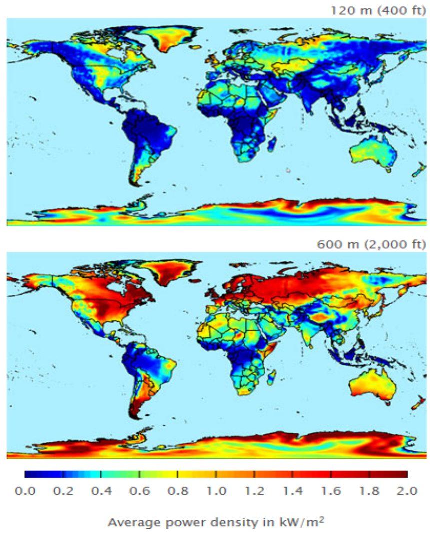

Figure 5: The avarage power density in kW/m^2 on 120 meters (top) and 600 meters (bottom) Source: website of the JobyEnergy.

2.5. Airborne Wind Energy (AWE) systems

Airborne wind energy systems (AWES) are defined as a high–altitude wind power technology. The upper boundary layer caught the attention of many engineers all around the world. Therefore, there are several types of the AWES worldwide by many companies, research centres and universities. Their concepts are maybe different; however, their aim is always the same; harvesting power from the wind at the upper boundary layer. In this chapter, an introduction to the basic working principles and some examples to illustrate the diversity are described. [16]

2.5.1. Classification of AWES

An airborne wind energy system usually has three main components; a ground station and one aircraft which is mechanically (or sometimes electrically) connected by rope(s), also known as tether(s). If the electrical energy is produced by the ground station, called Ground-Gen airborne wind energy system. In this case, the aircraft generates the traction force for the drum of the generator by the tether; this converts to mechanical energy to electrical power. The aircraft is controlled by a control unit from the ground station. Also, it is important to mention that either flexible wing aircraft or rigid ones can be used, it depends on the preference of the user or designer. Additionally, there are different types of ground stations; fixed (the generator fixed to the ground) and moving ground station (the ground station is a moving vehicle). [16]

Another type is fly-gen AWES. Their main disparity from the Ground-Gen system is that the electrical energy is produced on the aircraft and it is conveyed to the ground station by a special tether. Fly-Gen systems generate the energy from the cross-wind or non-crosswind, so we can also contrast them, it depends on how they bring about the power. [16]

So what makes the system an AWE? Technology becomes airborne wind energy system when an aircraft use the kinetic energy of the wind, which causes traction force on the tether; the rope is connected to the drum which converts the energy to mechanical power and in the end, via the generator, to electrical energy. Or if we have an aircraft in a high-boundary layer with turbines which generate electrical power on the aircraft and it is delivered to the ground station; we also talk about AWES. There are several options to create an airborne wind energy system. Thus all prototypes are unique. Different systems have different efficiencies. On Table 2, there are some examples for AWES with their main attributes and their producers can be seen. The diversity between prototype's efficiencies resulted by the market. Companies and their systems aim distinctive possible users; thus their attributions are variable too.

Table 2.: Examples of planned airborne wind energy systems and their attributions. (self-edited[3])

Name of the company	Rated Power	Ground station	Position of the generator	On-shore/ off-shore	Airborne system	Main force / flying principle	Actuators	Number of the ropes	Energy generation system
SkySails Power	1,5-3 MW	Fixed ground-station	Ground-Gen	Off-shore	Foil kite	Lift	On the aircraft	1	------
Twing Tec	100 kW	Fixed ground-station	Ground-Gen	On-shore	Glider with rotors	Lift	On the aircraft	2	------
Ampyx Power	50kw – 2MW	Fixed ground-station	Ground-Gen	On-shore	Glider	Lift	On the aircraft	1	------
EnerKite	30 kW	Fixed ground-station	Ground-Gen	On-shore	Foil kite	Lift	On ground	3	------
		Fixed ground-station	Ground-Gen	On-shore	Delta kite	Lift	On ground	3	------
		Fixed ground-station	Ground-Gen	On-shore	Swept rigid wing	Lift	On ground	3	------
Kite Power	20 kW	Fixed ground-station	Ground-Gen	On-shore	Leading edge inflatable kites	Lift	On the aircraft	1	------
KiteGen Research	3 MW	Moving ground-station	Ground-Gen	On-shore	Leading edge inflatable kites	Lift	On ground	1 kite = 1 rope	------
Altaeros Energies	30 kW	Fixed ground-station	Fly-Gen	On-shore	Turbine on 'a lighter than the air' balloon	Buoyancy non-crosswind	------	1	1 turbine
Joby Energy	2 MW	Fixed ground-station	Fly-Gen	On-shore	Turbines on a tether aircraft	Buoyancy non-crosswind	------	1	Several turbines
Makani Power	20 kW	Fixed ground-station	Fly-Gen	On-shore	Turbines on a tether aircraft	Wings lift	cross - wind	1	6/8 turbines

[3] Data were collected from: [16] [17] [18] [19] [20] [20]

2.6. Utilization

On Table 2, the rated power of different prototypes are mentioned. This rated power depends on the needs of the consumer. Due to the diversity in the AWES systems available, they can be utilised around the world for various purposes. Additionally, because of their design, we have more freedom to use them in different situations. [16]

An airborne wind energy system does not occupy a large space on the ground; usually, 20 m^2 is enough for the ground station. However, it is indispensable to ensure enough space in the air for it. Thus, while considering the utilisation of AWES, the first thing to be aware of the space which the chosen system requires – for instance, a 20 kW system of the KitePower company needs 20 m^2 place on the ground for the ground station and the flying area is 120x120x400 meters. In this case, the AWES with similar space needs are perfectly useable on the agricultural fields. The kW power classed AWES can ensure energy for the buildings in an agricultural area; at least reducing the electrical bills. Meanwhile, they do not disrupt the farming activities because of their small place needs on the ground. These kind of AWES can also be useful for the military insomuch as the mobility of this systems. Additionally, they can fulfil the energy needs of a mine or a similar industrial facility. Airborne wind energy systems in MW class were usually designed only for electric power producing. Their construction is more complicated because of the bigger size. For example; SkySails Power plans an off-shore wind farm with their AWE system, and there is Joby Energy's prototype which needs similar space as mentioned before, however, this system contains little turbines on the aircraft. These types, just like wind turbines, are made for producing energy and being connected to the power system. Turbines are not able to produce power constantly because of the wind is unstable under 300 meters. However, with AWES the upper boundary layer of the atmosphere becomes accessible and wind can be used as a constant source of energy. This makes the connection to the power system much easier. [22]

Summing up, two main attributes should be considered when deploying an airborne wind energy system; the place and space needs and their rated power. AWES make possible to use wind as a constant energy source; but the question is, what is their impact on the environment?

2.7. AWES impacts on the environment

Airborne wind energy systems have several impacts on the environment. But which of them are significant is to be determined? AWES are relatively new technology, and most of them are in the test period, so until now, there has been less focus on their environmental impact. However, the prototypes are closer for commercial exploitation, and most of the countries have environmental legislation which might be relevant for the AWES projects. Thusly, we need to confirm that the systems have factually low-environmental-footprint.

