PRELIMINARY STUDY ON AN
OFFSHORE WIND ENERGY RESOURCE MONITORING SYSTEM

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Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

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I certify that all materials presented here are of my own creation, and that any work adopted from other sources is duly cited and referenced as such.

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ABSTRACT

The expansion of offshore wind energy is part of many national programs for the implementation of renewable energies. Recent developments focus, among others, on the exploitation of wind resources in deep water areas using floating wind turbines. The assessment of the wind resources in those areas requires versatile and cost effective monitoring systems, due to the high costs of existing technologies (such as floating lidars or meteorological masts). A preliminary design for such an alternative system has been developed in this work. Solutions to meet the diverse requirements of such a system have been proposed and evaluated. Furthermore, they were summarized in a morphological matrix and filtered with respect to operational feasibility, costs and expected R&D efforts. A final design was selected and visualized. The cost for the system are estimated to be below 180.000€, approximately a fifth of the market price of a floating lidar system. Several critical points for a possible realization were identified and discussed. Those are the survivability of the aerostat and the tether, the absence of commercial feed-tubes and the motions of the sondes. Future developments to overcome those issues at hand are proposed. Those proposals are accompanied by a general development strategy to accelerate the overall realization process.

KEYWORDS: offshore wind assessment, tethersonde, data buoy, morphological matrix, aerostat, cost analysis

RESUMO

A expansão de parques eólicos offshore é parte integrante de diversos programas nacionais para a implementação de energias renováveis. Desenvolvimentos recentes têm tido foco, entre outros, na exploração dos recursos eólicos em águas profundas, usando aerogeradores flutuantes. A avaliação dos recursos eólicos nessas áreas requer sistemas versáteis e economicamente viáveis, devido ao elevado custo de tecnologias existentes, tais como, LIDAR e torres meteorológicas. Neste trabalho, um projeto preliminar de tais sistemas alternativos foi desenvolvido. Soluções visando obter diversos requisitos foram propostas e analisadas. Além disso, as soluções foram resumidas numa matriz morfológica e ordenadas de acordo com a viabilidade, custo e esforço previsto em atividades de I&D. Finalmente, um projeto foi selecionado e visualizado. O custo para o sistema foi estimado em aproximadamente €180000, o que representa um quinto do preço de mercado de um sistema LIDAR. Diversos pontos críticos para uma possível implementação foram identificados e discutidos. Entre eles, o tempo de vida do aeróstato e da corda, indisponibilidade de tubos de alimentação comerciais e o movimento das sondas. Soluções futuras para estes problemas foram também propostas, juntamente com uma estratégia de desenvolvimento que visa acelerar a realização do processo.

KEYWORDS: Viabilidade de parques eólicos offshore, tethersonde, data buoy, matriz morfológica, aeróstato, análise de custo

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AC	alternating current
AIS	Automatic Identification System
DC	direct current
DGPS	Differential Global Positioning System
EGNOS	European Geostationary Navigation Overlay Service
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
IPCC	Intergovernmental Panel on Climate Change
ISM	Industrial, scientific, medical (band)
Lidar	light detection and ranging
MWT	micro wind turbine
NMEA	National Marine Electronics Association
O&M	operation and maintenance
R&D	research and development
Sodar	sound detection and ranging
VDL	VHF data link
VHF	very high frequency (radio)

1 DESCRIPTION OF THESIS

Very recently two successful floating wind turbine prototypes demonstrated the technical feasibility of deep offshore wind, one of which is the WindFloat project developed by a consortium led by EDP Inovação and under sea trials at Póvoa do Varzim. However, one of the present problems related to the development of offshore wind energy is a proper knowledge of the offshore wind resource. Wind measurement onshore is made through a monitoring mast typically a few tens of meters height where several anemometers are placed. More recently Lidar systems are being used, these allowing for the vertical velocity profile to be measured continuously in time and space. When going offshore in shallow waters the standard solution is the instrumented mast, however this solution is very expensive in deep waters (the cost of the mast is in excess of 1 million euros) as the mast needs to be mounted in a stable floating foundation. Floating Lidars are being developed, but their cost is also of the same order. Most of these deep offshore solutions are not yet certified by international bodies.

The purpose of this thesis is to do a preliminary analysis of a measuring system based on an instrumented balloon and cable. The following steps were followed:

1. Literature review on wind resource measurement, including the standard solutions for onshore applications;
2. Literature review on aerodynamic vibration on cables and cylinders;
3. Preliminary design of the balloon and cables, including the expected dynamics due to wind turbulence and vortex shedding;
4. Selection of the instrumentation
5. Cost analysis
6. Design of experimental onshore trials
7. Thesis submission

2 INTRODUCTION

> *"Climate change is one of the great challenges of the 21st century. Its most severe impacts may still be avoided if efforts are made to transform current energy systems. Renewable energy sources have a large potential to displace emissions of greenhouse gases from the combustion of fossil fuels and thereby to mitigate climate change."*
>
> - ***Renewable Energy Sources and Climate Change Mitigation*,**
> **Special Report of the Intergovernmental Panel on Climate Change (IPCC)**

Among all renewable energy sources, particularly wind energy offers significant potentials for greenhouse gas emission reduction. In 2009 electricity produced from wind energy was capable of meeting 1.8% of worldwide electricity demand and could grow to meet 20% by 2050. However, the onshore expansion of wind energy is constrained in several ways, e.g. by limited wind and land resources (Edenhofer, et al. 2012). The expansion to offshore sites is the natural alternative. Offshore wind turbine power plants benefit from a more reliable wind resource and can be built in larger size with increasing economy of scale potentials. However, installation costs increase with water depth as bigger foundations are necessary. To exploit wind resources in deep water areas floating wind turbines are in development. They offer access to large additional wind resource areas and could make turbine and support structure designs largely independent of water depths and seabed conditions (Edenhofer, et al. 2012).

To explore the wind resource in these areas appropriate monitoring technologies are necessary. Existing technologies, such as meteorological masts or remote sensing systems, have significant cost, which makes wider wind assessments economically unattractive (Brown 2012). Therefore, a need for new systems, which offer the possibilities to assess the wind resource in deep offshore areas more cost efficiently, has been identified.

The intended design, which shall be developed in this work, is based on the idea of an aerostat launched from a buoy with instrumentation along the tether. This design offers the possibility to assess deep water wind resources at potentially lower cost in comparison to other existing technologies. The intention of this work is to develop a preliminary design for such a system, analyze its cost structure, identify its critical aspects and derive a guideline for further developments.

3 LITERATURE REVIEW

This chapter will give an introduction to wind assessment in an offshore environment. Understanding this field in more detail will support the development process of this work. The state of the art technology and instrumentation - which are commercially available - for offshore wind monitoring is presented. This is followed by an outlook on the mathematical equations, which translate the meteorological data into a wind characterization. Finally, a detailed researches is done on wind induced oscillations of cables and balloons.

3.1 OFFSHORE WIND ASSESSMENT

As of today, even after 20 years of offshore wind plant operations, there is no standard solution for offshore wind assessment. There is still a variety of measurement methods in application to assess possible offshore wind plants (Brown 2012). The most used methods can be divided into three categories: meteorological masts, surface-based remote sensing systems and weather buoys. Meteorological masts and surface-based remote sensing systems can measure the wind speed from sea level to the hub height of an offshore wind turbine or even above. The characteristics of selected turbine models are summarized in Table 1 to see their dimensions. To assess the wind resource of the full rotor diameter a monitoring corridor from sea level to roughly 200m above is desired.

Table 1: Offshore wind turbine dimensions

Turbine type	Rated power MW	Rotor diameter in m	Hub height in m
Siemens SWT-3.6-107	3.6	107	90
Siemens SWT-3.6-120	3.6	120	90
NREL 5MW OWT	5	126	90
Repower 5M	5	126	85-95
Alstom Haliade™ 150-6MW	6	151	100
DTU 10MW RWT	10	178	119

Source: Manufacturers information[1]

3.1.1 Meteorological masts

A meteorological masts (also called met mast) is a construction that consists of a foundation, grounded on the seafloor, and usually a lattice structure built on top. The lattice structure above sea level carries the necessary instrumentation. Figure 1 shows a typical met mast. The costs to raise such a tower are very high, ranging from two to eight million euro. These high cost are due to the harsh offshore environment with strong currents, high waves and gusty winds. The massive tower foundations have

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[1] All specifications and prices in this thesis are obtained from manufacturer websites, official distributor websites, official quotes or from personal communications. If prices or specifications have been assumed they are marked as such.

to withstand these forces and have to be securely attached to the sea floor. This results in extremely high cost, which grow strongly with increasing mast height and sea depth.

Figure 1: Meteorological mast at the OWEZ wind farm (P.J. Eecen 2008)

The mast height typically matches the hub heights of the planned wind turbines which are in the range of 80-100m (Elliot, et al. 2012), again see Table 1. For example, the FINO 3 met mast in the Baltic Sea has a height of 120m above sea level with instrumentation for wind assessment up to 100m (Stein 2012). The instrumentation is typically mounted on several monitoring heights, with anemometers on every tower face. This redundant setup reduces the influence of the large tower on the wind measurement and provides a better data recovery. The structure of the tower poses the main challenge to measure the wind correctly. Therefore booms are used to separate the instrumentation as much as possible from the disturbing lattice structure (Brown 2012). The wind measurement can also be disturbed by a deflection of the tower by wind and waves but this influence was found to be less (ca. 1%) than the influence of the structure (3%) itself (P.J. Eecen 2008).

3.1.2 Surface-based Remote Sensing Systems

This category comprises two technologies, lidar (**Li**ght **d**etection **a**nd **r**anging) and sodar (**So**nic **D**etecting **A**nd **R**anging), whereas only lidars are in significant use in the industry nowadays. Sodars are susceptible to acoustic interferences which hindered further commercial development. Lidars, however, are commonly used for offshore wind assessment. These systems are relatively small and have lower costs than most met masts. Therefore they are mostly used as a complementary method to extend the measurement above the top of a meteorological towers (which are at about 100m). The recent trend, however, is to use lidars as stand-alone systems. Commercial developments are e.g. the *Wind Sentinel*™[2] from AXYS Technologies, the Flidar from 3E or the KIC InnoEnergy project *Neptune* (Neptune 2014), see Figure 2. The cost of such systems are in the range of 0.9-1.2Mio € (Randolph

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[2] It was recently announced that the Wind Sentinel™ is scheduled to be part of the ongoing validation of the WindFloat project by EDP, see the chapter “Introduction”. (Thomsen 2014)

Kashino from AXYS Technologies and Axel Albers from WindGuard Consulting, personal communications, 20.05.2014 and 25.07.2014). These systems are deployed on a buoy platform and allow the measurement of the wind speed up to 200m above sea level. The buoy platform is a less expensive alternative to the foundations discussed in the previous section and one major factor for the lower costs of this type of systems. It also extends the field of application to deeper water with less additional efforts. Alternatively lidars can be deployed on foundations like those of meteorological masts. Operation on offshore structures such as oil platforms or low lying island are also possible. Lidars are prospected to become competitive systems to tower based measurements in the mid- to long-term. Nevertheless considerable validation and testing is necessary before they are fully accepted by wind farm developers (Brown 2012).

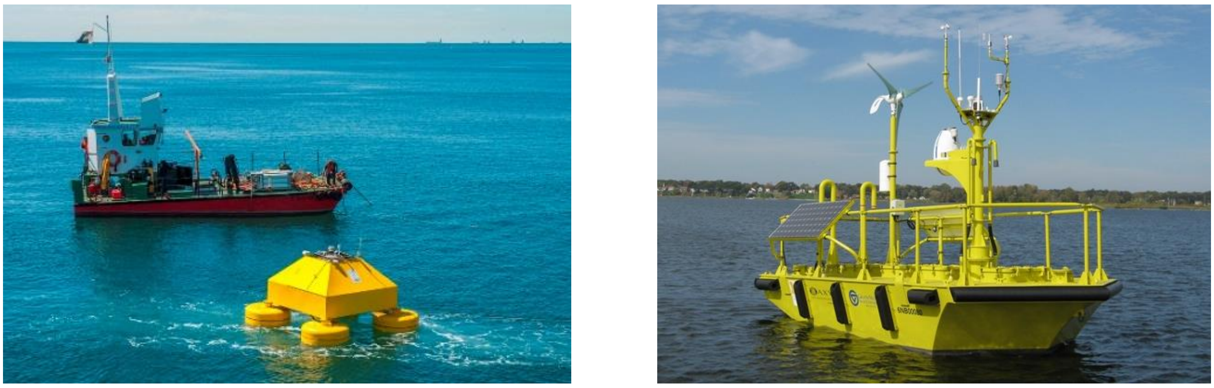

Figure 2: Neptune buoy by KIC InnoEnergy (left) and Wind Sentinel™ by AXYS Technologies (right)

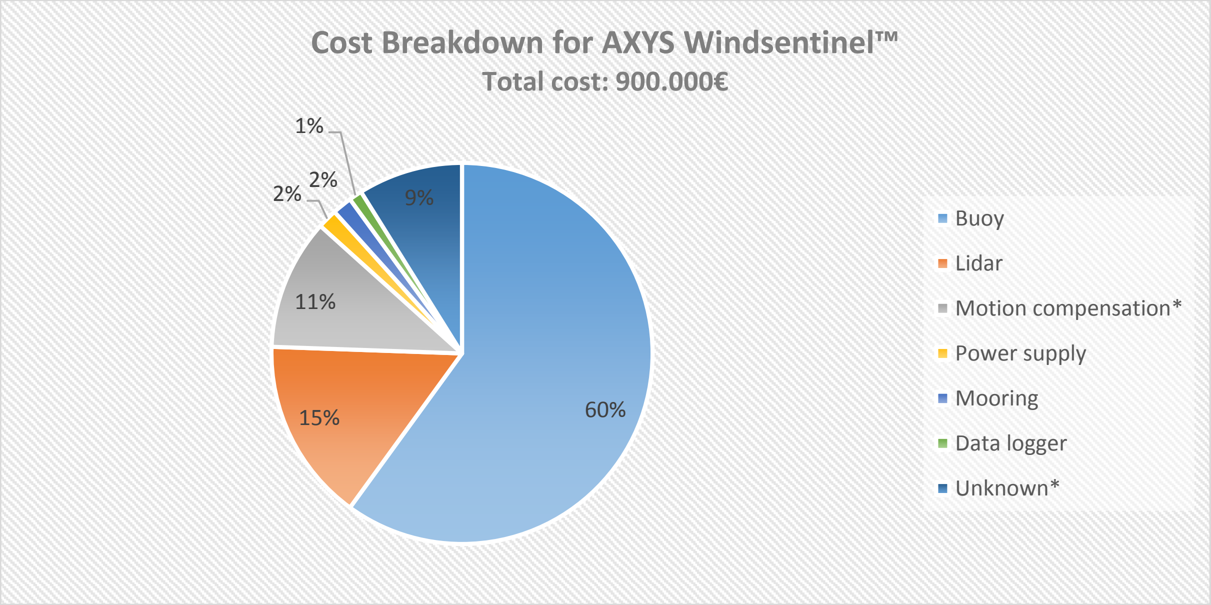

*Figure 3: Cost break down for the WindSentinel of AXYS Technologies (*assumptions)*

The exact cost of a lidar systems and their components are difficult to obtain, as most are still in development. However, a rough cost breakdown can be performed for the WindSentinel™ using the market prices[3] for the individual components and the total system, it is shown in Figure 3. The buoy accounts obviously for the biggest cost item with more than half a million euro, which is 60% of the total cost. The actual lidar system, in contrast to the buoy, accounts for significantly less costs (140.000€). Together with the power supply and the data logger it sums up to only 18% of the overall cost. The exact cost for the motion compensation were assumed to be in the range of 100.000€ because no specific data was found. Typically the compensation is performed on a mechanic and digit level, depending on the system. The gap between the known cost items and the total cost of the system remain unknown, most likely it accounts for the commercialization of the system.

3.1.3 Weather buoys

Weather buoys are mainly used for two purposes: preliminary wind site assessment and gathering of ocean parameters. They have smaller permitting hurdles for deployment. Therefore they are ideal to gather first on-site data in the early development phase. Their preliminary wind measurements give a first indication on the wind resource on-site. Additionally gathered ocean data can support the development of a possible follow-up assessment system (such as a lidar or a met mast). The wind speed is usually measured at the altitude of 5m (NOMAD buoy, 3-meter buoy) to 10m (10-/12-meter discus buoy) (US Department of Energy 1993). If a weather buoy is deployed in combination with a met mast the data from both systems can be combined. This yields a more detailed wind assessment (Brown 2012). A weather buoy from the National Data Buoy Center of the US can be seen in Figure 4.

Figure 4: Weather buoy (credit NOAA)

3.2 INSTRUMENTATION

The instruments that are used to measure wind speeds, also called anemometers, in an offshore environment have different working principles. They can be divided into two groups: sonic anemometers and cup anemometers. To measure the wind direction additional wind vanes can be used. Both anemometer types are presented in the following sections in more detail.

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[3] The real cost are much lower than the market prices, most likely in the range of 40-60%. But the percentage distribution should be of the correct order.

3.2.1 Cup Anemometers

Figure 5: Cup anemometer (Credit FuehlerSysteme eNET)

This type of anemometers uses several cups that are spun by the wind. The motion occurs due to the different drag coefficients of the front and back of each cup. From the rotational speed the average wind speed can be derived. The three or four cups typically have the shape of cones or hemispheres, depending on the manufacturer. An example can be seen in Figure 5. The advantages of cup anemometers are their robust design and low maintenance requirements. This results in a generally high lifetime. Also they come at relatively low cost (approximately 500-1000€) compared to sonic anemometers. On the downside cup anemometers can not measure the wind direction, thus a wind vane is necessary to complement the wind assessment. Cup anemometers have a medium precision. This is due to the inertia of the cups, which keeps the cups spinning when the wind stops abruptly. Also the startup is delayed due to friction when the wind picks up again. The drag coefficients of the cups depend on the Reynolds number, which demands precise calibration (Deiss, et al. 2001). Finally the moving parts of the anemometer can be critical in a marine environment. Nevertheless, they can be used for offshore wind assessment on meteorological masts (Stein 2012).

3.2.2 Sonic Anemometers

In contrast, sonic anemometers do not have moving parts. Their working principle is based on the emission of sonic pulses and the measurement of their travel time. Since this travel time is influenced by the motion of air between the transducers, speed and direction can be derived from those overlaying speeds. Sonic anemometers exist in different versions, depending on their number of ultrasound paths (1-3 paths), see Figure 6. Thus, they can measure the wind speed and direction in up to three dimensions. In contrast to the cup anemometer, which are adversely affected by salty air, sonic anemometers are appropriate for long term use in exposed conditions. Moreover, sonic anemometer have a very fine temporal resolution which makes them favorable for turbulence measurement. The speed of sound is nearly constant with air pressure, but changes with air temperature. Therefore sonic anemometer can also be used as thermometers (Deiss, et al. 2001). Sonic anemometers also have disadvantages. First, their measurement can be negatively influenced by rain. Second, the flow of air is distorted by the supporting structure. Finally, the prices compared to cup anemometers are usually higher (Deiss, et al. 2001). Especially 3D sonic anemometers are in the range of several thousand dollars, whilst 2D versions can still be found with prices comparable to those of cup anemometers. Some examples are given in the following Table 2.

Figure 6: Two different sonic anemometer designs: 3D-anemometer (left, credit Gill Instruments), marine 2D-anemometer (right, credit LJC)

Table 2: A selection of anemometer and their quoted prices

Anemometer model	Working principle	Price in €
Vector A100L2	Cup	580.00€
Gill 12102	Cup	430.00€
Young 85106	3D sonic	1,330.00€
Thies 4.3519.0	3D sonic	4,221.00€
Thies 4.3519.0	Cup	340.50€
JLC CV7	2D sonic	616.00€

Source: Manufacturers information

3.3 WIND CHARACTERIZATION

Once the wind data has been gathered and validated, it can be analyzed and translated into the numbers that characterize the wind resource. Wind in proximity to the ground is always turbulent and has to be measured and characterized as such. This means the turbulent flow is characterized by spatial and temporal fluctuations. Typically, this fluctuation is overlaid by a main flow. Thus, the wind speed v generally consists of the mean wind speed $\bar{v}$ and its fluctuationv': $v = \bar{v} + v'$. The component $\bar{v}$ can fluctuate as well, this is called fluctuation of the mean wind speed, whereas the high frequency fluctuation v' is called turbulence. The distinction between these two fluctuations is temporal (Deiss, et al. 2001), as illustrated in Figure 8 in section 3.3.3, which depicts a typical wind energy spectrum.

3.3.1 Mean Wind Speed

The mean wind speed is the average of the speed values for a certain time period. This interval is typically 10min or 30min for a wind resource assessment. The mean wind speed therefore is calculated as follows,

$$\bar{v} = \frac{1}{N}\sum_{i=1}^{N} v_i$$

with v_i being the wind speeds measured in discrete time steps in the respective interval. The obtained mean wind speeds are the initial values for the further mean wind speed calculations. For example, monthly and annual averages or an annualized mean wind speed can be calculated. Whilst the monthly and annual averages use the same methodology, the annualized mean wind speed is more sophisticated. It tries to give a more realistic estimate, than the annual mean wind speed, in cases where the period of records is not an integer number of years. For example, the double occurrence of two very windy winter months in a period of record of 14 months can lead to an overestimation of the annual mean wind speed. Therefore the data is first averaged for each month and then in a second step annualized as follows:

$$\bar{v}_{annual} = \frac{1}{365{,}25} \sum_{m=1}^{12} D_m \overline{v_m} = \frac{1}{365{,}25} \sum_{m=1}^{12} D_m \left(\frac{1}{N_m} \sum_{i=1}^{N_m} V_{im} \right)$$

The outer sum is over 12 months, with D_m being the average number of days in the month m (365.25 to account for leap years). The inner sum is over the wind speeds in the particular month (Brown 2012).

3.3.2 Wind shear

The wind shear relates the wind speeds on two different heights and is usually described using a dimensionless exponent called alpha (α). Depending on the wind speeds that are used, the wind shear is subsequently also an averaged exponent over e.g. a month or a year. The power law equation is expressed as follows (Brown 2012):

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1} \right)^{\alpha}$$

Where v_1 and v_2 are the measured wind speeds at the heights h_1 and h_2. This can be converted to express α in terms of measured mean wind speeds and heights:

$$\bar{\alpha} = \frac{\log \overline{v_2} - \log \overline{v_1}}{\log h_2 - \log h_1}$$

The calculation is sensitive to errors in the measured wind speed. Therefore three rules are pointed out by (Brown 2012) to prevent errors.

- The speed ratio $\frac{v_2}{v_1}$ should only be calculated from concurrent and valid speed records.
- Second, the two heights used for the shear calculation should be separated as far as possible (at least 1.5 ratio).
- If data is obtained from a meteorological tower, the anemometers should operate under equal conditions (orientation to tower, boom length)

For applications at sea a value of α=0.11 ± 0.3 has been found under near neutral conditions[4] (Hsu, Meindl und Gilhousen 1994). This value is smaller than 0.14 or 0.143, which is used typically for applications on land. It is also referred to as the “One seventh power law”. A list of typical values can be seen in Table 3 and some examples are illustrated in Figure 7.

Table 3: Typical shear exponents for different site conditions (Brown 2012)

Terrain type	Land cover	Approximate range of annual mean wind shear exponents
Flat or rolling	Low to moderate vegetation	0.12-0.25
Flat or rolling	Patchy forests or forest	0.25-0.40
Complex, sheltered valley	Varied	0.25-0.60
Complex, ridgeline	Forest	0.20-0.35
Offshore, temperate	Water	0.10-0.15
Offshore, tropical	Water	0.07-0.10

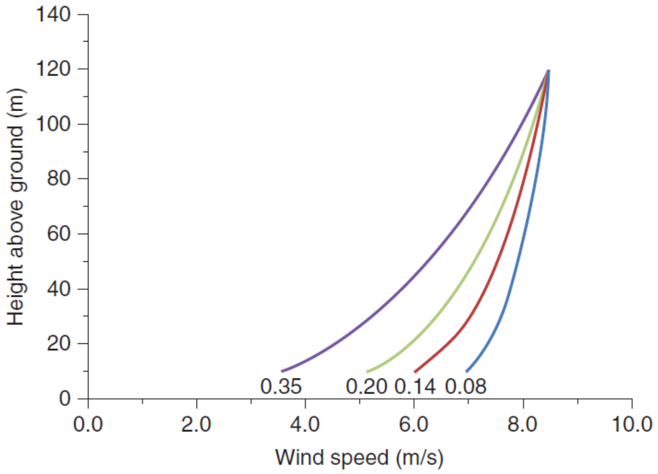

Figure 7: Theoretical profiles of wind speed with height (Brown 2012)

3.3.3 Turbulence

The term turbulence describes rapid fluctuations in the wind speed (and direction). It is a random phenomenon. Therefore it is typically expressed by its statistical properties. For example, the wind spectrum, which describes the energy content over the frequency, can be examined. Figure 8 shows such a spectrum. Another indication is the standard deviation σ of the wind speed (measured at 1-2s rates):

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(v_i - \bar{v})^2}$$

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[4] The near-neutral condition was defined by (S. Hsu 1992) and describes the atmospheric turbulence. It is depending both on the air-water temperature difference and the wind speed.

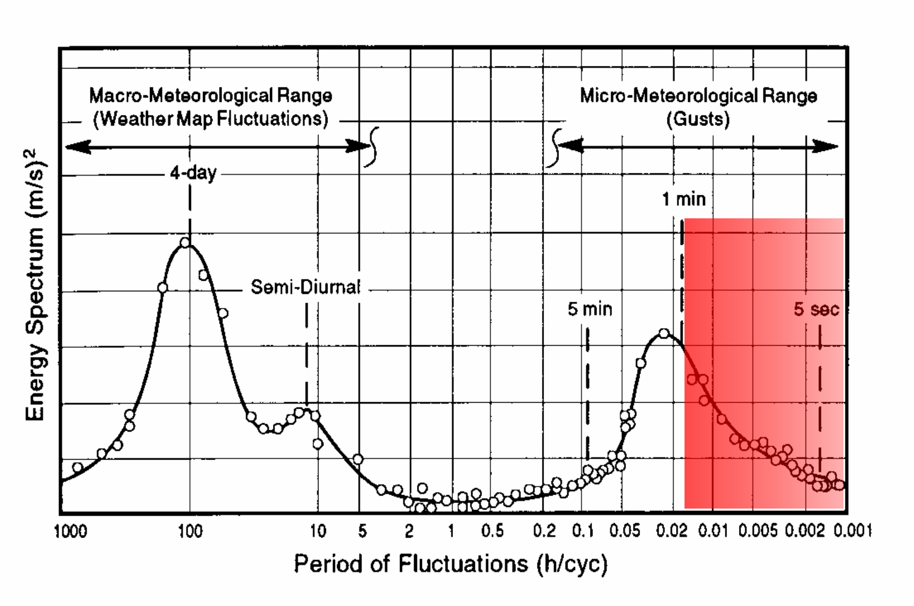

Figure 8: Energy spectrum of wind speed fluctuations, turbulence is indicated with red

In a second step one can divide the standard deviation by the mean wind speed to obtain the turbulence intensity:

$$I = \frac{\sigma}{|\bar{v}|}$$

The turbulence intensity can have a significant impact on the turbine performance. A high turbulence intensity can increase the wear and tear of the turbine and shorten its lifetime. Dynamic loads on the blades can increase too (Green Rhino Energy Ltd. 2013). For this reasons the turbulence intensity is considered while selecting a turbine type for a wind farm (Brown 2012).

3.3.4 Wind rose

In addition to the previous characteristics, the wind rose plot is presented. It is a polar plot showing the frequency of the wind by its direction. It is created by sorting the wind data into the desired number of sectors, typically 12 or 16. Wind roses also can contain information in addition to the directional wind distribution (Brown 2012). For example, the wind speed distribution or the energy content can be depicted too. Figure 9 shows a typical wind rose plot.

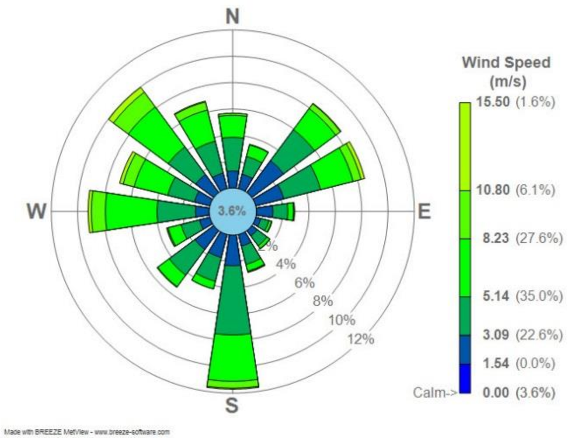

Figure 9: Wind rose plot showing directional and wind speed distribution (LaGuardia Airport, New York)

3.4 WIND INDUCED OSCILLATIONS IN CABLES AND AEROSTATS

In the previous section existing systems for offshore wind resource assessment have been presented. It was found that oscillation in a meteorological tower are neglectable as described in (P.J. Eecen 2008) and lidar systems suffer primarily from the motions of the buoy, which can be influenced by the wind but are primarily induced by waves.

However, a tethered aerostat can be strongly influenced by wind. The focus of this work is an investigation of the application of a tethered aerostat for wind assessment. Consequently, it is necessary to carry out research to understand the implications of using a rather flexible platform to carry the instrumentation. Motions and oscillations in the cable, which carries the instrumentation, can affect the wind speed measurement. Oscillations will not affect the mean wind speed because the temporal average of its vectorial velocity is zero for a typical time sample (10 to 30 minutes). The measured turbulence intensity, on the other hand, can be affected by a vibrating cable. Therefore some research is necessary to identify the oscillations that can occur.

3.4.1 Cables

Wind-induced oscillations in cables have been subjected to research for many years. Two big fields of research are e.g. cable-stayed bridges and overhead transmission lines. During this research four main types of wind induced vibrations have been identified and shall be presented in this section: Vortex-induced vibrations, galloping, flutter and buffeting (Kumar, Sohn und Gowda 2008).

Vortex-induced vibrations (VIV)

> Vortex shedding occurs when a bluff body is subjected to a fluid flow, which separates from a wider section of the body and gives rise to periodic vortex shedding from either sides of the body. This process causes fluctuating pressure forces on the body which lead to vibration. Figure 10 shows this process. Consequently a coupling between flow field and oscillating body develops (Kumar, Sohn und Gowda 2008). A lock-in phenomena[5] can be observed, usually if the frequency of vortex shedding is close to the natural frequency of the tether. Cables can oscillate heavily at non-natural frequencies too (Kumarasena, et al. 2007). A review of research results on VIV came to the conclusion that amplitudes of cable oscillation did not exceed an amplitude/diameter-ratio of 1.19 over a wide range of investigations. But data suggests that this is not the limit and more research is necessary (Williamson und Govardhan 2007). Considering the width of a typical tether of max. 10mm, this phenomena seems neglectable.

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[5] The phenomenon of "lock-in" describes the synchronization of the vortex shedding frequency and the natural frequency of the oscillating structure (Williamson und Govardhan 2007).

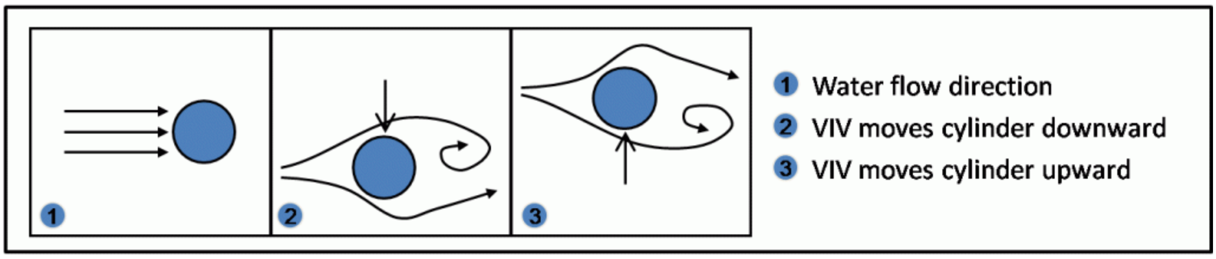

Figure 10: Vortex induced vibration of a cylinder in water

However, it shall be pointed out that passive control mechanisms have been developed to suppress VIV, which may be applicable to tethers. Some examples can be seen in Figure 11.

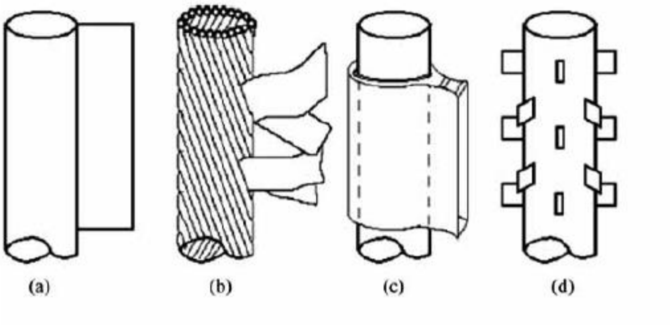

Figure 11: A selection of passive devices to control VIV

Galloping

Another type of vibration is called galloping and is a fluid-elastic and self-exited phenomenon. It is characterized by low frequencies and high amplitudes. The vibration occurs in the direction normal to the flow direction. Therefore it poses a problem for e.g. transmission lines, where winds can flow in parallel to the cable and thus induce heavy oscillations (Kumar, Sohn und Gowda 2008). In the case of a tethered aerostat however the flow of the wind will be mostly normal to the tether and therefore hardly induce vibrations. Figure 12 shows a bridge suffering from galloping.