An airborne wind energy system always claims a lot of space in the air which will cause that they can be in the way of the birds (and bats). The aircraft is constantly moving with the thin tether which makes it difficult to see for the birds; the result can be a fatal collision. Bird mortality is a well-known parameter in the airspace fields. Unfortunately, it is inevitable not to hurt the birds, inasmuch as we use there living-space. And the tether makes noise too which can have an unfavorable environmental impact on flora and fauna. Alongwith the tether noise, ground station generator generates constant noise around too. These noises can also have effect on the environment. On the other hand, AWES do not have pollutant emission, and they do not produce any waste; which makes the airborne wind energy systems more promising. However, it is time to affirm it with some results. [23] [24]

With this, it is safe to say that the most relevant impacts of the airborne wind energy systems are bird mortality and the noise emission; these impacts are discussed in the next chapters.

2.7.1. **Bird mortality**

As mentioned above, AWE systems use the air; Therefor, the phenomenon of bird mortality should be considered into account. An AWE system has two main parts which can be dangerous for a flying bird; the tether and the aircraft. These two components can be in the way of the birds, while they commute or migrate which can lead to a fatal encounter with the tether or the aircraft. The risk zone is where they encounter these two elements. Spending time in the danger zone raises the chance of the collision. And the time that they spend in this area depends on their flying behaviours[4] and their size. In this case, the chance of deadly encounter depends on these parameters mainly. [24]

Mortality by tether:

The risk of the collision with the tether increases proportionally with their size and their velocity too. Bigger bird means larger contact area which can lead to the unwanted confrontation easier than with a smaller body. Additionally, when the speed of the bird raises, also the fatal completion of the collision will increment. What is more, flying habit of the birds also merge their encounter with the tether. The bird who just fly across straight of the risk zone, spending there less time than the bird who not. This results that the birds – who just fly directly through on the risk zone – have less chance to collide with the tether. But we also need to know that sometimes the collision with the tether does not end with death for the birds (or bats). [24]

Mortality by aircraft:

[4] Flying behavours = different species may have different flying habits. They fly on different altitude or they can fly in different way –straight, in circles, random, etc.; and also they fly with different speed.

Collision with the aircraft is more lethiferous; however, there are fewer species which fly above 400 meters. As discussed above the chance of the confrontation with the tether is influenced by flying behaviour and size of the birds. Unfortunately, the chance to survive an encounter with the aircraft is less than it was with the tether; but it may be compensated by the fact that the higher altitude means fewer species which can collide with the aircraft. [24]

The Ampyx Power company made the first review the ecological aspects of airborne wind energy system in which they concluded that their PowerPlane prototype – with 1 km long tether, motorized airplane and which one is working constantly all year round. Their results are impressive. They concluded that 2-13 birds will collide with the aircraft annually. With the tether, they assume that about 11 birds will encounter per year. In total, according to their research, the system will cause 13-24 fatal collision annually. It should be considered that the system probably will not be able to work constantly over a full year (sufficient wind force, service time); thus the number of the bird mortality will probably decrease. Additionally, there is evidence that birds can survive a confrontation with the tether without damage. Their numbers made possible to create the first comparison with conventional wind turbines. The mortality by wind turbines depends on their location; thus it is hard to give an average number of the caused mortalities annually worldwide and it would be absurdity because of the differences between the wind turbines would be too blurry. However, giving average by regions still ensure comparable data. On Table 3, we can see an example from the US wind turbines and their mortality rate. [24] [25]

Table 3.: Estimates of bird mortality annually due to wind turbines in the U.S. (self-edited[5])

Region	Total # of turbines	Total mortality	**Mortality per turbine**	Total MW capacity	**Mortality per MW**
California	13,851	108,715	**7.85**	5796	**18.76**
East	6,418	44,006	**9.86**	11,390	**3.86**
West	5,757	27,177	**4.72**	9590	**2.83**
Great Plains	18,551	54,115	**2.92**	29,896	**1.81**
Total U.S.	44,577	234,012	**5.25**	56,852	**4.12**

As the example shows, the bird mortality in wind turbines case, similar with the results by Ampyx Power company. There is a several studies and research which prove that mortality by turbines is inevitable fact; unfortunately, producing energy by wind is clear, but this is an impact which we cannot be avoided, only

[5] Data were collected from Scott R.LOSS, Tom WILL, Peter P.MARRA: Estimates of bird collision mortality at wind facilities in the contiguous United States. [25]

minimized. But wind turbines still kill less birds than cats, or our buildings, power lines, and communication towers. [25] [26]

2.7.2. Noise from the AWE systems

AWES were made for using high altitude wind. Thus they are wind energy technology which makes them part of renewables. However, there is no technology, device or activity which does not have an effect on our environment. AWES are a promising technology, but their environmental impact should be considered. There is no previous study about the acoustic impact of the AWES.

There are three components of an airborne wind energy system which can be the source of noise – the generator, the tether and the aircraft. Although there was no supportive evidence for this. The frequency and SPL[6] (dB) of the average noise is not determined yet. Obviously, the noise depends on the measuring system. However, as mentioned before, there is no published study about it currently. I had an opportunity to measure the noise of the Kite Power prototype; thus measure foremost the acoustic impact of an AWE system.

[6] Sound Pressure Level; in decibel

3. MATERIAL AND METHODOLOGY

3.1. Study Area Description

As described above, there are many types of the airborne wind energy systems. The prototype of the Kite Power company uses the inflatable wing, and their tether is made from a flexible, robust and lightweight material. The generator based on the ground-level, where also the facilitates servicing bases. This structure is ideal for being a mobile wind energy system. A teleoperated airborne unit is responsible for the flight of the kite. The kite can attain higher altitude far beyond the limit of traditional wind turbines which is usually 200 meters. The capacity factor of the conventional wind turbines is 20-35% at this altitude. In contrast, the kite can fly above 200 meters where the wind is more permanent and stronger which eventuate that the capacity factor increasing to about 60%. [27]

But how does it work? „The system is operated in periodic pumping cycles, alternating between reel-out and reel-in of the tether"[7]. The kite flies figure-eight manoeuvres at high speed (about 70 to 90 km/h) meanwhile the reel-out period. These results in a high traction force which is converted into electricity by the tether and the connected 20 kW generator. The average traction force is 3.1 kN at 7 m/s wind speed. When the kite pulls out the maximum length of the tether, the kite is de-powered by releasing the rear (steering) lines. Due to this movement, the whole kite rotates and aligns with the current wind. The generator is used as a winch; thus the kite pulls back to the original position and starts the next pumping cycle. De-powering decreases the traction force during reel-in, and because of this, the consumed energy during the reel-in is only a small part of the energy which generated during reel-out. The radical part of the technology is the automatic control and synchronisation of the generator module with the flight dynamics of the kite. [27]

3.1.1. Required sources

General setup devices

- A laptop with a Windows MS; windows noise/voice recorder
- One Philips microphone SBC MD650
- One tape measure (25 meters)

Hardware and software

- Laptop with MS Windows
- Sound recorder
- Philips microphone SBC MD650

[7] Website of the Kite Power [27]

- MatLab

3.1.2. Progress of the measurement

To achieve the aims, a set up which can ensure to us to measure the full acoustic noise of the kite and the environment, and which allows to identify the source of the noise later in the analysing data part is needed. There are three acoustic sources of the kite power system. First one is the generator, the second one is the tether and the third source is the flying kite. To identify the origin of the noises, measurements should be taken at different points under the working kite. On Figure 6, it is seen the microphone points which illustrate the measurement plan. The first measurement point is set 5 meters away from the generator. The second is placed with 10 meters away and the third points 25 meters away from the ground station. The fourth, fifth and sixth points are located 75-, 100- and 200 meters far from the generator. The six points are based on one straight line.

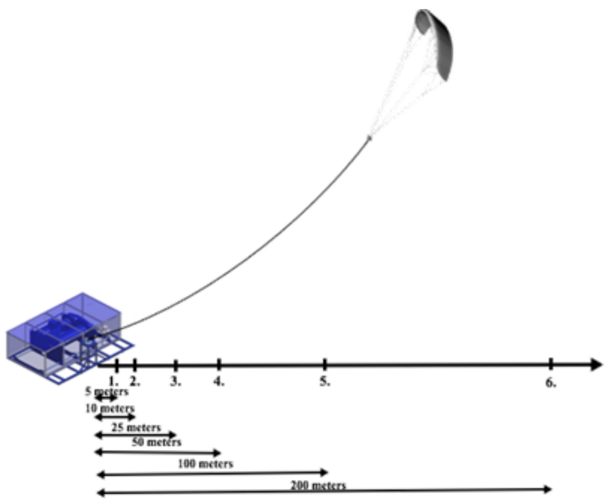

Figure 6: Illustration of the measurement set up (self-edited)

3.2. Analisying the collected data

Environmental noise is collected by a microphone (Philips microphone-SBC MD650), using Windows Sound recorder. Thus data is obtained in the Windows Media Audio format (.wma). With MatLab the files are converted from WMA to a visible form, counting on the Fourier Transform which has already built in the MatLab. With the next code, we can convert our data to a more interpretable and more spectacular form:

```
% This script reads the audio file determined by the variable
% control.file and makes a small signal processing: plotting the waveform
% with the effective pressure, the OSPL vs time and the spectrogram.
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%
>>close all
>>clear all
>>
>>control.file = 'name_of_the_file.wma'; % NAME OF THE AUDIO FILE TO READ
>>filename=fullfile('Audio Files',control.file);
>>control.nfft = 2048; % Number of samples for the FFT.
>>dti = 0.125; % Length of the time intervals for calculating OSPL vs t.
>>
>>[y,fs]=audioread(filename);
>>y = y(:,1);
>>Ns=length(y);
>>dt = 1/fs; t = 0:dt:(Ns-1)*dt;
>>
>>% Play the sound signal
>>z=y/max(y);
>>sound(z,fs)
>>
>>% Pe vs time calculation
>>ti = 0 : dti : t(end);
>>
>>for k = 1:length(ti)-1
>>    tia (k) = (ti(k+1)+ti(k))/2;
>>    I=find(t >= ti(k)&t<ti(k+1));
>>    pe(k)=sqrt(sum(y(I).^2)*dt/dti);
>>    M(k)=mean(y(I));
>>end
>>
>>% Plot the sound signal
>>fig=figure (1);
>>plot (t,y,'-b')
>>xlabel ('Time, [s]'); ylabel ('Pressure, [Pa]')
>>hold on
>>plot (tia,pe,'-r')
>>plot (tia,M,'g')
>>hold off
>>T = findall(gcf, 'type', 'text'); % find all text
>>set(T, 'FontSize', 16,'FontName','Times New Roman');
>>set (gca, 'FontName','Times New Roman', 'FontSize',16);
>>title([control.file, ' - Waveform'], 'FontSize',20,'FontName','Times New Roman');
>>folder = fullfile('Plots','Waveforms');
>>if exist(folder ,'dir') ~= 7
>>   mkdir(folder)
>>end
>>saveas(fig, fullfile(folder , [control.file ' - Waveform.eps']), 'epsc')
>>saveas(fig, fullfile(folder , [control.file ' - Waveform.png']))
>>saveas(fig, fullfile(folder , [control.file ' - Waveform.fig']))
>>
>>% OSPL vs time calculation
>>OSPL = 20*log10(pe/2e-5);
>>fig=figure ();
>>plot (tia,OSPL,'-k','LineWidth',2)
```

```
>>xlabel ('Time, [s]'); ylabel ('OSPL, [dB]')
>>T = findall(gcf, 'type', 'text'); % find all text
>>axis ([0 max(tia) 0 70])
>>set(T, 'FontSize', 16,'FontName','Times New Roman');
>>set (gca, 'FontName','Times New Roman', 'FontSize',16);
>>title([control.file, ' - OSPLmax: ', num2str(round(max(OSPL))),' dB'], 'FontSize',20,'FontName','Times New
Roman');
>>folder = fullfile('Plots','Waveforms');
>>if exist(folder ,'dir') ~= 7
>>    mkdir(folder)
>>end
>>saveas(fig, fullfile(folder, [control.file ' - OSPL.eps']), 'epsc')
>>saveas(fig, fullfile(folder, [control.file ' - OSPL.png']))
>>saveas(fig, fullfile(folder, [control.file ' - OSPL.fig']))
>>clear it
>>
>>%% Spectrogram generation
>>window = hanning(control.nfft);
>>noverlap = control.nfft/2;
>>[S,F,t] = spectrogram (y,window,noverlap,control.nfft,fs);
>>S = S/control.nfft;
>>data.P = 2*sqrt(S .* conj(S));
>>SdB=20*log10(data.P/20e-6);
>>
>>fig=figure ();
>>pcolor (t,F,SdB)
>>shading flat
>>colormap (jet)
>>colorbar
>>cb = colorbar('location','Eastoutside');caxis([-20 60]); ylabel(cb,'SPL, [dB]'); %Colorbar
>>axis ([0 max(t) 0 3000])
>>xlabel ('Time, [s]')
>>ylabel ('Frequency, [Hz]')
>>T = findall(gcf, 'type', 'text'); % find all text
>>set(T, 'FontSize', 16,'FontName','Times New Roman');
>>set (gca, 'FontName','Times New Roman', 'FontSize',16);
>>title([control.file, ' - OSPLmax: ', num2str(round(max(OSPL))),' dB'], 'FontSize',20,'FontName','Times New
Roman');
>>folder = fullfile('Plots','Spectrograms');
>>if exist(folder ,'dir') ~= 7
>>    mkdir(folder)
>>end
>>saveas(fig, fullfile(folder, [control.file '.eps']), 'epsc')
>>saveas(fig, fullfile(folder, [control.file '.png']))
>>saveas(fig, fullfile(folder, [control.file '.fig']))
```

After running the post processing algorithm, three different plots are obtained. The first one gives the measured noise in a waveform. The two axes will be the time (s) and the pressure (Pa). The second figure converts the collected data and show the relationship between the measured Sound Pressure Level (SPL) and the time (s). The third figure is the most informative because it shows the relationship between the pressure (Pa), SPL (dB) and the time (s) in a spectrogram. Thus, the third plot – spectrogram – contains all the three parameters which have to be analysed.

3.3. A few questions may arise

How can the noise from the moving kite be measured accurately? And how can the source of the noise be identified?