Flutter

Even though being similar to galloping, flutter is characterized by high frequencies and small amplitudes. It occurs typically at aircraft wings and turbo machine blades. Especially non-circular sections are prone to this kind of vibrations as well as galloping (Kumar, Sohn und Gowda 2008). Thus, circular tethers are likely not affected by it. In Figure 12 a glider with fluttering wings can be observed.

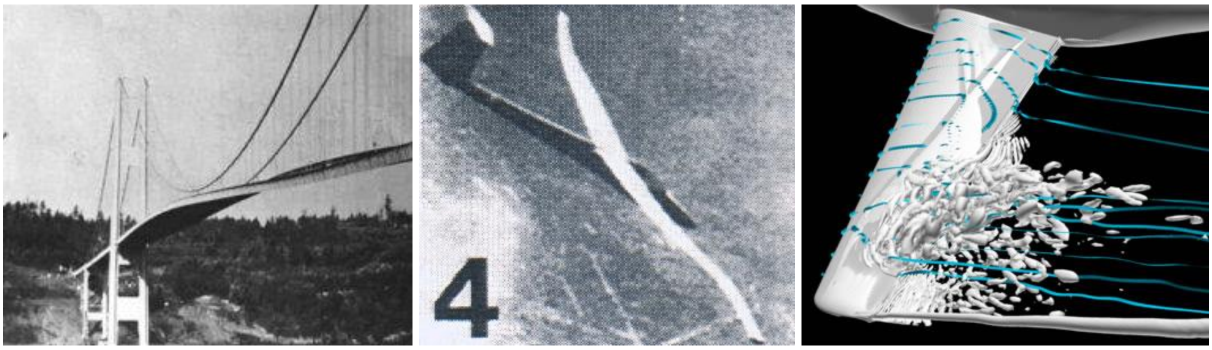

Figure 12: Examples for flow induced vibrations: A bridge suffering from a galloping runway, a glider with fluttering wings and downstream turbulence structures in a flow past a wing that can cause buffeting (from left to right)

Buffeting

The last type of flow-induced vibrations is buffeting. It is a random phenomenon induced by turbulences in the flow (Kumar, Sohn und Gowda 2008). For example, it can affect the tail unit of an aircraft structure due to air flow past the wing, see Figure 12.

The review on literature about flow-induced vibrations in cables leads to the conclusion that the effects on wind measurements are neglectable. Even the phenomenon most likely to occur, vortex-induced vibrations, produces vibrations of neglectable magnitudes.

3.4.2 Tethered aerostats

Not only is the tether prone to vibrations, but also the aerostat will undergo certain motions, if exposed to a fluid flow. In the literature research two approaches have been found to investigate the oscillations and motions of tethered aerostats.

The first approach - see (Sakamoto und Hanui 1989) and (Govardhan und Williamson 1997) - is to investigate the vortex shedding and the induced vibrations of a (tethered) sphere. Some conclusions were that the Strouhal number[6] of a sphere is close to 0.2 and different regions of vortex shedding can be identified (Sakamoto und Hanui 1989). Furthermore it has been found that translateral oscillation frequencies seem to be twice the transverse frequency, thus the sphere's trajectory is shaped like a lemniscate (Govardhan und Williamson 1997). However these results are only valid for low Reynolds numbers ($< 2x10^4$). This is much smaller than the expected Reynolds numbers for an aerostat in marine winds (which are already bigger than $Re = 10^6$ for a 5m sphere in 4m/s wind). The practical relevance of these findings for the progress of this work is therefore questionable.

The second approach is the performance of a stability analysis for a tethered aerostat, see (Coulombe-Pontbriand and Nahon 2009), (DeLaurier 1972) and (Lambert und Nahon 2003). During the

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[6] The Strouhal number is a dimensionless number describing oscillating flow mechanisms. It is defined as $St = \frac{fL}{v}$ where f is the frequency of vortex shedding, L is the characteristic length and v the fluid velocity.

investigation of a tethered sphere (tether length 15-45m) in an outdoor environment it was found that the sphere oscillated strongly in transverse direction. The normalized amplitude[7] was found to be increasing with increasing reduced velocity[8] and with values reaching 4. It also seemed independent of the tether length (Coulombe-Pontbriand and Nahon 2009). Another study was investigating the motions of a tethered blimp at two different heights (33.3m and 300m). They found the systems lateral pendulum mode to be more stable in high wind speeds with a short tether and in low wind speeds with a long tether. The amplitudes of the oscillation were not given in the paper. The periods in the range of 170-200s for the translateral were more than twice as high compared to the 30-40s for the transverse mode at 300m (Lambert und Nahon 2003). A third study investigated a similar blimp in much higher altitudes (up to 2400m). The ratio of transverse and translateral oscillation was, in contrast to the previous study, smaller than 1 with periods of 60-80s and 50-70s respectively. (DeLaurier 1972)

The presented findings indicate that aerostats will undergo substantial motions if exposed to wind. The oscillations seem to dominate in the transverse direction. However, the shape and type of aerostat seems to have a big influence on the frequency and the amplitude of the oscillation. Also the tether length has an influence. Therefore a detailed study is necessary that determines the exact behavior of the selected aerostat. A motion detection during operation seems advisable and ways to mitigate or control those motions should be investigated.

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[7] The normalized oscillation amplitude is defined as follows: $A^* = \frac{\sqrt{2}\sigma_{y'}}{D}$ where D is the aerostat diameter and $\sigma_{y'}$ is the rms value of the lateral transverse position.

[8] The reduced velocity normalizes V_R the fluid velocity U with the natural frequency of the tether f_N and its diameter D: $V_R = \frac{U}{f_N D}$

4 BALLOON-BOURNE MONITORING SYSTEMS

This chapter focuses on the application of balloons or aerostats for environment monitoring. After a brief outlook on the history of such operations, recent examples are presented. This gives an impression of the functionality and the capabilities of other balloon-bourne monitoring systems.

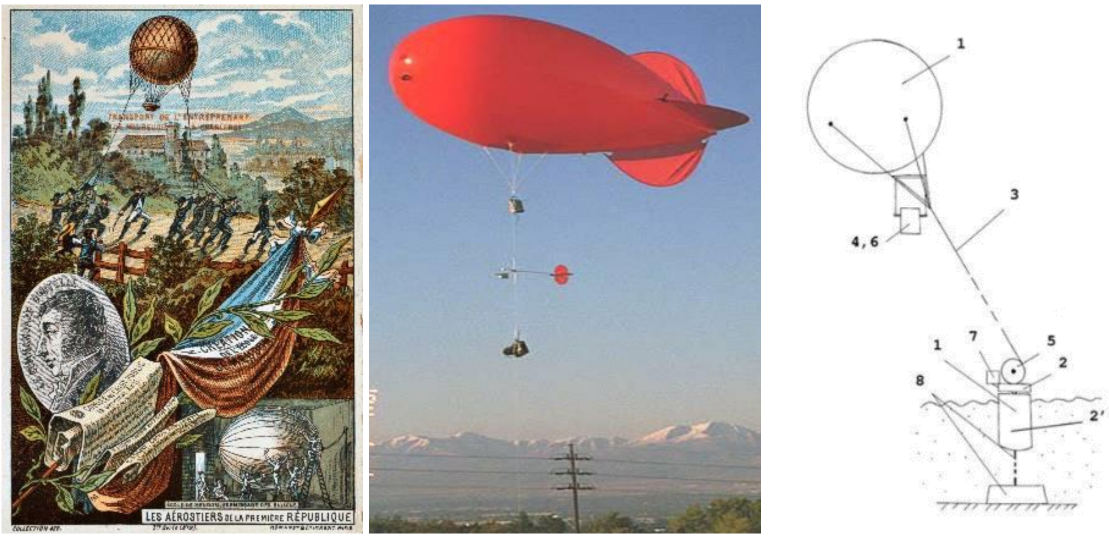


Figure 13: Development of balloon-bourne monitoring systems: Battlefield surveillance in the 18th century, a modern tethersonde system from Vaisala and a draft of an offshore monitoring system by Andriy Lyasota (from left to right)

4.1 HISTORY OF BALLOON-BOURNE METEOROLOGICAL MEASUREMENTS

The use of balloons for investigative purposes dates back to the nineteenth century. At that time airships were mainly used for military exploration and battlefield observations. During flights, for scientific purposes, the pilots carried so called meteorographs on the balloon. These were instruments that measured and recorded meteorological data such as temperature, pressure and relative humidity. Some of those devices also included simple anemometers to measure the average wind speed during the observation period (Lyasota 2013). In a marine context the operation of tethered balloons dates back to 1890. For research purposes the tethered balloons have the advantage that the marine boundary layer is relatively thin and ocean winds are often less turbulent than those over land (US Department of Energy 1993).

4.2 VAISALA

In 2003 the Finnish company Vaisala launched the DigiCora Tethersonde System for onshore boundary layer observations, Figure 14 (left) depicts such a tethersonde. The sondes comprised a cup anemometer, other meteorological instruments and a radio transmitter, each of which supplied by a battery pack. The main features of the sonde are listed in Table 4. The whole system could be attached to the tether at a point of choice, see the sonde in Figure 13. Two setups could be used for wind profiling, either one sonde or up to six sondes were attached along the tether. In the first case the aerostat would rise during operation whereas in the second case it would stay at constant altitudes. Apparently the production of the Tethersonde was canceled as it can not be found on the corporate website anymore. The DigiCora line, however, is still in operation using free-flying balloons to carry the instrumentation instead. This system is still operated by the U.S. Department of Energy (Holdridge, et al. 2011).

4.3 ANASPHERE

Another company that developed a tether-based system for boundary layer wind profiling is *Anasphere*. It is a US American company focused on research equipment for atmospheric analysis. Their tethersonde system is comparable to the one developed by Vaisala. It features similar instrumentation (anemometer, compass, temperature, pressure and rel. humidity sensors), a guide vane, wireless data transmission to a central receiver and is also supplied by batteries (Anasphere 2014). The sonde can be seen in Figure 14 (right). The price is around 5,500€ per sonde (Ed Figelman from FigTreeEnvironmental, personal communication, 24.01.2014). A self-selected aerostat for lifting the tether can be used. The system specification with the main features is listed in Table 4.

Table 4: Comparison of tethersonde systems by Anasphere and Vaisala

Tethersonde model	Weight in g	Operational time in h	Max. sampling rate in Hz	Max. wind speed in km/h	Instrumentation	Prince in €
Anasphere	737	9-11	1	50	Pressure Temperature Rel. humidity Wind speed Wind direction	5,500€
Vaisala	300	5-10	n/s	n/s	Pressure Temperature Rel. humidity Wind speed Wind direction	n/s

Source: Manufacturers information

Figure 14: Tethersondes by Vaisala (left) and Anasphere (right)

4.4 RECENT DEVELOPMENTS

Besides the two presented companies two additional developments were found, that are not commercialized yet.

4.4.1 Andreiy Lyasota, Universitat Politècnica de Catalunya

First, the work of Andreiy Lyasota at the Universitat Politècnica de Catalunya shall be mentioned (Lyasota 2013). In his master thesis he developed a system consisting of an aerostat with a landing platform that carried several meteorological instruments. Test flights at day and night were performed in wind speeds of up to 30km/h. Good precision of the wind measurements has been found in wind speeds of up to 10km/h. Further testing is planned with two additional anemometers, one close to ground and one attached to the tether. A patent has been filed at the *Spanish Patent and Trademark Office* (Lyasota 2013), seen Figure 15.

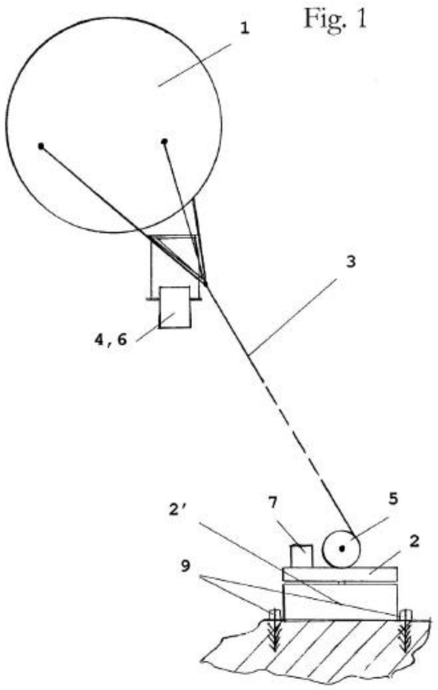


Figure 15: Drawing from the filed patent (Lyasota 2013)

4.4.2 ALLSOPP HELIKITES Ltd

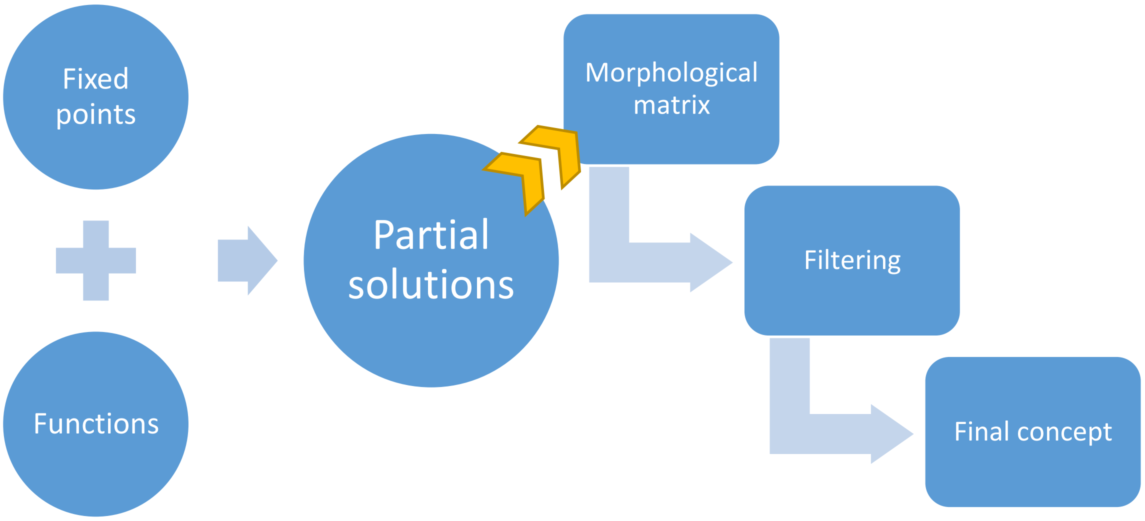
A second development was found during contact with officials from the company *ALLSOPP HELIKITES Ltd*, England. Allsopp is a supplier of helikites. They canvassed many wind companies on UK wind fares and developed a conceptual design to use their aerostat for offshore wind assessment. They see two major advantages over meteorological mast: much lower cost and the possibility to change the monitoring position. With the same investment to build one mast, a big number of “Helikite Met Mast” could be deployed to investigate the wind resource in a much larger area. The development is still in the R&D stage (Sandy Allsopp from Allsopp Helikites, personal communication, March 11, 2014).

5 DESIGN DEVELOPMENT OF AN OFFSHORE MONITORING SYSTEM

The obtained information, from the previous chapter, is the basis for the following development process. This process seeks a conceptual design for a new monitoring systems, which can operate in an offshore environment. To perform this development process several steps are necessary, which are:

1) Definition of the fixed points of the system including safety features
2) Definition of the functions the system has to fulfill
3) Proposition and detailing of partial solutions to implement this function
4) Transformation of the partial solutions into a morphological matrix
5) Filtering of the morphological matrix (Operational feasibility, cost, R&D efforts)
6) Final determination and visualization of the conceptual design

These steps can be transformed into a process which looks as follows:



The expected outcome of this process is one conceptual design. This concept consists only of partial solutions that meet the operational target, at low or medium cost and require little R&D efforts.

5.1 FIXED POINTS

The development of this conceptual design is different from a typical product development in two points. First, the desired outcome is not a product, it is a conceptual design. This means that many sub functions are excluded from this process. Once a conceptual design is determined it can be the basis of a product development with detailed engineering. The second point is that some of the features design are already fixed by the description of this work. Therefore they are excluded from this development process. Nevertheless they have a passive influence as they partially determine the functions of this process. The fixed features are as follows:

- The instrumentation is lifted to its operation altitude by a tethered aerostat.
- The measurement altitude is defined to be from 0 to 200m.
- The aerostat is launched from a buoy.
- The buoy is moored.
- The instrumentation is carried by sondes, which are attached to the tether.
- At least 3 sondes shall be used.
- A central data logger on the buoy with a wireless onshore connection.

Safety measures have to be implemented as well to ensure a secure operation of the system. Two things have to be safeguarded: a secure operation on sea and a secure operation in the air space above.