> The aim of this test is to confirm the statements that the technology has low environmental foot-print. So the set up allows us to measure the total environmental noise while the kite is in operation. Although the collected data will contain the sound of the wind and maybe other noises from the environment, it contains the acoustic noise of the kite too. The data is gathered in Media Audio file which can converted into spectrograms with the Fourier Transform easily, owing to MatLab. On the spectrograms, the frequency, the sound pressure level and the time differences between the type of noises in every selected measurement point can be obtained; by analysing the record, it can be identified.
>
> In the end, the distance of the measurement from the generator and the difference in the intensity of the noise from different noise sources can be detected.

4. RESULT AND DISCUSSION

After the measurement on one of the test flight, MatLab was used to analyse the audio records. In this chapter, the results obtained from the experiments and the experiences of the author on the field are discussed.

4.1. Distance from the generator - 5 meters

The first point was 5 meters far from the generator. The measured audio file was converted to a spectrogram to visualising the data. This can be seen in Figure 7. The noise generated by the wind is the major component of this plot. The generator also produces noise; however, the noise of the wind masks it. There are some visible lines which require some explanation; they are created by sharp and short noises – in a small fragment of one second - which probably originate from the drum or a different part of the generator. So they do not influence the results. In total, one concrete number about the SPL which is 68 dB. But as mentioned before, the measured data also contains the noise of the wind. Considering this, the final conclusion can be drawn; If the noise produced by wind is subtracted from the data, the total noise from the system, 5 meters far from the generator is obviously less than 68 dB.

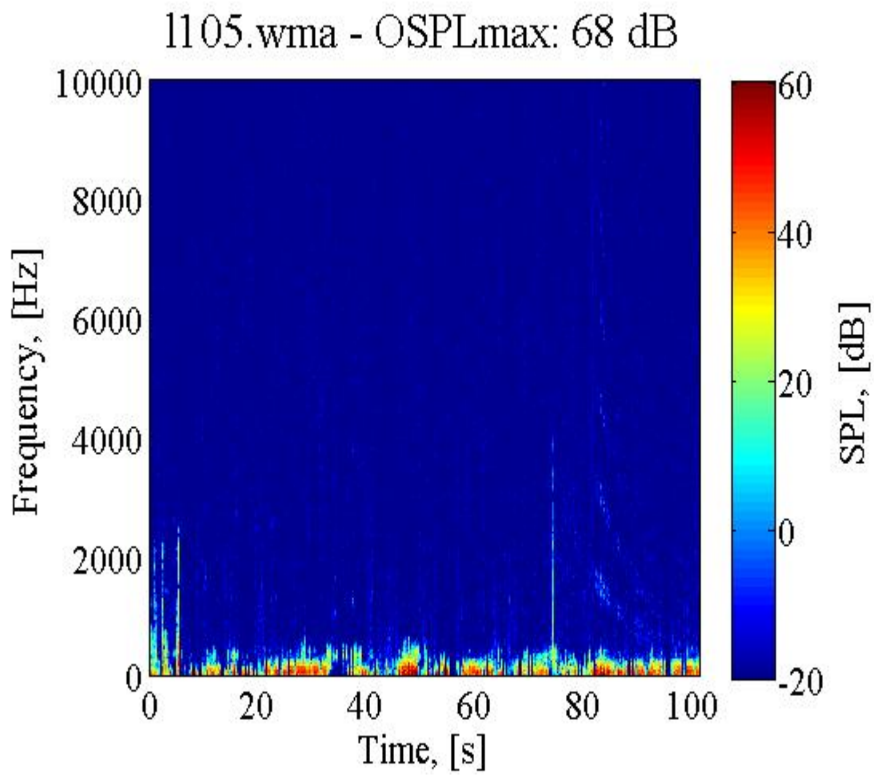

Figure 7: Measured noise 5 meters far from the generator. (self-edited)

4.2. Distance from the generator - 10 meters

The next measurement point was 10 meters far from the generator. The measured result is 64 dB in this point which is less than it was on the first point. It is observed in Figure 8, it is again mainly the wind which produces the noise measured. However, the result is smaller than it was in the first point, thus it fits into the reality; The noise from the generator can be identified.

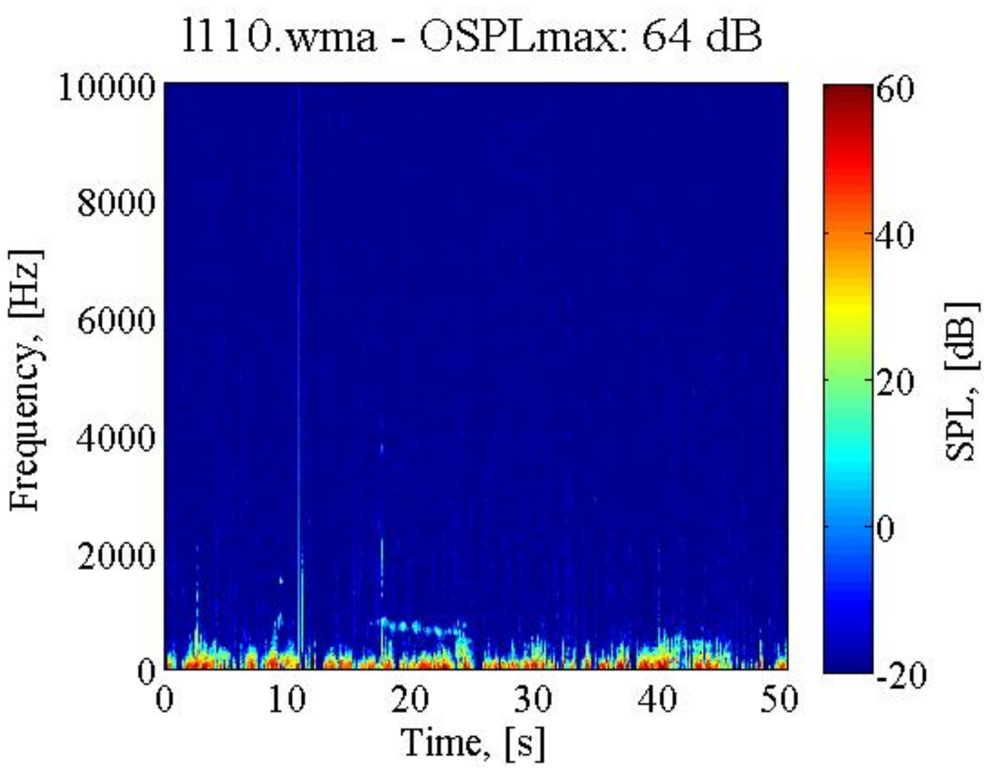

Figure 8: Measured noise 10 meters far from the generator (self-edited)

We can also espy a higher frequency noise around 20 seconds. Because of the better visibility, we can observe this higher frequency noise closer on Figure 9, which is signed by the white rectangle.

Bycarefully analysing the audio file, the measured audio file on this point, the noise from the tether can be identified. While the kite is pulling out the tether (reel-out), there is tension on the rope which causes it to vibrate. The whispering noise which is seen on the spectrogram and hear in reality, it is the vibration of the tether because of the tension. In contrast, the tether can also be strained while the reel-in. The singing of the tether is not constant. As observed in the spectrogram, it barely appears. However, the frequency of the tether's noise moves between 500-1000 Hz, which is the principal speech frequency region8. The Kite Power group has made an observation about horse's behaviour and the noise of the tether. According to them, the horses get stressed due to the noise from the rope. It should be taken into consideration while using this system in the agricultural fields that the frequency at which the tether vibrates bothers the animals. An assumption about this would be that this noise makes the horses tense because they cannot identify where the noise comes from, not because of the special frequency.

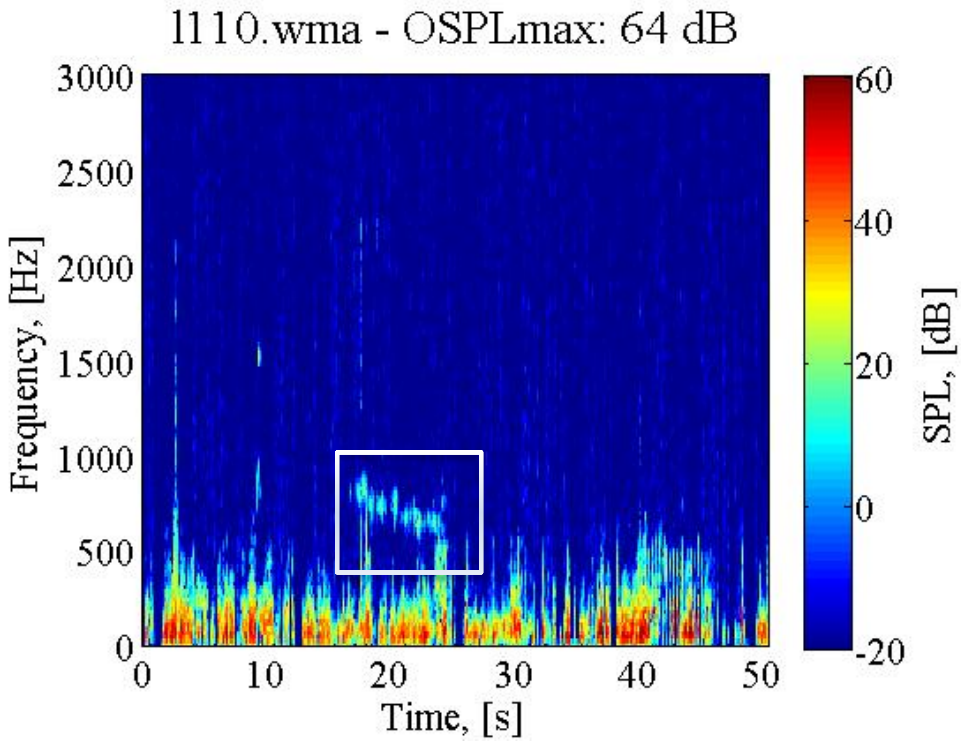

Figure 9: Measured noise 10 meters far from the generator; the rectangle sign the noise of the tether. (self-edited)

[8] Dr. Sean A. FULOP – Speech Spectrum Analysis, 57. page [28]

4.3. Distance from the generator - 25 meters

On the third point, the measured value is 72 dB. Observing the spectrogram (Figure 10), it can be seen that there is no sign of the whispering tether; however, the measuring point is 15 meters farther than the previous point.

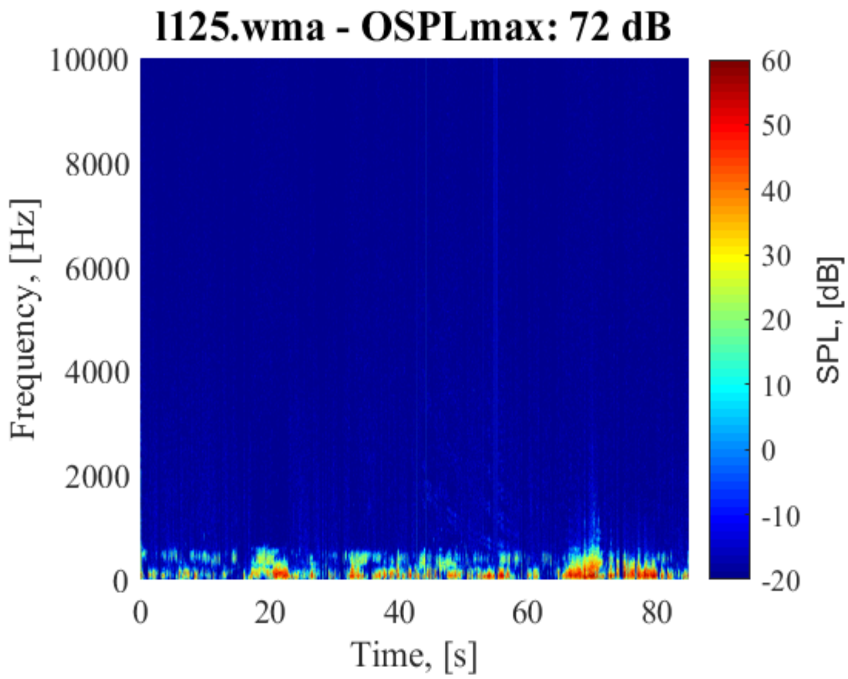

Figure 10: Measured noise 25 meters far from the generator (self-edited)

Relistening the audio record, the wind with some stronger wind gust can be heard. Counting on the real experiences, the noise of the generator is simultenously in the value of 72 dB; the reason why it is a higher value than on the previous point is due to the stronger wind gusts.

4.4. Distance from the generator - 50 meters

50 meters far from the generator, the measured SPL is 61 dB. From the audio records, the noise produced by the wind can be heard and no visible sign of another noise source (Figure 11). We can also notice that the measured value is less than it was in the previous set-up point.

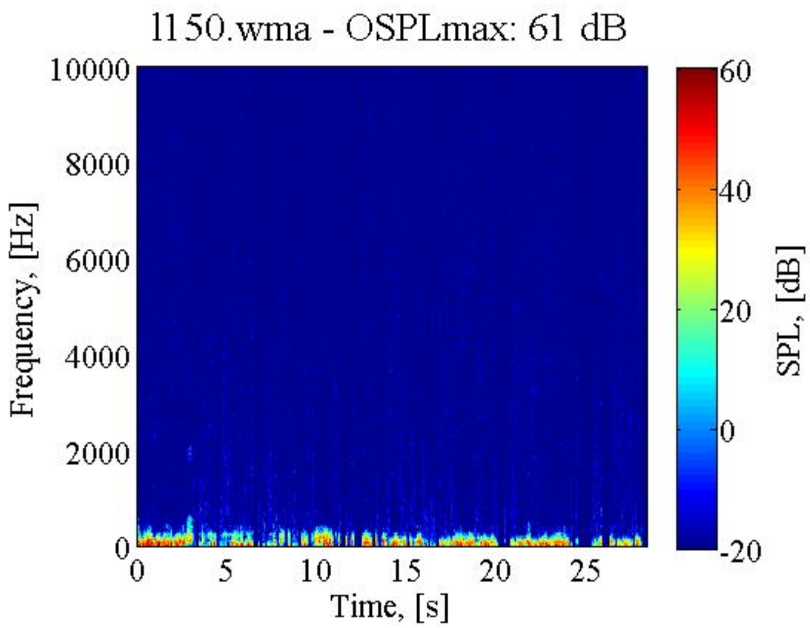

Figure 11: Measured noise 50 meters far from the generator (self-edited)

4.5. Distance from the generator - 100 meters

100 meters far from the generator, the measurement point was directly under the kite. On this measurement-point, the SPL value is 80 dB. Relistening the recorded audio file and checking the spectrogram (Figure 12), noise of the wind can be heard. There is also a frequency which changes periodically. This value is higher than what it was at 50 meters from the generator. So, it is safe to assume that the noise is from the flying kite because we know the kite's flight path. The kite flies between 200 and 400 meters, describing figure-eight. This means that the kite has higher and lower position while it flies; thus when it is closer to the ground level, the perceived noise from the kite increases which cause the periodical changes.