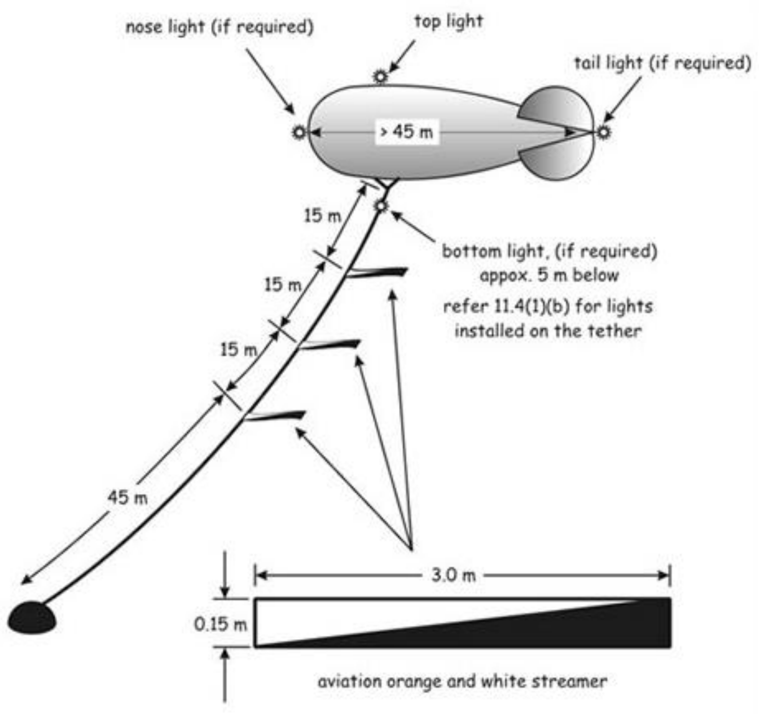


Figure 16: Safety measures for a moored balloon (credit Department of Transport, Canada)

A tethered balloon has to comply with the national aviation regulations if it enters the air space 150m above ground. Regulations usually demand two strobe lights, one on top of the aerostat and one below. Both must be visible from 360° and have either a red or a white light. Additional markings are necessary along the tether. For example, to comply with Canadian Aviation Regulations the respective safety measures are illustrated in Figure 16.

For the marine safety two measures are required, which are a radar deflector and a position light for operation at night. Also the buoy must be painted yellow to indicate, that it is no navigation aid and ships should generally not approach them.

5.2 REQUIREMENTS AND PARTIAL SOLUTIONS FOR AN OFFSHORE MONITORING SYSTEM

The fixed points and safety obligation were presented in the previous section. This section will discuss the functions that are required for the design development. For each function possible solutions are presented. An introduction is an outlook on the requirement list – focused on the aerostat – by Andriy Lyasota in his master thesis. According to him the "balloon in this case has to meet various special requirements":

- First, the aerostat has to survive the occurrence of harsh offshore winds with wind speeds up to 50m/s
- Second, the aerostat has to maintain a predetermined altitude independent of changes in the wind speed.
- Third, the aerostat has to stay in the air without losing altitude as long as possible to reduce costly offshore maintenance. (Lyasota 2013)

This can be interpreted as a first indication, which requirements are important. However, the listed requirements do not cover all the features of an offshore monitoring system. This may be caused by the focus of his work, which is primarily on a balloon for offshore wind monitoring. Also his work is limited to the stage of onshore trials and lacks the perspective for the complete future system.

In the development process of this thesis the requirements shall be laid out with a broader perspective and with the intention to cover all the necessary features. Therefore the presented requirements are translated into functions. The main functions are divided into five categories: operation time, data acquisition, energy supply, data transmission and supporting platform. These categories can also be called a transmission path or a primary function (Weber 1998). In each section the primary function is explained and broken down into several sub-functions. In a second step partial solutions for each sub-function are laid out. All this is done in the same section of this thesis for a better and clearer understanding.

5.2.1 Operation time

The first main function is the operational time of the system. As already pointed out in the section before, it is of crucial importance. Offshore maintenance is expensive and should therefore be limited to be done only once or twice a year. If the system is used for a preliminary site acquisition of one year, one offshore maintenance is necessary. The next maintenance can be combined with the relocation of the system. The most important thing to guarantee is the remaining of the instrumentation in the monitoring corridor. This means that the aerostat has to sustain its lifting force over the complete operation time. The lifting force is created by the buoyancy of the aerostat. To preserve its buoyancy the aerostat has to be filled with a gas, which is of lower density than air. Typically helium or hydrogen is used. Over time the lifting gas leaks out of the aerostat. The exact leaking rate is yet uncertain without real testing. Statements about leakage rates range from 0.7% of the volume per day (Steffen 2014) to 3% of the volume per day (Kevin Hess from Aerial Products, personal communication, 25.04.2014). Other sources estimate the losses as 0,0061m³ per square meter per day (Lee 2011). Apart from the aerostat materials the hull design (single/double ply) certainly has an influence too, see paragraph *Helikite/Spheroid* on page 33. The lost gas must be replaced constantly to maintain the lifting force. To execute the replenishment enough lifting gas has to be provided. Finally, the system has to resist strong winds as they increase the drag on the aerostat and eventually destabilize its flight and push it down. This should be prevented.

How can the lifting gas be replenished?

Overloading

A first possibility has already been pointed out by (Lyasota 2013) and is characterized by an overloading with helium and consequently a pressurized balloon. Since the balloon pressure is increased before launching, the additional lifting gas can compensate the leakage and thus increase the operational time. In his work Lyasota expects an operation time of on month can be achieved with a 25% overloading (using a loss rate of 5% per week). If the same calculation is done for the desired 6 month operation time, the pressure had to be increased by 361%. The subsequently increased helium density reduces the gross buoyance by roughly 42%, not accounting for a stronger and heavier aerostat design which is probably necessary to withstand the higher internal pressure. To compensate the loss in buoyance a bigger aerostat must be used to be able to lift the same payload a non-pressurized aerostat could lift, e.g. a 75m³ pressurized aerostat is necessary to obtain the same gross payload as a 43m³ aerostat with normal pressure. (An aerostat size of 43m³ is selected to check the several solutions, see annex A for the preliminary calculation.) The calculation was done without an increased leakage rate induced by a higher internal pressure. Therefore the overloading rate probably has to be even higher. In fact, the gas transmission through the aerostat material is directly proportional to the pressure differential between the partial pressure of helium inside and outside the aerostat (Ashford, Bata und Walsh 1986). Therefore the leakage rate will be substantially higher, while pressurizing the aerostat. Thus the overloading has to be even higher. Due to this fact the feasibility of this approach is more than questionable.

Take down

A second way to replenish the leakage of lifting gas is a tank on the buoy and an automated take-down and replenishment system. For onshore aerostat systems this is a standard procedure and has to be done manually by two persons once a week (Charlie Steffen from

Skydoc™, personal communication, February 28, 2014). Offshore only an automated process would be feasible, due to the high offshore maintenance cost. Therefore the buoy had to carry (in addition to the tank for the lifting gas) a winch for taking down the aerostat, an automated landing platform with a filling mechanism and a smart device that detaches and reattaches the meteorological sondes before and after filling. This means the buoy size has to be adjusted for the extra equipment. The necessary landing platform for a 43m³ sphere (with a 4.5m diameter) will need much extra space. Figure 17 depicts a similar onshore landing platform.

Figure 17: Heavy duty aerostat launcher from Skydoc (Steffen 2014)

Marine DC-winches, which are powered from batteries, can be found up to 1kW power (more powerful winches require usually AC supply). The necessary pull is at least 1t for a 43m³ aerostat (Charlie Steffen from Skydoc™, personal communication, February 28, 2014, for more detail see annex B). At this pull the speed of the winch is limited to 0.1m/s, again see annex B. This means the aerostat would need approximately one hour to land plus the time for refilling and launching. During this time no measurements can be done, which affects the wind assessment quality. Also a sufficiently large battery (around 1.5-2kWh, see annex B) is needed with appropriate energy production to power the winch. The topic of energy production is also discussed later in this chapter. Furthermore additional R&D will be necessary to develop the filling mechanism and the device to handle the sondes along the tether. Automated winches and landing platforms however are commercially available. For example, the winch and motor of the landing platform in Figure 17 are quoted at around 9,000€ (Steffen 2014).

Feed-tube

To avoid all the issues mentioned in the paragraph above, a third way to replenish the aerostat shall be presented. This option makes use of a feed-tube connecting a gas storage on the buoy with the aerostat. The feed-tube can either be embedded within the tether or run parallel to it. An embedded tube is better protected from the environment and will not induce vibrations by the formation of a non-circular tether crosssection, see section 3.4.1. For low altitude aerostats (less than 100m) generally helium bursts with high pressure can be used to feed an aerostat manually. However, this method suffers from two problems: The higher pressure bursts require a thicker tube wall, which results in a higher tube weight, and the friction of the gas in the tube creates heat which can damage the feed-tube. A patent claiming to overcome those issue has been filed in 2011 in the US (Lee 2011). One of the claims in the patent describes the composition of the tether and how the feed-tube is embedded, see Figure 18.

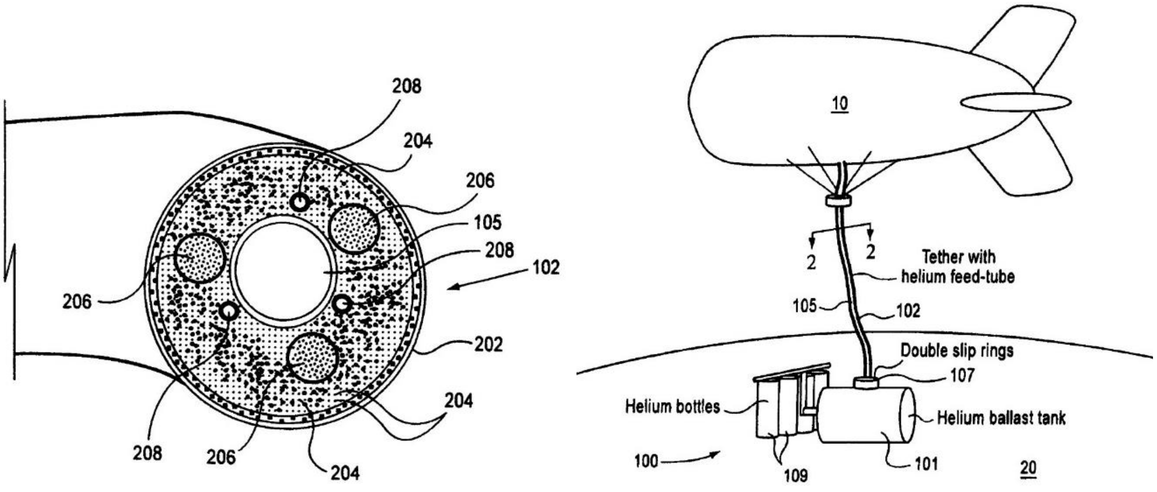


Figure 18: Left: Crosssection of tether (102), it features several components: a jacket for protection (202), the feed-tube (105), high tensile strength fibers (204), electrical cables (206) and optical fibers (208) Right: Feeded aerostat from a helium tank (101) and a double slip ring connector (107), attaching the tether to the tank; (Lee 2011)

Only the strength fibers should be under tension during operation, therefore the other components follow a catenary trajectory along the tether. The dimension of the different components depends on the specific requirements of the aerostat. The feed-tube must be wide enough to constantly replenish the lifting gas at low flow speeds. Further the electrical conductors are dimensioned according to the power demand of the aerostat. Finally the strength member must resist the expected forces on the aerostat. The tank is filled from helium bottles via computer controlled valves and a bi-directional pump (Lee 2011). The bi-directional pump is used to precisely control the pressure of the blimps. For the purpose of this system it is not necessary, because the aerostat will not be pressurized. Therefore a simple valve would be enough to release the helium from the tank into the feed-tube (or a pre-tank) to replace the leaking helium. The patent seems to be commercialized (AEROSTAT SOLUTIONS, LLC 2014) and is intended for the use of aerostats which provide telecommunication services (Stratocomm Corp. 2014). The system is called StratoComm *Helium Replenishment System* (SHRS) and can provide up to 8,5m³ of helium per day to an altitude of 1500m according to the manufacturer (Stratocomm Corp. 2014). Specific information about the system could not be obtained as no contact to the company could be established. Still the weight can be estimated to be around 6-10kg, see annex B.

The different partial solutions to fulfil the sub-function ***lifting gas replenishment*** of the main function ***operation time*** are summarized in the following table:

Partial solution	**Overloading**	**Take down**	**Feed-tube**
Operational feasibility?	No.	Yes.	Yes.
Cost	n/s	9,000€ +	n/s
Advantages	+ No extra devices necessary + Continuous operation	+ No additional weight + Standard procedure + Winches and landing platforms available	+ System available + Continuous operation
Disadvantages	- Bigger and stronger aerostat (at least 175%) - Less gross payload (at least 40%) - Leakage rate increases proportional with pressure	- increased buoy size (≈ $5m^2$) - R&D for filling mechanism and sonde handling - Battery pack (1.5-2kWh) - Energy production (several 100W)	- Extra weight (6-10kg) - Limits operation altitude - Still in development

How can the necessary lifting gas be provided?

<u>Helium cylinder</u>

The standard onshore solution for helium supply are helium cylinder. The leakage rates are neglectable as pressure in gas cylinders remains constant over years if handled properly (Daniela Kienbauer from Linde Gas, personal communication, 24.4.2014). A standard steel cylinder (0.3m diameter, 1.5m height) can hold up to 50l of helium - which equals to $9.1m^3$ - at 200bar. Helium prices for those cylinders are in the range of 20-50€/m^3. An alternative are the GENIE® gas cylinders from Linde AG. They store gas at higher pressures (300bar) and therefore have a more compact and lightweight design. Also they are resistant to direct sunlight, which can be an issue on an exposed buoy. Regulator options for helium are in the range of 0-10bar. In terms of required space the 20l GENIE® is more compact compared to standard steel cylinders. A visual comparison, see Figure 19, shows the more compact design of the 300bar cylinders. Additionally one GENIE® cylinder is only 0.6m tall which makes it easier to store on a buoy, since gas cylinder should be stored upright. (Linde AG 2012) Considering the 43m³ aerostat with a leakage rate of 0.71% per day, the lost gas will sum up to nearly 60m³ for a 180 day deployment. To provide this amount of helium either six 50l steel cylinders or ten 20l GENIE® cylinders are necessary. The steel cylinders weight around 325kg in comparison to 176kg for the GENIE® cylinder. The prices for the two setups are different. The steel cylinders with helium costs about 2650€, including the rent for the cylinders for 6 month and the initial filling. If supplied in GENIE bottles the costs are about 4600€. For the complete calculation see annex D.

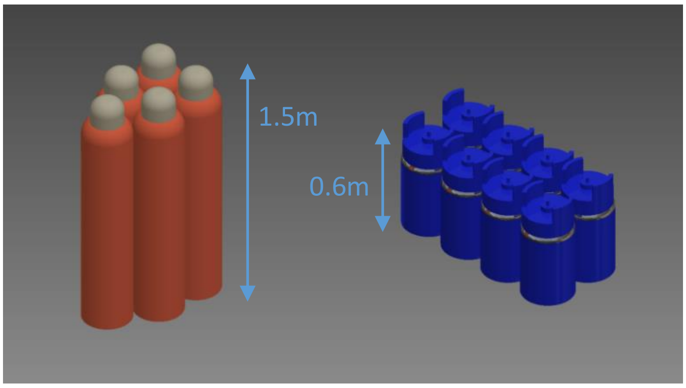


Figure 19: Same amount of helium in standard cylinders (left) and GENIE cylinders (right)

Hydrogen Cylinder

Even though helium is the standard lifting gas, the use of hydrogen should be considered for two reasons. First, hydrogen is lighter. The buoyance at sea level of hydrogen is 11.183N/m³ compared to 10.359N/m³ of helium (Breukels 2007). The second reason is the price difference, helium is more expensive than hydrogen. If the same amount of bottles with hydrogen instead of helium is used, the total cost are below 1200€. Nevertheless hydrogen is hardly used as a lifting gas today. The reason is its high explosion potential if mixed with oxygen. In combination with the electrical equipment of the aerostat and the sondes this can be a critical issue. A feed-tube having a hydrogen-hose and electrical conductors running side by side is a potentially even more dangerous combination.

Electrolyser

A third option is a production of hydrogen on site. As a result no more gas storage would be necessary. Small electrolysis systems are available on the market. For example the Hylyzer™-1 from Hydrogenics is such a small scale unit, using a Proton Exchange Membrane Elektrolyser, see Figure 20. It produces up to 1m³/h of hydrogen and requires 6.7kWh/m³ of energy and 0,83l/m³ of highly purified water. The system can be supplied from DC sources and produces hydrogen at up to 8bar pressure (Hydrogenics 2013). With a leakage of 0.22m³ per day the daily energy demand is roughly 1.5kWh and the average energy consumption 60W - assuming a continuous operation. This amount of energy has to be provided additionally and increases the necessary battery capacity. The amount of water needed for a 180 days deployment is roughly 50l. Furthermore the gas would be pressurized sufficiently by the elektrolyser to feed the aerostat directly without an additional compressor. A major disadvantage of such electrolysers is their design, which is intended for indoor operation. The feasibility of an offshore operation is uncertain. Even if a marine system can be developed a failure in the hydrogen production will soon terminate the mission and make expensive maintenance necessary. Furthermore the system is quite heavy (with a gross weight of 250kg) and expensive. A comparable system from HGenerators with a production capacity of 0.012m^3/h costs about 4000€. (HGenerators 2014). The required space is not significantly less as for gas cylinders. If the aerostat was larger, this solution would make more sense because of the high hydrogen production potential.