On Figure 13, an illustration of the relationship between the flying method and the measured data can be seen.

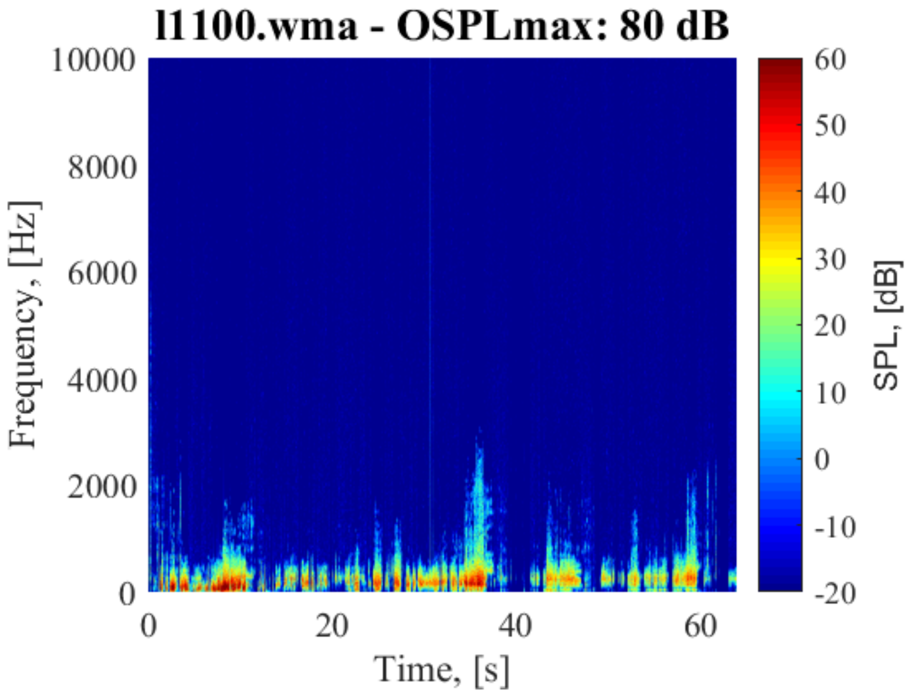

Figure 12: Measured noise 100 meters far from the generator (self-edited)

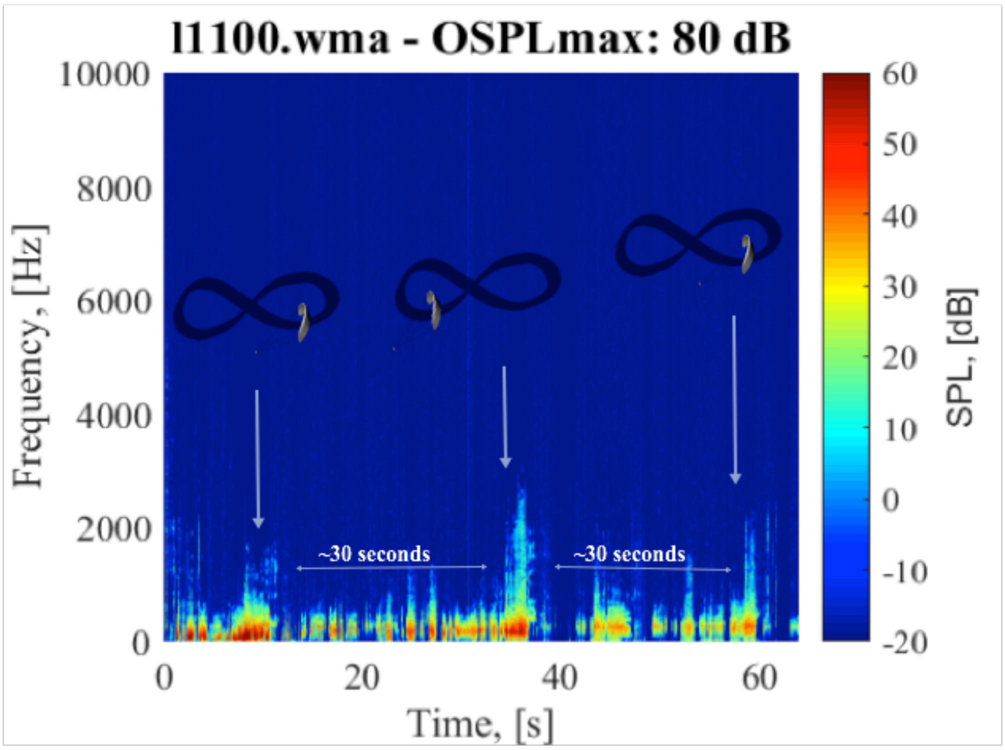

Figure 13: Measured noise 100 meters far from the generator, the illustrated kite position and the periodicity (self-edited)

4.6. Distance from the generator - 200 meters

200 meters far from the generator, counting on experiences too, the flying kite and wind can be heard. However, the measurement point is no longer under the kite, as it was 100 meters before. Thusly, on Figure 14, we can only see the noise of wind because it washed the kite’s noise.

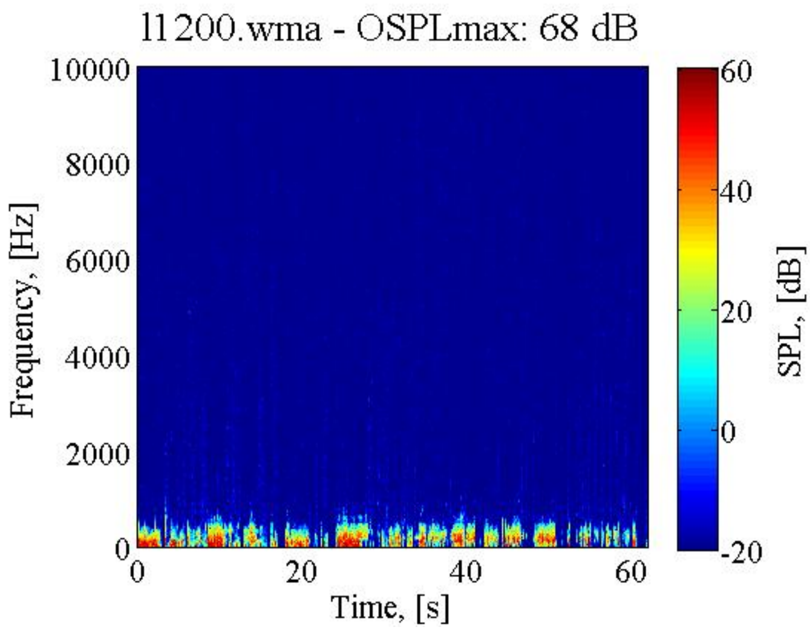

Figure 14: Measured noise 150 meters far from the generator (self-edited)

4.7. Source of the noise

After evaluating the results point by point, the relationship between the values could be analysed. Table 4 contains the measurement points and it's SPL values which result were converted to a chart (Figure 15).

Table 4: Measured SPL and the distance from the generator. (self-edited)

Ditance from the generator (meter)	Sound Pressure Level (dB)
5	68
10	64
25	72
50	61
75	55
100	80
200	68

If the relationship between the Sound Pressure Level (SPL) and the distance are represented in a figure, it can be seen how the SPL value changes with the distance from the generator. As mentioned above that the noise sources can be identified; Now, the relationship between the distance and the intensity of noise should be analysed.

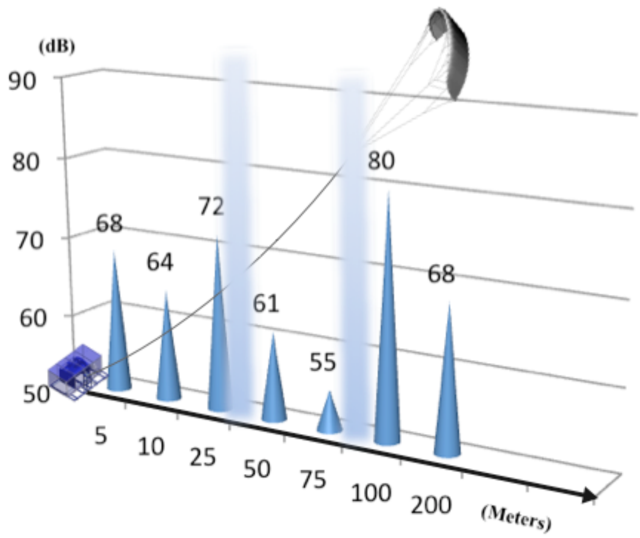

Figure 15: The changing Sound Pressure Level with the distance from the generator.The illustrated system is intended to show which part of the system influenced the measured value. And the three noise zones are signed by the green lines. (self-edited)

On Figure 15, the measured SPL values and illustrated the Kite Power's system are depicted; the aim of this is to show which part of the prototype influenced the values of the given measurement point.

- With 5 meters from the generator, the measured value was 68 dB, and on the next point (10 meters from the generator), it decreased to 64 dB which coincides with our expectation. Namely, farther from a noise source, the noise heard is of lesser intensity. However, it should be mentioned that 10 meters far from the generator, noise of the tether was also recorded; Therefore, it can be determined that the measured 64dB is due to the noise produced by the wind, the generator and the tether.
- SPL of 75 dB was measured at the next measurement point. It must be higher value because of the wind gust; additionally we can see that 50 meters far from the generator the value is smaller than it was in the 10 meters point and there is also no sign of the tether's noise in the audio records; which also confirm the assumption that the 75 dB value is higher than it should be. It

leads me to assume that the generator can be heard more or less in 30-meter radius circle around the generator which is affected and can be changed by the wind.

- A big difference between 75 meters point and 100 meters point can be observed. Analysing the audio record, it is seen that the main source of the noise is the kite 100 meters far from the generator. It also confirms by the field experience – Measurement was taken exactly under the flying kite on this measurement point.
- On the 200 meters point, 68 dB was measured; in the first point (5 meters far from the generator) we measured the same value. Thus it is assumed that 100 meters far from the previous point, additional noise sources along with the wind are present, which can be only from the flying kite.

In the end, three different noise zones can be assumed, which the next table summarise (Table 5). On Figure 15 (above), we can also see this three zones – signed by the blue shadows.

Table 5: Three noise zone under the kite. (self-edited)

Zone	Distance from the generator (meters)	Main source of the noise	Avarage SPL (dB)
I.	≈0-38	Generator and tether	≈68
II.	≈38-88	Tether	≈58
III.	≈88-200	Kite	≈74

After separating the three noise zones, the average SPL values of this region are considered which creates the opportunity to see the most dominant noise source of the system; which is the kite itself. The second strongest noise source is the generator. The tether generates the less noise in the system.

4.8. Comparison with home-devices and human activities

The SPL is a decibel value and not a well-known parameter in our daily life. In view of this, in the next table (Table 6), noises from some regular devices and human activities are collected to make it easier to compare the results.

It should be also considered the measured values contain the noise of the wind, so, it can be concluded that the actual noise produced by the AWES system is lesser than the measured values.

Table 6: Comparison of the noise of the Kite Power system with daily life's noises (self-edited[9]).

Distance from the generator (meter)	Sound Pressure Level (dB)	Examples from our daily life
5	68	< Shower, dishwasher
10	64	< Conversational speech, airconditioner
25	72	< Shower, dishwasher
50	61	< Conversational speech, airconditioner
75	55	< Light trafic, microwave
100	80	< Vacuum cleaner, toalet flushing, alarm clock
200	68	< Shower, dishwasher

The results show that the most dominant part of the system is the kite with 80 dB value, which compares with an operating vacuum cleaner in a general home. At a distance of 5 metres from the generator, the measured value was 68 dB which is quieter than a dishwasher, but this noise source depends on the type of the generator which the system is currently using.

As mentioned above, this airborne wind energy system requires space, so it was planned for spacious field in reality. Considering this, there is no situation when the generator would be installed closer than 200 meters far from a house where the noise from the system is less than 68 dB, which value is equal with for instance a

[9] Reference examples were collected from: Methods of measurement for peak noise during loading and unloading (2015 update) by Stichting Piek-Keur [29]

working dishwasher. However, a spacious field can be used by an agricultural activity. The constant noise of the system – even if it does not seem to be disturbing – could have a negative effect on the animal husbandry but the analysis of this issue is out of the scope of current research study.

4.9. Comparison with wind turbine

AWES do not have any regular noise standards, therefore, the results of this study are compared with the controversial wind turbines. The National Institution of Deafness and Other Communication Disorders (NIDCD part of NIH) has a standard where they compare the average wind turbine noise with the regular noise of household devices (Figure 16.). For the sake of simplicity, the results obtained from this study are compared to the ones available from the NIDCD (Table 7). [30]