Figure 20: Hylyzer-1, size 0.75 x 0.66 x 1.17 (WxDxH)
(credit Hydrogenics)

The different partial solutions to fulfil the sub-function ***provision of lifting gas*** of the main function ***operation time*** are summarized in the following table:

Partial solution	**Helium cylinder**	**Hydrogen Cylinder**	**Elektrolyser**
Operational feasibility?	Yes.	Yes.	No.
Cost	2600-4600€	1200€	4,000€
Advantages	+ Robust design + Compact design available	+ Robust design + Cheap + Compact design available	+ Hydrogen production adjustable to leakage + No gas storage necessary
Disadvantages	- Storage space necessary (≈ 1m³) - Expensive	- Hydrogen is highly explosive - Storage space necessary (≈ 1m³)	- Expensive - Requires energy (60W) - Storage for water (50l) - Indoor design

How can the system keep its altitude in strong winds?

Helikite/Spheroid

One way to maintain the altitude can be achieved by increasing the lifting force in the event of strong winds. This can be achieved by using the force of the wind and translate it into a lifting force, similar to a kite. A kite, however, is not capable of carrying payload in no wind conditions. Therefore a combination of both - a balloon and a kite - is necessary. There exist three manufacturers that produce aerostats with this capability: Aerial Products (Aeriel Products 2014), Skydoc Systems LLC. (Steffen 2014) and Allsopp Helikites Ltd. (Allsopp Helikites 2014). Their products are spheroidal aerostats combined with a wing or kite construction, see Figure 21. All three types have in common the ability to resist strong winds. The maximum wind speed depends on the manufacturer, see Table 5. However, the aerostat will lose altitude and will not stay above its tethering point. To compensate and to guarantee measurements in the monitored corridor the aerostat should be positioned well above it in light wind conditions, see Figure 22. Also the influence of the hull design on the helium loss rate is of importance. Each of the mentioned manufacturer produces single ply and double ply aerostats. Double ply versions have a second and very resistant outside ply around the bladder containing the helium. However, double ply aerostats suffer from higher helium effusion. The helium in the aerostat will change its volume with temperature. In a double ply aerostat the outer and more resistant hull is usually less flexible too (compared to the flexible inside bladder). Therefore helium has to be vented if the helium heats up and increases in volume, which increases the overall losses (Lyasota 2013). For this reason the loss rates should also be considered while selecting the aerostat.

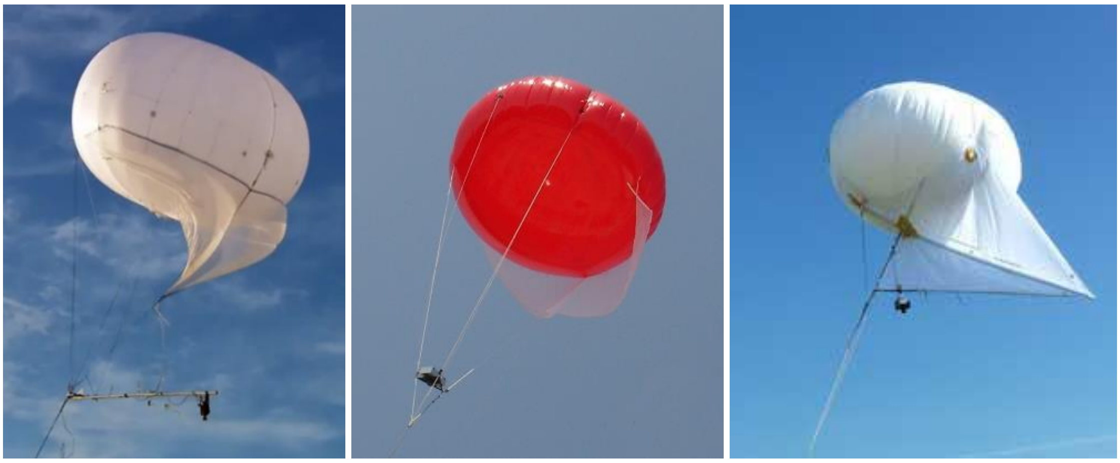


Figure 21: Aerostats types: Aerial Products (left), Skydoc (middle) and Allsopp (right)

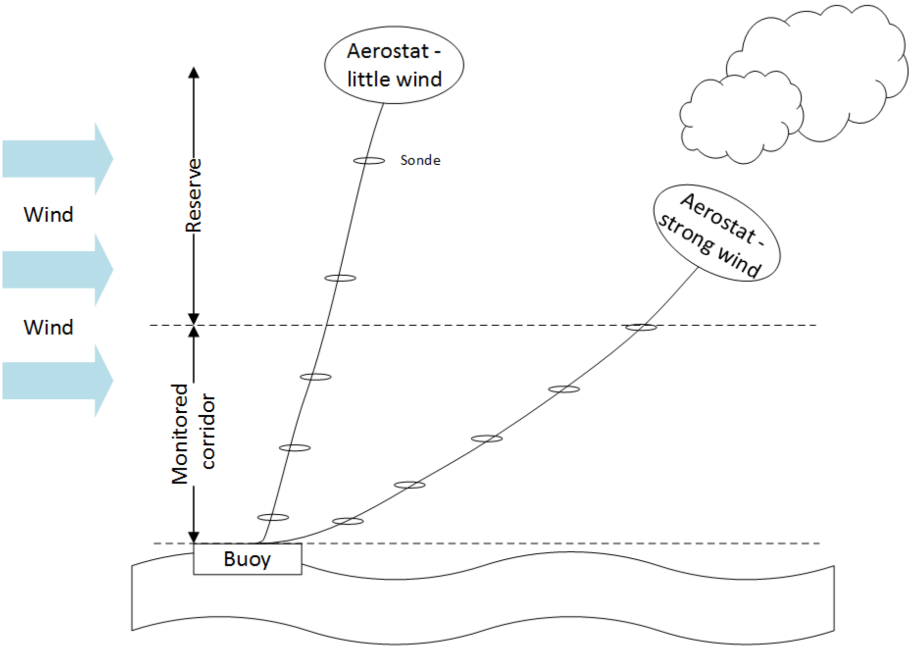


Figure 22: Aerostat behavior in strong winds

The characteristics of the different aerostats are summarized in Table 5 (again the products closest to approximately 43m³ in volume are used). One can see that the aerostats have similar properties. The maximal expected offshore winds in Portugal are in the range of 120km/h, see annex C. This equals to Beaufort number 12, which indicates a hurricane storm. Considering the occurrence of gusts, with even higher wind speeds, the aerostats from Skydoc™ are the only ones which are operational in this kind of conditions. However, the claim by Skydoc™ to supply hurricane-prove aerostats is questioned indirectly by other manufacturers on their websites (Aeriel Products 2014) (Allsopp Helikites 2014). Therefore this is a critical issue. The exact behavior in strong winds is not provided by the manufacturers either. Therefore field testing is necessary to understand the limits of the aerostat in terms of wind speed. Also the exact behavior of the aerostat and the loss of height as a function of the wind speed should be investigated, also see chapter 8. Even if the aerostat proofs its survivability it needs precaution measures in case of an emergency. A first measure could be a deflation device that can be activated in the event of a snapping tether. Such devices are offered by the manufacturers. A second thinkable measure is a breaking point in the tether. This device would measure the tension in the tether and disconnect it from the aerostat before the tether snaps. In that case only the aerostat is lost, but the buoy and the tether remain intact. Also the sondes could be recovered and reused if they remain sealed and unharmed by the waves and the sea water.

Table 5: Overview aerostats with wind resistant design

Aerostat	Volume in m³	Gross payload (no wind) in kg	Max. altitude in m	Max. wind speed in km/h	Helium loss rate	Price in €
Aerial Kingfisher™	48	30	1500	80	1-3%/day	7,500.00€
Skydoc™ Singleply	50	32	n/s	140	0.5%/day	6,500.00€
Allsopp Desert Star	34	14	2000	65	n/s	(assumed) 11,000.00€

Source: Manufacturers information

Winch control

A second approach to maintain altitude in strong winds is realized through a variable tether length, which is adjusted by a winch on the buoy. If strong winds occur more tether is let out, with little wind the tether is retrieved. This concept was found twice during state-of-the-art search too. One study came to a negative conclusions and doubted its feasibility (Lyasota 2013). The company Allsopp Helikites, however, implemented such a mechanism in a conceptual design (Sandy Allsopp from Allsopp Helikites, personal communication, March 11, 2014). The critical aspect of this concept is the power or rather the pull necessary to retrieve the tether in strong winds. In a prior paragraph it was already mentioned that a pull of 1t is necessary to retrieve the aerostat, which limits the speed of the winch dramatically. With such a slow winch speed an effective control of the aerostat seems questionable. A stronger AC-powered winch by a diesel generator could overcome this problem. A diesel generator, however, would make the buoy more complex and heavier. Also the storage of fuel on board makes the buoy more complicated in terms of legal and O&M requirements (Neptune 2014).

The different partial solutions to fulfil the sub-function ***keeping altitude in strong winds*** of the main function ***operation time*** are summarized in the following table:

Partial solution	**Helikite/Spheroid**	**Winch control**
Operational feasibility?	Yes.	Yes.
Cost	6,000-11,000€	Additional 9,000€
Advantages	+ Passive system + Several designs available + No extra equipment	+ Active control
Disadvantages	- Altitude changes with wind - Exact behavior is unknown - Survivability is questionable	- Powerful winch + generator (≈ 1kW) - Complicated legal and O&M requirements

5.2.2 Data acquisition

The second main function is focused on the acquisition of meteorological data. Meteorological data can be divided into two categories, primary quantities that are directly measured and secondary quantities that are derived from the former ones. In the DigiCora system with an ascending free balloon by Vaisala the division is as follows:

Primary quantities: pressure, temperature, relative humidity, wind speed and wind direction

Secondary quantities: altitude, dew point, ascent/descent rate, latitude and longitude of sonde (Holdridge, et al. 2011)

For the sondes along the tether the ascent and descent rate are not of importance, also the latitude and longitude will not change significantly. The most important quantities for a wind resource assessment are rather the wind speed and wind direction. Therefore appropriate instrumentation is necessary. Also the height of each wind measurement is of critical importance as already pointed out in section 3.3.2. Relative humidity and temperature are quantities that are easy to measure without major challenges. The main challenges are therefore the accurate measurement of the position, orientation and motion of the instrument during operation. Finally a hardware platform that combines all this features has to be selected, because the different sensors and instruments in the sonde need a common platform to gather, process and store their data.

Which instrumentation shall be used to measure the wind?

Instrumentation has already been discussed in section 3.2 and the two different anemometer styles were presented and discussed. For an offshore assessment the sonic anemometer seem to be more suitable compared to the cup design. Reasons are the robust design which is not negatively affected by a harsh environment with water and salt, the high temporal resolution to measure turbulence and a design without moving parts. The high prices for sonic anemometers can be overcome if a 2D version is used. Finally it shall be mentioned that the use of cup anemometers is not categorically unthinkable as they have been used on offshore met masts before.

The two partial solutions to fulfil the sub-function ***monitoring the wind*** of the main function ***data acquisition*** are summarized in the following table:

Partial solution	**Cup anemometer**	**Sonic anemometer**
Operational feasibility?	Yes.	Yes.
Cost	300-600€	500-2500€
Advantages	+ Simple design + Low to medium costs	+ 3D measurement possible + Better resistance towards marine environment and potential submersion + High temporal resolution
Disadvantages	- Moving parts - Need precise calibration - Medium lifetime in marine environment	- Expensive - Can be affected by rain

How to detect the position and motion of the instrument?

<u>DGPS (EGNOS)</u>

One way to detect the position and motion of the instrument is the use of a GPS receiver in the sonde. The GPS signal will indicate the position of the sonde as well as its motion over ground. Since the standard GPS has a horizontal accuracy of only 17m (Global Navigation Satellite Systems Agency 2014) a more precise system is necessary. For example, a differential GPS (DGPS) system, which corrects the GPS signal using reference stations on the ground, improves the accuracy significantly. Stand-alone DGPS systems with an on-site reference point are very precise (few cm accuracy) but very costly too; for example the equipment used in (Coulombe-Pontbriand and Nahon 2009) was quoted at 16,000€. Thus, a public system like the European Geostationary Overlay Service (EGNOS) is a reasonable alternative. The EGNOS system was launched by the European Union as a part of the European Satellite Navigation Policy in 2003. The system makes use of distributed ground stations to improve the GPS accuracy. The system was developed for marine navigation and can also be used offshore, see the availability map in Figure 23. By using such a system the accuracy can be improved to less

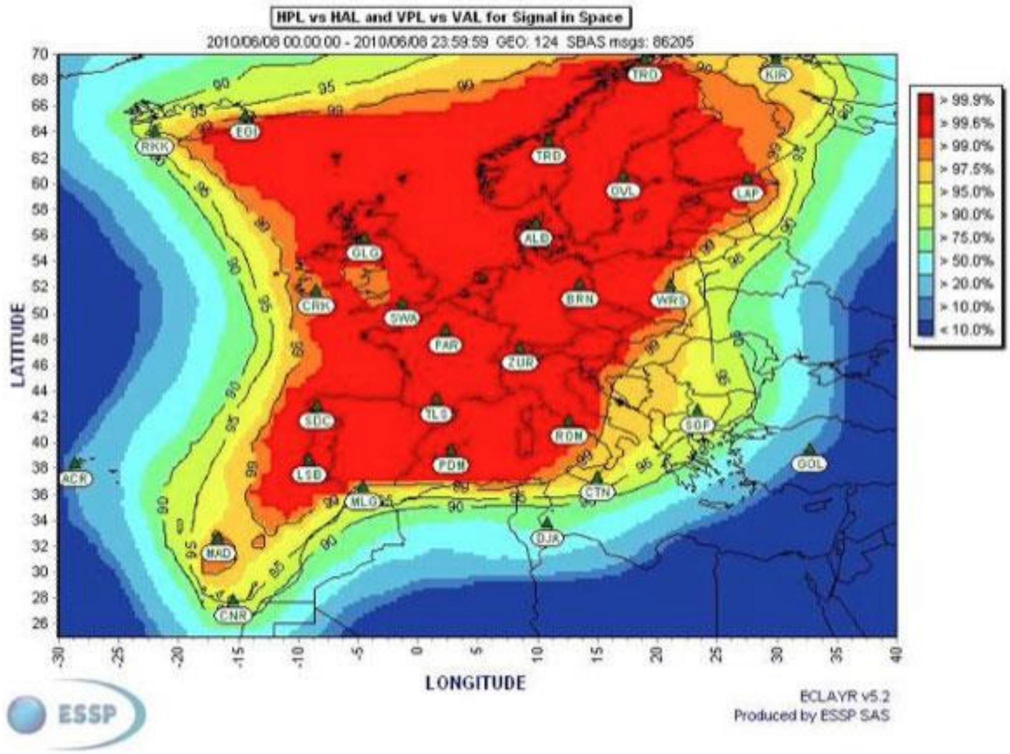


Figure 23: Availability and reference ground stations of the EGNOS system

than 2m, in Lisbon the vertical and horizontal accuracy are 1.7m and 1.1m respectively (Global Navigation Satellite Systems Agency 2014). Estimating the height of the sonde with such an accuracy seems appropriate. In annex E an error estimate was calculated for a typical measurement. An error of 0.44% was found for the estimated wind speed. This is seems to be a tolerable error range, considering that meteorological towers have a 3% measurement error induced by the tower structure disturbing the wind (see section 3.1.1). One disadvantage of (D)GPS is the energy consumption of the receivers (0.01W for a GPS Shield with EGNOS supply, see annex E). However an intelligent software routine may overcome this issue with e.g. sleeping routines. EGNOS compatible receivers are widely available in different applications with cost comparable to regular GPS receivers.

Orientation sensor (pressure + acceleration)

A second possibility is the use of a combined orientation sensor. The measured pressure is used to derive the altitude of the sonde. This is combined with an accelerometer, which detects the motions of the sonde. The application of a barometer as an altimeter has been approved to be successful for indoor and outdoor navigation, enhancement of GPS navigation or sports and leisure activities. Also for the purpose of balloon-bourne monitoring – e.g. see (Holdridge, et al. 2011) and (Lyasota 2013) – the pressure has been used to calculate the measuring height. The change of pressure with height is approximately 1hPa per 8,2m (Lyasota 2013). To correct for the occurring daily pressure variations the atmospheric pressure at sea level can be used as a reference. Recent barometer chips offer very low noise and high resolutions, see annex E, but have a critical accuracy. For example, the barometer in the DigiCora system (Holdridge, et al. 2011) uses a barometer with 0.1hPa resolution and has an accuracy of only 0.5hPa (corresponding to a variation of 4.1m). A more precise BMP280 pressure sensor from Bosch has an absolute accuracy of 1hPa and a relative accuracy[9] of 0.12hPa. Assuming this two accuracies as the maximum altitude errors, which is corresponding to a variation of 8m/1m, the same calculation can be done as in the paragraph before. The error in the estimated wind speed is 2.1%/0.26% for those two cases. Turbulence in the wind may also affect the measured atmospheric pressure, even though no literature was found to verify this doubt. Due to this lack of information on the exact accuracy, intensive testing in operation conditions is necessary. The horizontal displacements can not be quantified with a pressure sensor, but seem to be less important. They could be measured with an accelerometer, which measures the acceleration of the sonde and derives its motions. Accelerometer and barometer are widely commercially available and have low costs and low energy consumptions. Also combined, and more costly, “orientation sensors” can be found with an integrated pressure measurement like the VN-200 SMD from Vectornav.

Optical/Ultrasonic range finder

A third possibility to detect the height could be a range finder that uses laser or sound pulses to detect the distance to the sea surface. Ultra sonic range finders exist in many variations and are applied e.g. in automated robots. However their range is usually limited to a few meters, which is not sufficient. Range finders working with time-of-flight lasers have bigger ranges of over 1000m. The most common application for this devices are e.g. military purposes or golf sport. The products for this markets are typically hand held and battery powered. Hacking them for engineering purposes can be very difficult (Seidle 2011). Thus they seem inappropriate for this purpose. Industrial laser sensors finders can be used alternatively. They have serial connections for communication with an external device. They have been used for altimetry purposes before, e.g. by the NASA for unmanned autonomous vehicles (Acuity 2014). A selection of appropriate range finders in annex E shows their high energy consumption, high costs and high weight. Therefore the application would be advisable only for the aerostat, but not for the sondes. If used on the aerostat, a vertically orientation must be guaranteed, e.g. by a special mounting.

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[9] *Relative accuracy* means for a pressure of 950-1050hPa and at temperature of 25°C.

The different partial solutions to fulfil the sub-function ***detect position and motion of instrument*** of the main function ***data acquisition*** are summarized in the following table:

Partial solution	**DGPS (EGNOS)**	**Orientation sensor (barometer + accelerometer)**	**Optical/Ultrasonic range finder**
Operational feasibility?	Yes.	Yes.	Yes.
Cost	< €100	< €50	900-2600€
Advantages	+ Simple design (uses GPS hardware) + Same prices like regular GPS receivers	+ Very good resolution available + Cheap + Low energy consumption	+ High precision + Used for similar purposes before
Disadvantages	- Mediocre accuracy (1-2m) - High energy consumption (≈ 0.1W) - Availability <100%	- Bad absolute accuracy (4m+) - Exact accuracy unknown (temperature, wind)	- Costly - Heavy - Vertical orientation must be guaranteed

How to detect the cardinal direction of the sonde?

Digital 3D magnetometer

The standard solution to detect the cardinal direction of the sonde is a digital compass. The system from Vaisala and Anasphere described in sections 4.2 and 4.3 both make use of such an instrument. A digital compass is basically a magnetometer measuring the magnetic field of the earth. Applications are e.g. handheld devices or smartphones. The prices for three-axis magnetic sensors range below 1€ (Jones 2010).

The partial solution to fulfil the sub-function ***detect cardinal direction of instrument*** of the main function ***data acquisition*** is given in the following table:

Partial solution	**Digital 3D magnetometer**
Operational feasibility?	Yes.
Cost	1€
Advantages	+ Mature hardware + Very low cost
Disadvantages	- Possible perturbations by electric equipment

How are the different components in the sonde combined?

Hacking an existing sonde

Looking at the existing tethersonde systems presented in Chapter 0, a first idea would be to take an existing sonde and try to "hack" it. This means buy the sonde, change and implement new hardware if needed and fit it for a 180 days offshore mission. Apart from the technical challenges this seems not a very cost-effective solution considering the price for a T*ethersonde* from Anasphere of 5,500€.

Arduino

A more promising alternative in terms of costs is an Arduino[10] based system. The application of Arduino hardware for weather observation is not difficult. Many modules (including sensors and power supply modules) are commercially available at online shops, e.g. *Seeedstudio* or *Sparkfun*. However, the necessary casings with IP 68[11] standard do not come off-the-shelf and have to be custom-made. Tutorials of existing system can be found, e.g. building a remote weather station for kitesurfing (Sanchez Clariá 2014). Since the Arduino system is focused on prototyping, the different modules are very low cost. A sonde with a comparable setup to the Anasphere tethersonde could be bought for a fraction of the money, see annex F. Also compatibility with external instrumentation is no problem. Marine sensors usually communicate using the NMEA0183 protocol[12] which can be processed by every Arduino or Raspberry Pi (Christophe Michel from LCJ Capteurs, personal communication, March 31, 2014).

Figure 24: Arduino weather station design (Sanchez Clariá 2014)

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[10] „Arduino is an open-source electronics prototyping platform based on flexible, easy-to-use hardware and software. It's intended for artists, designers, hobbyists and anyone interested in creating interactive objects or environments." (Arduino 2014)

[11] The Ingress Protection code classifies and rates the degree of protection provided against e.g. intrusion, dust and water. The code 68 classifies a casing, which is dust tight and protected against continuous immersion in water. (NEMA 2004)

[12] The NMEA 0183 standard is a voluntary industry standard, first released in March of 1983, by the National Marine Electronics Association (NMEA). It defines an electrical interface and data protocol for communications between marine instrumentation. (Betke 2000)

Custom microcontroller

The third solution, the development of a custom microprocessor board, is the logical continuation of an Arduino-based system. As soon as a proof of concept has been achieved, the development of a custom microcontroller board is advisable. Basically the same chips and modules are used but implemented on a dedicated board. Therefore redundant chips and wires are not needed anymore, which will reduce cost and weight. The system is more compact and can be suited exactly for the needs of the instrumentation. Again a watertight casing with IP marking of 68 or higher is necessary. It requires additional R&D, but, once developed, this board can potentially be produced at lower cost than an Arduino-based system.

The different partial solutions to fulfil the sub-function ***combination of sonde components*** of the main function ***data acquisition*** are summarized in the following table:

Partial solution	**Hack existing sonde**	**Arduino**	**Custom microcontroller**
Operational feasibility?	Maybe.	Yes.	Yes.
Cost	> 5,500€	< 1200€	<< 1200€
Advantages	+ Use of existing structures	+ Fast prototyping and developing + Cheap + Flexible	+ Probably cheaper than Arduino + More compact + Mass producible
Disadvantages	- Expensive sondes - Technical challenges	- Redundant parts e.g. cables, connectors, etc. - Not mass producible - Limited hardware selection	- R&D to develop board - Not flexible

5.2.3 Energy supply and storage

The equipment of the total system has to be supplied with energy. One can divide the energy supply for the whole system into three subsystems, which are: The supply for the buoy, the sondes and the aerostat. For each of the subsystems either independent energy production plus storage or a way to connect it to another subsystem has to be identified. The energy supply of the subsystems obviously depends on the other partial solutions of the system. For example a winch on the buoy would dramatically increase the energy demand. Therefore different energy consumption characteristics have to be kept in mind while detailing the partial solutions. A short overview of the different consumers is given in Table 6 to understand these characteristics. The basic consumption is the energy consumption of equipment which will definitely be implemented, whilst the additional consumption depends on equipment which may be implemented depending on the particular concept. The peak and average consumption are given since they can be different.

Table 6: Expected energy consumptions for the subsystems, including possible additional consumptions

	Basic consumption			Additional consumption		
	Type	Peak	Average	Type	Peak	Average
Sonde	Instrumentation:	0,25W	0.25W	Radio link:	>0.1W	0.1W
Aerostat	Position lights:	55W	11W			
Buoy	Data logger incl. satellite link:	50W	10W	Winch height control:	1000W	500W
	Position lights:	27.6W	5.5W	Winch take down:	1000W	10W
				Elektrolyser:	60W	60W

After presenting the dimensions of the necessary power demands, different solutions can be developed and laid out appropriately.

How can the aerostat be supplied with energy?

Battery

Beginning with the aerostat, several solutions are conceivable. The standard solution which is also promoted by the aerostat manufacturer is the use of a battery pack. Several battery types can be used, an overview of the most common battery types is given in Table 7. Obviously lithium (ion) polymer batteries have the highest power density, which makes them the most suitable for the application in an aerostat.

Table 7: Battery type characteristics (Thackeray 2004)

Battery type	Theoretical spec. capacity in Ah/kg	Open circuit voltage in V	Theoretical spec. energy in Wh/kg	Practical spec. energy in Wh/kg	Number of cycles
Lead acid	83	2.1	171	50	500-1000
Nickel-Cadmium	162	1.35	219	60	2500
Lithium-polymer	340	2.6	884	155	600

With the energy demand of the aerostat and the minimum operation time the weight of such a battery can be calculated using the characteristics given in Table 7. In the case of a lithium polymer battery this would be more than 300kg, see annex G. An additional payload of this magnitude is not acceptable, thus this solution is not feasible.

Via Tether

Since batteries are no viable option, other solutions must be identified. As mentioned before tethers can comprise electrical conductor to power the aerostat. This option is offered by aerostat manufacturers for the tether and is part of the feed-tube concept described in section 5.2.1. The conductors are designed for the power demand of the aerostat to minimize the weight as much as possible. Two position lights on the aerostat require 0.5A each. Thus, the conductor diameter has to be at least 0.6mm considering the allowed ampere capacity (ampacity) for copper, see annex G. A slightly bigger conductor of 0.7mm copper wire will account for an additional payload of 2.7kg for a 400m length. Being only a fraction of the weight for a battery this is a reasonable option. The additional cost are around 1,100€ for two conductors (Charlie Steffen from Skydoc™, personal communication, 05.05.2014). Considering the sheath of the wires a total weight of 3kg seems reasonable. Applying such a powered tether also poses some difficulties. One is the fatigue of the conductors. During operation it has to be made certain that the conductors are not exposed to tension during buoy and aerostat motions. The tether is expected to act like a spring between buoy and aerostat. During operation it will undergo millions of cycles of elongation and contraction to compensate the motions of the buoy and the aerostat. This would certainly break any other member of the tether that is exposed to this forces. Also the weight of the conductor increases by the square of the conductor diameter, which makes this partial solution very sensitive to the conductor diameter. With a 1mm conductor the extra weight is already more than 5kg.

Solar panel

A third option for the aerostat is direct on-board energy production. A solar panel makes the most sense because the top of the aerostat is always exposed to sun, energy production is predictable and solar cells are lighter than wind generators. The solar cell must have around 250-300W to ensure sufficient power. The size of the solar cell depends on the type, anyway it should fit on a 43m^3 aerostat, for further information see annex G. The price for those cells are in the range of 2,700-5,200€ including batteries for 24h backup. To have energy supply at night an additional battery pack is needed, with a backup capacity of 24h this weights around 0.5kg using four 6.6Ah lithium polymer batteries. All in all, this setup is in an acceptable weight and price range. It is an independent system mounted directly on the aerostat. Therefore no conductors are exposed to the forces in the tether. Flexible solar cells intended for outdoor application are commercially available and are field proof. See one example in Figure 25. Attaching a solar cell of this size on the aerostat could be challenging. To avoid disturbances of the aerodynamic behavior the solar cell must be fixed firmly. One thing to note here, is that a solar based solution is heavily dependent on the geographic position, especially in winter. For example, the lowest radiation in winter in Porto is around 1kWh/day, whereas on Madeira the lowest radiation in winter is twice as big with 2kWh/day. If the system is supposed to be operated further north during winter, bigger solar panels are necessary.

Figure 25: Flexible solar cell: rolled up, unrolled and in action (credit PowerFilm®)

The different partial solutions to fulfil the sub-function ***supply aerostat with energy*** of the main function ***energy supply*** are summarized in the following table:

Partial solution	**Battery**	**Via tether**	**Solar panel**
Operational feasibility?	No.	Yes.	Yes.
Cost	15,000€	1,500€	2,700-5,200€
Advantages	+ Standard solution onshore	+ Medium weight (extra 3kg) + Offered by aerostat companies + Low cost	+ Medium weight (6.5kg) + Medium cost
Disadvantages	- Very heavy (>50kg) - High cost	- Conductors may break due to tether motions/forces	- Attachment may be challenging - Sensitive to irradiation - Medium cost

How can the sonde be supplied with energy?

Battery

Basically the solutions for the sonde are the same as for the aerostat, but on a smaller scale. Also for sondes an energy supply from batteries has been the standard option, as described in section 4.2 and 4.3. Again the same calculation can be done as for the aerostat with the result of a battery weight of at least 8kg to power a 180-day mission. This is not a viable option.

Via tether

The option of an energy supply from the tether is possible for the sondes, too. However, with some additional challenges. With several consumers along the tether the most convenient way to connect them is in series. But if a conductor breaks, the whole system becomes inoperative. For that reason a parallel connection is preferable, which increases the amount of conductors and consequently the weight. Even though the power demand of a sonde is very low, the conductor diameter can not be decreased equally for two reasons: first, a very thin conductor has a high resistance which accounts for higher voltages losses in the tether and secondly, a thinner conductor will break easier. Using a 0.4mm conductor for the sondes, the additional weight for the conductor is 1.15g/m, which sums up to 0.45kg per sonde for a 400m tether. This is substantially lighter than the battery solution. Although power supply via tether for the aerostat has been developed and is commercially available, a method to supply equipment along the tether has not yet been introduced. The conductors would have to connect many points along the tether, which is significantly harder to realize than embedding two conductors over the whole tether length. To achieve such a multi-point connection, either an adaptor for each sonde would be needed, interrupting the prefabricated tether or, alternatively, the connection points for equipment are already implemented during fabrication. The first option seems technically challenging considering a tether with a feed-tube for helium and possibly optical conductors inside. The second seems less difficult, but still poses challenges (R&D, cooperation with manufacturer etc.). Either way, breaking of conductors is still a possible source for failure. Since this option is not commercially available, no prices are available.

Solar panels

Also an energy supply from small solar panels, similar to the solution for the aerostat, is possible, see Figure 26. To power the sonde a solar cell of about 9-12W is sufficient, see annex H. The face of the solar cell(s) will be of 0.07m². This is not much - for comparison, a DinA4 paper has 0.063m² - and can be put on a sonde. However, it has to be considered that such a big surface may induces motions on the sonde while being exposed to the wind. Therefore an intelligent implementation in the sonde design is necessary, e.g. using the cells as a wind vane. The weight of the cells will be around 200-300g, depending on the cell configuration (4x3W, 6x2W etc.). The corresponding battery for 24h backup weights around 160g. The whole equipment is not costly. If such a solution is used it is beneficial if the power consumption is as low as possible. First to reduce the size of the solar panel and thereby reducing the weight and the surface area as much as possible too. And secondly to overcome the same geographic restrictions as discussed before and make an operation in northern Europe possible. The biggest consumers onboard are the microcontroller onboard and the anemometer. A GPS module and a radio transmitter also have high consumptions if used, see annex F. Therefore the biggest efforts should be invested to lower their consumption, e.g. by reducing transmission time and power of the radio link or GPS location rates.

2W Solar Panel 80X180

USD ⌄ $7.95

SKU: POW816520
Weight: 65 g
Designer: Others

Figure 26: Solar panel from Seeedstudio.com

The different partial solutions to fulfil the sub-function ***supply sonde with energy*** of the main function ***energy supply*** are summarized in the following table:

Partial solution	**Battery**	**Via tether**	**Solar panel**
Operational feasibility?	No.	Yes.	Yes.
Cost	500€	n/s	< 50€
Advantages	+ Standard solution onshore	+ None	+ Low weight (0.5kg) + Low cost
Disadvantages	- Very heavy (8kg)	- Conductors may break due to tether motions/forces - Heavier tether - Not offered by supplier - Additional adapters have to be developed	- Big surface exposed to wind - Sensitive to irradiation

How can the buoy be supplied with energy?

Battery

Just as the sondes and the aerostat could the buoy be powered from batteries. It is more sensible since the weight is not as critical as on the floating parts of the system. The amount of batteries is depending on the power consumption of the different components. Earlier in this chapter a 2kWh battery bank was discussed. A battery pack that can supply just the 10W (for the beacon light and the central data logger plus communication) for 180 days already requires 14 batteries with a price of about 15.000€. They would consume around 0.5m³ of storage space and weight around 800kg. This setup (to sustain an average consumption of 10W) already is very costly and needs a lot of space.

Renewable Sources

As batteries are very expensive the option of onboard production is discussed next. The two renewable energy sources that are typically used on buoys are solar panels and micro wind turbines, as done on the Wind Sentinel™ in Figure 2 or the Neptune in Figure 27. Marine solar cells and marine micro wind turbines are commercially available in many sizes and power ratings, see annex I. Solar cells are available up to 300W whilst wind turbines can be found with higher power ratings. Usually a utilization of both, wind and solar energy sources, is preferable to level out the production and have a redundant supply. For example in winter solar irradiation is low but average wind speeds are high, whereas in summer when the solar irradiation reaches its maximum the wind speeds tend to be lower.