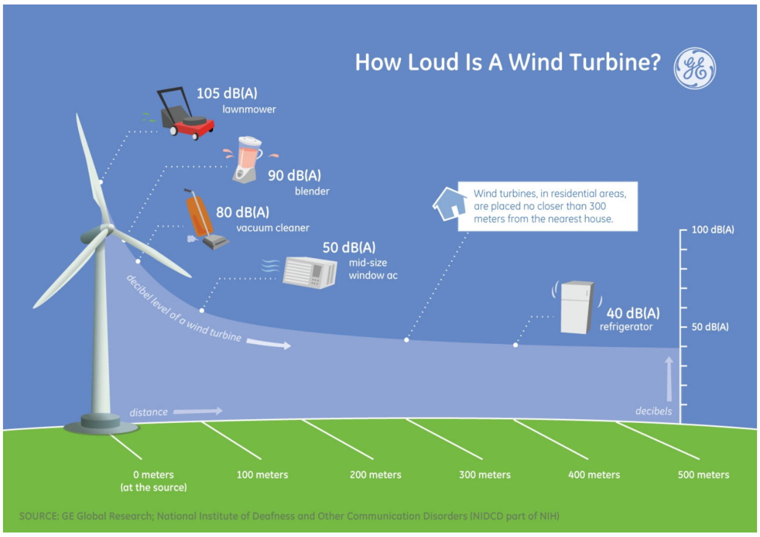

Figure 16: Noise comparison of regular house-hold devices and a wind turbine. Source: GE Global Research, The National Institution of Deafness and Other Communication Disorders (NIDCD part of NIH); (self-edited)

Table 7: Comparison of controversial wind turbine and my result (self-edited)

Distance	**Controverisal wind turbine's noise**	**Noise of the KitePower's system**
0-5 meters	105 dB	<68 dB
25 meters	90 dB	<72 dB
50 meters	80 dB	<61 dB
100 meters	50 dB	<80 dB
200 meters	No data	<68 dB
400 meters	40 dB	No data

In conclusion, the AWE system is quieter, and the range of the noise is smaller than a controversial wind turbine. While this is true, the wind turbine is one concrete source of the noise, in contrary, an AWE system has three noise source which is also inferred from the results. In the present case, the reference point, which was the focus of the measurement, was the generator, and the airborne wind energy system was noisier with 100 meters from it; thus it is necessary to consider where the reference point is and must clear it in our future measurements.

5. CONCLUSION

The test campaign had two aims. Firstly, to identify the dominant acoustic source of the Kite Power's system since it has got three distinct noise sources. The results show that the dominant acoustic source of the system is the flying kite, then the generator and the tether which emits the least. Secondly, the measurement also intended to confirm the statement that the airborne wind energy systems are environment-friendly by the Kite Power company's leading edge inflatable kite system. The airborne wind energy systems do not have regular noise standards yet. Therefore, the results were compared to the noise of devices and human activities from daily life and also with controversial wind turbine noise. Although the results contain the wind's noise too, it is seen that the system is less noisy than a traditional wind turbine. However, it should be considered that the wind turbine can be handled as one point noise source but the KitePower's system has three different noise sources. This should be considered for the future research.

Finally, it can be concluded that the system has low environmental footprint considering the noise impact. The measurement requires further steps in the future; however, this study provided a basic view about the acoustic level of the airborne wind energy systems which reinforce the technology as green and renewable.

6. RECOMMENDATION

The results give a good feedback about the acoustic impact of the airborne wind energy systems; however, to see how the noise of the AWE system spreads, the measurement must be repeated two more times on different lines. The azimuthal angle between this two lines should be 90˚which is illustrated in Figure 17. With this data, more accurate results about the total acoustic emission of the chosen AWE system can be obtained and a 3D distribution of noise level can be generated.

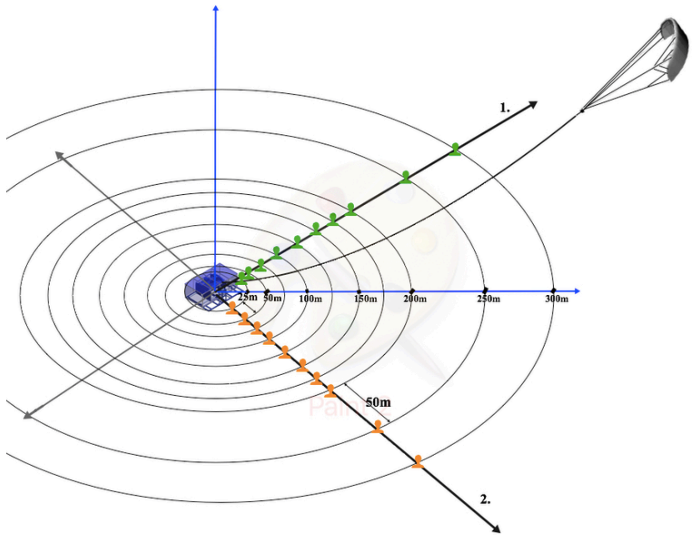

Figure 17: Illustration of the two additional measurement lines. (self-edited)

Besides that, another recommendation would be to repeat the test campaign to verify the repeatability of noise levels. Additionally, as discussed earlier, the results also contain the noise of the wind. If the test is repeated, and there is also collected data from the two additional measurement lines, a more reliable picture of the acoustic impact of the working airborne wind energy system can be obtained.

Furthermore, I also would recommend measuring directly on the parts of the AWE system – generator, tether, kite; thus the values of the system can be deducted from the data measured on the ground level. It would allow to us to get the results without the noise of the wind – unfortunately not perfectly – but it could give more accurate results about the ground heard noise intensity.

Finally, I would recommend making a measurement when the reference point is the kite (about 100 meters from the generator) instead of the generator. Thus the spreading of the noise from the kite would also be describable.

7. SUMMARY

The constantly increasing energy deficit takes the energy sector under huge pressure which resulted that renewable technologies got more attention than ever. Wind is one of the renewable energies. Generating electrical energy from the movements of the air has several advantages. It is not only non-polluting but also a free energy source. Using wind energy makes it possible to reduce the emission of the harmful greenhouse effect raiser gases and prove cheaper energy. Not accidentally, we have been using wind to produce energy for ages.

Unfortunately, wind is not permanent and strong as required everywhere hence the wind energy technologies cannot operate sufficiently in the rest of the midlands – where the topographical conditions weaken the speed of the wind. However, since George Gustav Hellmann, it is known that the wind speed is proportionally rising with the altitude. As a result, we built our wind turbines as tall as we could, but the laws of physics limited the height of them. This led on to rethink our methods of earning electrical power from wind and try to find a new way to go higher and harvest the high altitude wind in the constant flux layer where wind is more permanent and stronger. The fact about upper boundary layer caught the attention of many engineers all around the world, and several types of airborne wind energy systems appeared. Most of them are promising solutions, however, there are only a few data about their environmental impact – bird mortality was observed, but data about acoustic emissions was not existing. Thus the question was the acoustic impact of an airborne wind energy system on the environment.

I had opportunity to perform a measurement campaign on the prototype of the Kite Power company which uses inflatable wing, and their tether is made from a flexible, robust and lightweight material. The system's generator based on the ground-level, simultaneously with the facilitates servicing. Their structure was idealized for being a mobile airborne wind energy system.

The planned set up made possible to get information about the source of the noise with different intensity from the system. The results showed that there are three different sources of the noise thus three categories were created, and firstly I compared them with noise of devices from our daily life to give references for the comparability. Then I also compared the measured data from the airborne wind energy system with the conventional wind turbines. The final results showed that by and large the AWES prototype was quieter and the range of the noise is smaller than a controversial wind turbine.

The first aim of the measurement was to identify the noise sources which was completed by the categorization. Secondly, the most dominant part of the system was also identified. Above all, the comparisons made possible to image the noise of an airborne wind energy technology.

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10. List of Figures

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