Figure 27: Neptune bouy and comparable solar cells and wind turbines

The amount of energy production that can be installed depends on the size of the buoy. The 500W scenario can hardly be realized with renewable energy sources. But for a consumption of 15W and 85W appropriate equipment has been selected, see annex I. The price for such installations are between 2130€ and 6200€. Such a setup is very lightweight (10-35kg) and consumes little storage space inside the buoy, which both is advantageous.

Generator

If higher energy densities are required a generator can be used. The use of a generator and its implications have already been discussed in a previous section when discussing the necessary power for an electrical winch. In fact, an altitude control via a winch will likely be very energy demanding and require an AC power supply. In contrast to batteries, being a classic DC power source, a generator can produce 1-phase or 3-phase AC power, depending on the generator type. Combinations of an AC-winch plus diesel generator are also offered by aerostat manufacturers, like Allsopp (Allsopp Helikites 2014) or Skydoc™ (Steffen 2014). The higher legal and O&M maintenance requirements were mentioned before. Especially the O&M of a generator can be very demanding. For example, a Honda GX270 generator (which is specially designed for marine environments, see Figure 28) offered by Skydoc™ needs regular maintenance: oil has to be replaced every 100h of operation, air filters have to be cleaned every 50h and after 500h the combustion chamber has to be cleaned. A 180-day mission has about 4300h in total. The operation hours however depend on the power demand and the rated power of the generator, e.g. the GX270 has 6.3kW. To supply an average power demand of 500W it has to run almost two hours per day. Thus, an air filter change would be due after 25 days, an oil replacement after 50 days. Both is impossible on a 180 day deployment without maintenance. For the reduced consumption scenarios of 15.5W and 85W, however, the service intervals are bigger than 180 days. If a generator is selected the amount of fuel that has to be stored on the buoy should be estimated. For a half-year operation the necessary diesel fuel is around 25l, using an average power demand of 15.5W, and 822l for an average consumption of 500W, see annex I. An 822l tank would require a lot of space, almost 1m³, and hardly fit on a small buoy together with the gas cylinders. A 25l tank however is a small standard size, Figure 28 shows a model from Vetus. About the extra legal requirements no precise information were found, ventilation devices for the fuel storage and means for fire extinguishing are probably necessary. Also a generator is not an eco-friendly solution. However, generators are quite compact and have medium cost, e.g. the Honda GX270 can be acquired for around 1400-2200€ (plus tank and extras) and weights under 50kg. Even though requiring a lot of space for the fuel, a diesel generator is the only presented power source, which is theoretically able to supply a winch with enough power for aerostat control.

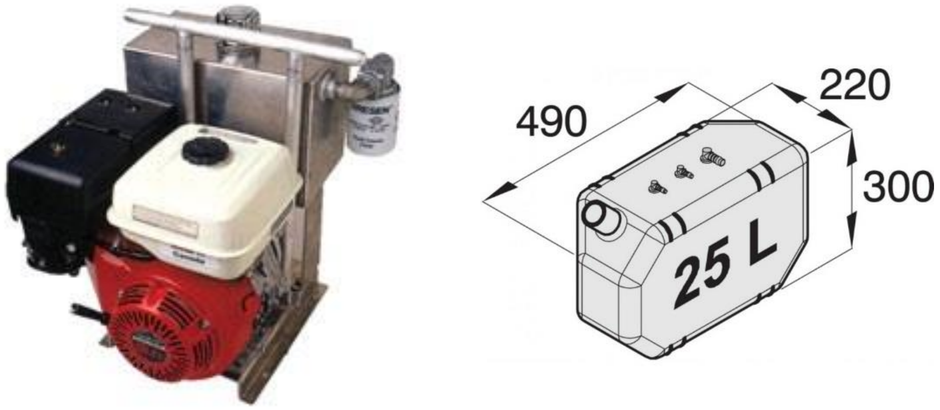

Figure 28: Honda GX270 and a 170l diesel tank

The different partial solutions to fulfil the sub-function ***supply buoy with energy*** of the main function ***energy supply*** are summarized in the following table:

Partial solution	**Battery**	**Renewable sources**	**Generator**
Operational feasibility?	Yes.	Yes.	Maybe.
Cost	> 15,000€	2130-6200€	1400-2200€
Advantages	+ Standard solution onshore	+ Redundant system + Medium cost + Low weight (<50kg)	+ High power density + Medium cost
Disadvantages	- Expensive - Storage space (0.5m²) - Heavy (800kg)	- Low power density - Depend on sun and wind availability	- Complicated O&M offshore - Probable legal issues - Fuel storage

5.2.4 Data transmission

The next category is the transmission of data. The transmitted data is mostly the sensor data from the sondes plus some options for e.g. emergency commands or online maintenance. A connection must be established between the sondes/aerostat and the buoy plus a connection from the buoy to shore. To select the right connection type the amount of traffic has to be calculated. For the sonde/buoy connection this is all the raw sensor data, which must be sent to the buoy for storage and further processing. The sensor data comprises meteorological data and information about the motion and position of the sondes or the aerostat. At a sampling rate of one second the data accumulation in the sonde is 64Bytes/s and on the buoy 640Bytes/s for ten sondes, see annex J. During a half year mission roughly 8GB of data accumulate and have to be stored on the buoy. Nevertheless a connection to shore is necessary to e.g. observe the live data, check the performance or to perform maintenance like software updates. Averaged values can be calculated, as described in section 3.3, to reduce the data amount that is sent onshore. Also some quantities can be excluded from the message. With this adjustments the daily traffic to shore reduces to 1-2kB/day, see annex J. For the aerostat no real data exchange is foreseen except information about its height and motion. Therefore the necessary data rate is very low.

How can information be sent from a sonde to the buoy?

Wi-Fi

One way to send informations over short distances is a Wi-Fi connection. This method was also used by (Coulombe-Pontbriand and Nahon 2009). Wi-Fi connections work on different frequencies, e.g. 5GHz or 2.4GHz. Ranges are typically below 100m, in outdoor conditions without obstacles and within line of sight it can go up to 300 m depending on the particular environment (Dhawan 2007). Since Wi-Fi is used worldwide, also due to its high baud rates of up to several hundreds of Mbps, the equipment is very low cost and available in many versions. Nevertheless the range is barely sufficient which questions the applicability of this technology. To overcome this drawback and to increase the range point-to-point or directional antennas can be used, also power amplifier are possible. System using this technologies are also referred to as *Long-Range-Wi-Fi* and are typically installed on fixed masts. Small scale versions fitting on a sonde have not been found.

ISM band

An alternative with a better range is the usage of an ISM (**I**ndustrial, **S**cientific and **M**edical Band) radio band (e.g. 868MHz or 915MHz) for data transmission. These bands are exclusively reserved for non-telecommunication purposes, e.g. industrial machines or micro waves can emit in these frequency bands without affecting telecommunication. Far offshore these bands are not disturbed. Radio link modules working on these frequencies are commercially available. In Europe only systems working on the 868MHz frequency can be operated. Modules working on the 915MHz band (for the US market) could interfere with mobile communication services like GSM or GPRS which work on similar frequencies in Europe (Rappaport 2002). For example the ZigBee or XBee standard uses an 868MHz frequency. This standard was developed for wireless communication for short distance networks. It offers encryption, the connection of hundreds of devices and the formation of mesh networks[13] to reduce power consumption. ZigBee modules offer relatively low data rates – compared to e.g. Wi-Fi - but have high ranges. Several kilometer in range can be achieved depending on the module type, its spatial distribution and the antenna type (ZigBee Alliance 2014). The baud rates of this modules are typically in the kbps range (1.2-200kbps) depending on the module. Since those baud rates are much bigger than 128Byte the data could be compressed and sent in packages every few minutes. This has two advantages, it reduces the duty cycle and thus its energy consumption. A low duty cycles reduces interferences with the transmission of other sondes. Standard radio links working on the 868MHz frequency can be used alternatively. They come at lower cost but lack a convenient communication standard like the ZigBee. Annex K lists some modules for comparison.

The different partial solutions to fulfil the sub-function ***transmission sonde to buoy*** of the main function ***data transmission*** are summarized in the following table:

Partial solution	**Wi-Fi**	**ISM band**
Operational feasibility?	Maybe.	Yes.
Cost	< 50€	50-150€
Advantages	+ Standard wireless connection + High data rates (several hundred Mbps) + Vast variety of equipment + Low cost	+ High range (1-20km) + Low cost + Established communication standards (ZigBee)
Disadvantages	- Medium range (max. 200-300m) - Range extension not applicable - Range sensitive to environment	- Interference with GSM band possible - Medium data rate (1.2-100kbps)

How can information be sent from the aerostat to the buoy?

Wi-Fi

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[13] In a wireless mesh network, the network connection is spread out among dozens or even hundreds of wireless mesh nodes that "talk" to each other to share the network connection across a large area (Roos 2007).

Like for the sondes an application of Wi-Fi is thinkable. However, the aerostat is even farther away from the buoy, which makes this option unfeasible.

ISM band

Again the alternative is the usage of an ISM band. The points mentioned in the paragraphs before are also valid for a connection from the aerostat to the buoy.

Optical cable

The only new existing option is the use of optical cables in the tether, as already described in the section discussing the feed-tube. An optical cable can connect two communication devices, one on the aerostat and one on the buoy, conveniently. As already mentioned before, optical conductors are offered by aerostat manufacturers as an option during tether selection. The data rate that can be achieved with optical conductors depends on the cable type, cable length etc. In general much higher data rates compared to wireless transmission can be achieved. For example, the *light peak* technology by Intel, which was later redesigned and is known as the Thunderbolt interface today, used optical cables and was able to transfer up to 10 Gbps over a distance of 100m. (Shankland 2009) This example shows that optical data transmission offers potentially higher data rates compared to those of the presented wireless transmission types. Since optical conductors are very thin and use non-metallic materials their weight is usually quite low, e.g. the weight of two fiber optics are quoted with an extra weight of around 1kg for a 300m cable (Charlie Steffen from Skydoc™, personal communication, 05.05.2014). Furthermore, the use of such a tether is quite costly and costs around 5000€, see annex L. This is partly due to the complex connection of the tether, to prevent tether distortion additional slip rings are necessary (Kevin Hess from Aerial Products, personal communication, 05.05.2014).

The different partial solutions to fulfil the sub-function ***transmission aerostat to buoy*** of the main function ***data transmission*** are summarized in the following table:

Partial solution	**Wi-Fi**	**ISM band**	**Optical cable**
Operational feasibility?	No.	Yes.	Yes.
Cost	< 50€	< 50€	4500-5000€
Advantages	+ Standard wireless connection + High data rates + Vast variety of equipment + Low cost	+ High range + Low cost	+ Very high data rates possible + Offered by aerostat suppliers + Lightweight materials
Disadvantages	- Range is to small - Range extension not applicable - Range sensitive to environment	- Platform type - Medium data rate	- Costly - Complex connection

How can information be sent from the buoy to shore?

<u>GSM/3G</u>

The first and most convenient solution would be the use of a mobile telecommunication network such as GSM or 3G. Using this transmission type has many advantages: High variety of equipment, high data rates (55 kbps for GPRS) and encrypted transmission. The fees for data transmission are relatively low, tariffs with unlimited traffic are available for less than 50€ per month throughout Europe. One major drawback, however, is the coverage. The hard limit for GSM communication is 35km. It is defined by the maximum timing advance[14] and is a pure software limit. The real limits of GSM coverage depend on additional factors, like the terrain or the transmission power of the tower. The limits for GSM on sea are thus very site specific and will hardly reach the values of 30km and more. Therefore the usage of this technology is only advisable for wind monitoring operations close to shore, most likely with line of sight to a transmission tower, and after testing the site for GSM/GPRS coverage. As a communication standard it seems inappropriate.

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[14] In the GSM cellular mobile phone standard, timing advance value corresponds to the length of time a signal takes to reach the base station from a mobile phone.

Marine Very High Frequency (VHF) radio

Another solution, which requires line-of-sight is marine VHF radio. It operates on frequencies between 156-162MHz. The range depends on the location of the antennas. For two aerials on sea level the range is about 10km, if the aerial onshore is on a hill of 200m it increases to 50km, see annex M. The same distance could be achieved if the aerial is mounted on the aerostat. If both aerials are at 200m the transmission distance is 100km in theory. Commercial solutions for data transmission are barely existing, one examples is the ***A****utomatic* ***I****dentification* ***S****ystem* (AIS) using a **V**HF **D**ata **L**inks (VDL). AIS is a VHF radio broadcasting system that transfers packets of data over a VDL and enables AIS equipped vessels and shore-based stations to send and receive navigational information (Australian Maritime Safety Authority 2008). An adapted AIS can be used for the transmission of different types of data too. AIS systems also offer encrypted transmission. However commercial AIS systems are very costly (e.g. an AIS VDL system from CNS Systems is quoted at around 12,000€). The prices for a custom solution may be more attractive but could not be determined. Furthermore a tower or mast is necessary to carry an aerial and receive the data onshore. The identification and acquisition of a suitable site may be problematic. Yet the placement of the receiving mast is crucial for this type of solution, making it very site specific as well.

Satellite

The standard solution for deep offshore telemetry without line of sight to shore is satellite communication. There exist many providers for this service such as Iridium or Inmarsat. It has good coverage almost worldwide, Figure 29 shows the coverage of the Inmarsat system. Besides the necessary equipment additional fees must be paid for the satellite data transmission. For the required amount of data this will be around 30-70€/month, see annex M. For half a year this sums up to 180-420€. The cost for the equipment is in the range of 200-500€, see annex M. The total cost are consequently around 700-1100€ for the first deployment. The running cost of the data transmission increase with the amount of data. The transmittable data is therefore restricted to some extent. Still the cost for 50kB per month is passable.

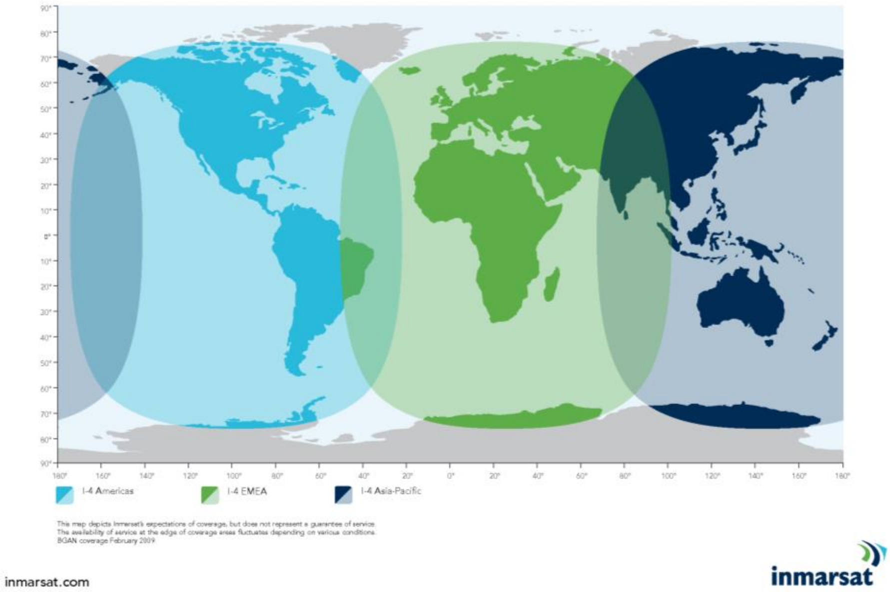

Figure 29: Coverage of Inmarsat satellites

The different partial solutions to fulfil the sub-function ***transmission buoy to shore*** of the main function ***data transmission*** are summarized in the following table:

Partial solution	**GMS/3G**	**Marine VHF radio**	**Satellite**
Operational feasibility?	Maybe.	Maybe.	Yes.
Cost	100€	n/s	500-1100€
Advantages	+ Standard wireless connection + High data rates + Vast variety of equipment + Low cost	+ Potentially high range + Arial on aerostat may improve range	+ Range almost world wide + Cheap equipment
Disadvantages	- Range is limited to 35km - Range is site specific	- Range is limited to line of sight and is site specific - Cost unknown - Requires mast plus antenna onshore	- Fee for transmission

5.2.5 Platform

To select the right buoy type for the system some points have to be checked first. These are the forces that can be expected from the aerostat and the mooring line, also the weight force of the buoy is important. It must be guarantted that the aerostat does not lift the buoy out of the water. The lifting forces of a 43m³ aerostat are around 1t, as mentioned in section 5.2.1. The exact direction of the pulling force is unknown but is assumed to be vertical to cover the worst case. The weight of the mooring can be expected to be around 500-1000kg, see the next chapter about mooring. This alone is nearly sufficient to compensate the pull of the tether. Nevertheless the weight of the buoy should be more than 500kg.

The second point are the dynamics of the aerostat and the buoy. As both are moving objects the tether will undergo a high number of cycles over time. With a standard wave period of 10s the buoy will have already over 8000 cycles per day. The motions of the aerostat are still unknown, but the findings from 3.4.2 suggest that oscillation occurs mainly in the plane perpendicular to the tether. Therefore they are neglectable for the buoy. Finally the buoy needs a mounting for the tether which can resist these oscillating forces.

Which type of buoy can used as a platform?

<u>Navigational buoy</u>

The simplest type of buoy is a navigational buoy, which are deployed in e.g. harbor entrances, rivers or open water. They have reasonable cost and can be bought off the shelf. Nevertheless they can hardly be used for this purpose for two reason. First, the hull of a standard navigation buoy (<1.5m diameter) seems not big enough to hold several gas cylinders. Also, their hull is typically not hollow but filled with Styrofoam to keep them floating when damaged by a ship. In that case no storage space at all is available inside the hull. A storage outside of one buoy, on the other hand, would disturb their balance. Therefore a combination of several buoys, with a custom structure in the middle, is the only practical option and has been discussed in annex N. This setup is in the range of 50,000-55,000€ depending on the number of buoys and the buoy type, not accounting for the development expenses. The robustness and survivability of such a construction remains uncertain.

<u>3m buoy</u>

The 3m discus buoy from AXYS Technologies is specially designed for the purpose of offshore monitoring. It is widely used as a weather buoy, as presented in 3.1.3. For example the National Data Buoy Center in the US to monitors wave and weather conditions in the Pacific Ocean or the Atlantic Ocean with 3m buoys. The buoy is designed for long term missions under the harshest offshore conditions. The aluminum hull is sealed and offers around 2-3m^3 of space for batteries or gas bottles. Solar panels or wind turbines can be mounted as well. The price for the hull is 103,000€ (Pedro Simoes from Lindley, personal communication, 23.06.2014). The buoy weights around 1,5t and has a total buoyancy of around 4.5t. A special top would be necessary to attach the tether and the feed-tube to the buoy. To deploy this buoy type, a towing ship with enough deck space and a crane, to lift the buoys into the water, is necessary.

Nomad

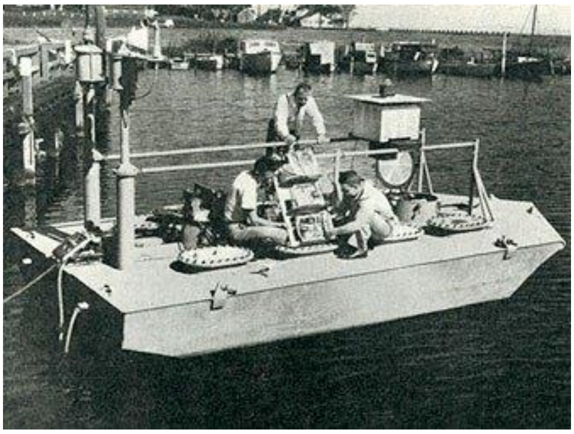

Figure 30: Early version (1950s) of the NOMAD buoy design

If more storage space is needed, the 6m-long NOMAD buoy from AXYS Technologies can be used. An example is shown in Figure 2, where the NOMAD is the platform for the WindSentinel™ lidar system. The NOMAD design was originally designed by the US Navy for ocean data gathering, an early version is shown in Figure 30. It has been redesigned and is used as a data buoy today. The bigger size comes at a significantly higher price of 540,000€ for the hull (Pedro Simoes from Lindley, personal communication, 23.06.2014). Its weight and total buoyancy are 5t and 17t respectively. Another difference between the NOMAD and the 3m-discus is the boat-like shape. This allows a towing of the buoy to its operational area, which requires a smaller boat without a crane. Nevertheless the towing speed is limited, which makes it only a viable option for areas close to shore.

The different partial solutions to fulfil the sub-function ***supporting structure*** of the main function ***platform*** are summarized in the following table:

Partial solution	**Navigational buoy**	**3m-buoy**	**Nomad**
Operational feasibility?	Maybe.	Yes.	Yes.
Cost	50.000-55,000€	103,000€	540,000€
Advantages	+ Low cost buoys + Size adjustable	+ Data buoy design + Medium cost + Storage space (2-3m³)	+ Data buoy design + Towable + Storage space (5m³+)
Disadvantages	- Connection and storage structure necessary - Stability and robustness unknown	- Limited deck space	- Extremely high cost - Complicated design

5.2.6 Mooring

All chain mooring

For the buoys described in the previous section and water depths of up to 200m the standard mooring solution is an all chain mooring (Randolph Kashino from AXYS Technologies, personal communication, 20.5.2014). It adds additional weight to the buoy and is attractive in terms of costs. The cost depend on the chain length and size, e.g. 1½ inch chain costs 60€/m plus 750€ for the sinker. A 100m long chain mooring thus costs 6,750€, a 50m mooring 3,750€. The netto weight is in the range of 11-25kg/m depending on the chain size, see annex N. For example, a 50m mooring would add a minimum of 550kg of weight to the buoy. If additional weight is needed a bigger chain size could be used. The only drawback of a chain mooring is the potentially bad effect on the surrounding seafloor by dragging chain members.

Partial solution	**All chain mooring**
Operational feasibility?	Yes.
Cost	3,750-6,750€
Advantages	+ Robust + Standard solution
Disadvantages	- May harm sea floor

5.3 MORPHOLOGICAL MATRIX

In the previous section the first step to develop the conceptual design has been carried out. Several main functions have been established containing several sub-functions, which are necessary to fulfil the operation of the system. For each function one or more partial solutions have been presented and discussed. Now, in a second step, all the partial solutions are combined. For this a so called *morphological matrix* is used. The morphological matrix is a tool which was developed by Fritz Zwicky in 1967-1969. It was developed to explore possible solutions to multidimensional problems. It also helps to comprehend complex systems (Ritchey 1998).

The morphological matrix of this work is depicted in Table 8. Every partial solution of the previous section can be found in it. The partial solutions are ordered by their respective main function. It is now possible to combine those partial solutions and try to find a good concept randomly. However, the task of this work is to find a conceptual design which promotes an operational system at low cost and with small development efforts. In order to achieve this target the matrix will be filtered before a specific design is being selected. First, all concepts which do not achieve the operational feasibility are being removed from the matrix. Therefore only viable partial solutions remain to find a conceptual design. In a second step the cost of the different partial solutions are evaluated. Solutions that can only be applied at very high cost are not considered for the further development either. Finally the partial solutions are evaluated with a focus on the R&D efforts that can be expected. Partial solutions whose selection require over-proportionate development efforts are also eliminated.

5.3.1 Filtering: Operational feasibility

As already pointed out, the operational feasibility, meaning the ability to achieve the operational targets, of the partial solutions is used as a first filter for the partial solutions. Three levels shall be used to rate the partial solutions, as already done during the previous section:

Category	**Description**	**Color code**
Yes	The partial solution can potentially fulfil the requirements and no major issues are expected.	Yes.
Maybe	The partial solution can potentially fulfil the requirements, but some issues are expected. For example, if the requirements can barely be met or if the foreseen technology has not been used in this context before.	Maybe
No	The partial solution can not fulfil the requirements for reasons which can not be overcome.	No.

The outcome of this process is depicted in Table 9. Six partial solutions have be classified as not operationally feasible. The first is the overloading of the balloon to prolong the operation time. The second is the application of an elektrolyser for hydrogen production. Energy supply from batteries for the sondes and the aerostat is not feasible either, due to excessive weight. Also the usage of Wi-Fi for data transmission from the aerostat to the buoy is eliminated due to range concerns. The partial solutions which can not fulfil the operational targets are removed from the further process. The removed solutions are depicted with a new color code in the following tables:

Category	**Description**	**Color code**
Eliminated	The partial solution is not considered anymore for the further progress of this development process.	Eliminated

Table 8: Basic morphological matrix

MAIN FUNCTION	FUNCTION	Solution #1	Solution #2	Solution #3
OPERATION TIME	Maintain lifting force	Overloading	Take down	Feed-tube
	Provision of lifting gas	Helium cylinder	Hydrogen cylinder	Elektrolyser
	Keep altitude in strong wind	Helikite/spheroid	Winch control	
DATA ACQUISITION	Instrumentation for wind assessment	Cup anemometer	Sonic anemometer	
	Detect position and motion of instrument	DGPS (EGNOS)	Orientation sensor (barometer + accelerometer)	Optical/Ultrasonic range finder
	Detect cardinal direction of instrument	Digital compass		
	Combine the hardware	Hacking	Arduino	Custom microcontroller
ENERGY SUPPLY	Aerostat	Battery	Via tether	Solar panel
	Sonde	Battery	Via tether	Solar panel
	Buoy	Battery	Renewable source	Generator
INFORMATION TRANSPORT	Transmission Sonde/Buoy	Wi-Fi	ISM band	
	Transmission Aerostat/Buoy	Wi-Fi	ISM band	Optical cable
	Transmission Buoy/Shore	GSM/3G	Marine VHF radio	Satellite
PLATFORM	Supporting structure	Navigational buoy	3m buoy	NOMAD
	Mooring	All chain mooring		

Table 9: Operational feasibility filtering

MAIN FUNCTION	FUNCTION	SOLUTION #1	SOLUTION #2	SOLUTION #3
OPERATION TIME	Maintain lifting force	Overloading	Take down	Feed-tube
	Provision of lifting gas	Helium cylinder	Hydrogen cylinder	Elektrolyser
	Keep altitude in strong wind	Helikite/spheroid	Winch control	
DATA ACQUISITION	Instrumentation for wind assessment	Cup anemometer	Sonic anemometer	
	Detect position and motion of instrument	DGPS (EGNOS)	Orientation sensor (barometer + accelerometer)	Optical/Ultrasonic range finder
	Detect cardinal direction of instrument	Digital compass		
	Combine the hardware	Hacking	Arduino	Custom microcontroller
ENERGY SUPPLY	Aerostat	Battery	Via tether	Solar panel
	Sonde	Battery	Via tether	Solar panel
	Buoy	Battery	Renewable source	Generator
INFORMATION TRANSPORT	Transmission Sonde/Buoy	Wi-Fi	ISM band	
	Transmission Aerostat/Buoy	Wi-Fi	ISM band	Optical cable
	Transmission Buoy/Shore	GSM/3G	Marine VHF radio	Satellite
PLATFORM	Supporting structure	Navigational buoy	3m buoy	NOMAD
	Mooring	All chain mooring		

5.3.2 Filtering: Cost

In the second filtering process the cost of the partial solutions is the decisive criterion. Mainly the cost to acquire the equipment is used. Installation cost or maintenance cost are usually not considered. They are strongly depended on the future assembly and manufacturing process of the whole system. Again three levels shall be used to rate the partial solutions, as already done during the previous section:

Category	**Description**	**Color code**
Low	The equipment of this partial solution can be acquired at very low or low cost in relation to the total cost of the system. These items will have a neglectable or very small impact on the total cost.	Low
Medium	The equipment of this partial solution can be acquired at medium cost in relation to the total cost of the system. This means the acquisition of the equipment will have a distinct impact on the cost development.	Medium
High	The equipment of this partial solution can only be acquired at high or very cost in relation to the total cost of the system. These items will dominate the total cost and drive them disproportionally.	High.
Unknown	The cost for this solution could not be found because the solution is still in development and not commercially available.	Unknown.

The application of this filter is shown in Table 10. It can be seen that seven partial solutions are rated as high cost. Of the main function *operation time* two partial solutions have very high cost. The usage of a winch on the buoy, either for altitude control or take down, plus the necessary energy production equipment is costly. The application of hacked sondes and optical range finders were also removed. All of which with respect to the excessive cost for the necessary equipment. Since cheaper solutions are available, the optical cable in the tether are also eliminated. Concerning the buoys, only the NOMAD design was removed, because of its extreme costs. And finally the energy supply from batteries for the buoy, while hypothetically possible, is very cost intensive too. All these partial solutions are therefore being eliminated.

Table 10: Cost filtering

MAIN FUNCTION	FUNCTION	SOLUTION #1	SOLUTION #2	SOLUTION #3
OPERATION TIME	Maintain lifting force	Tank on board	Take down	Feed-tube
	Provision of lifting gas	Helium cylinder	Hydrogen cylinder	Elektrolyser
	Keep altitude in strong wind	Helikite/spheroid	Winch control	
DATA ACQUISITION	Instrumentation for wind assessment	Cup anemometer	Sonic anemometer	
	Detect position and motion of instrument	DGPS (EGNOS)	Orientation sensor (barometer + accelerometer)	Optical/Ultrasonic range finder
	Detect cardinal direction of instrument	Digital compass		
ENERGY SUPPLY	Combine the hardware	Hacking	Arduino	Custom microcontroller
	Aerostat	Battery	Via tether	Solar panel
	Sonde	Battery	Via tether	Solar panel
	Buoy	Battery	Renewable source	Generator
INFORMATION TRANSPORT	Transmission Sonde/Buoy	Wi-Fi	ISM band	
	Transmission Aerostat/Buoy	Wi-Fi	ISM band	Optical cable
	Transmission Buoy/Shore	GSM/3G	Marine VHF radio	Satellite
PLATFORM	Supporting structure	Navigational buoy	3m buoy	NOMAD
	Mooring	All chain mooring		

5.3.3 Filtering: R&D efforts

In the third and last filtering process the partial solutions are filtered according to the efforts in research and development that come along with them. Partial solutions that e.g. come off-the-shelf require little efforts for implementation, whilst non-commercialized solutions, based on a patent or research findings, require substantial efforts to convert them into an operational solution. The three levels to rate the partial solutions based on their R&D efforts are as follows:

Category	**Description**	**Color code**
Small	The equipment of this partial solution comes off-the-shelf and is ready for the application. The designated purpose of the product and the actual application match.	Small
Medium	The equipment of this partial solution comes off-the-shelf, but requires some extra efforts. This may be due to a slightly different application or the necessity to adapt or process the equipment before it can be applied.	Medium
Big	The equipment of this partial solution does not come off-the-shelf and must be developed completely. The required efforts are unpredictable.	Big.

The application of this filter is shown in Table 11. Only two partial solution are expected to have big research and development efforts, which are conductors inside the tether to supply the sondes with energy and connected navigational buoys as a platform. The solutions are based on a similar applications, but do not exist in the form required for this work yet. Therefore they are eliminated.

5.3.4 Final matrix

After filtering the matrix several times it only contains partial solutions which potentially achieve operational feasibility, do no increase cost disproportionally and can be applied with no or small R&D efforts. This final matrix, see Table 12, will be used to determine the conceptual design in the next section.

Table 11:R&D filtering

MAIN FUNCTION	FUNCTION	SOLUTION #1	SOLUTION #2	SOLUTION #3
OPERATION TIME	Maintain lifting force	Tank on board	Take down	Feed-tube
	Provision of lifting gas	Helium cylinder	Hydrogen cylinder	Elektrolyser
	Keep altitude in strong wind	Helikite/spheroid	Winch control	
DATA ACQUISITION	Instrumentation for wind assessment	Cup anemometer	Sonic anemometer	
	Detect position and motion of instrument	DGPS (EGNOS)	Orientation sensor (barometer + accelerometer)	Optical/Ultrasonic range finder
	Detect cardinal direction of instrument	Digital compass		
	Combine the hardware	Hacking	Arduino	Custom microcontroller
ENERGY SUPPLY	Aerostat	Battery	Via tether	Solar panel
	Sonde	Battery	Via tether	Solar panel
	Buoy	Battery	Renewable source	Generator
INFORMATION TRANSPORT	Transmission Sonde/Buoy	Wi-Fi	ISM band	
	Transmission Aerostat/Buoy	Wi-Fi	ISM band	Optical cable
	Transmission Buoy/Shore	GSM/3G	Marine VHF radio	Satellite
PLATFORM	Supporting structure	Navigational buoy	3m buoy	NOMAD
	Mooring	All chain mooring		

Table 12: Final matrix after three filtering steps

MAIN FUNCTION	FUNCTION	SOLUTION #1	SOLUTION #2	SOLUTION #3
OPERATION TIME	Maintain lifting force	Tank on board	Take down	Feed-tube
	Provision of lifting gas	Helium cylinder	Hydrogen cylinder	Elektrolyser
	Keep altitude in strong wind	Helikite/spheroid	Winch control	
DATA ACQUISITION	Instrumentation for wind assessment	Cup anemometer	Sonic anemometer	
	Detect position and motion of instrument	DGPS (EGNOS)	Orientation sensor (barometer + accelerometer)	Optical/Ultrasonic range finder
	Detect cardinal direction of instrument	Digital compass		
	Combine the hardware	Hacking	Arduino	Custom microcontroller
ENERGY SUPPLY	Aerostat	Battery	Via tether	Solar panel
	Sonde	Battery	Via tether	Solar panel
	Buoy	Battery	Renewable source	Generator
INFORMATION TRANSPORT	Transmission Sonde/Buoy	Wi-Fi	ISM band	
	Transmission Aerostat/Buoy	Wi-Fi	ISM band	Optical cable
	Transmission Buoy/Shore	GSM/3G	Marine VHF radio	Satellite
PLATFORM	Supporting structure	Navigational buoy	3m buoy	NOMAD
	Mooring	All chain mooring		

5.4 DETERMINATION OF THE CONCEPTUAL DESIGN

After elaborating the morphological matrix in the previous section, it shall be used to determine the final design of the system. Several partial solutions have been eliminated during the filtering steps. If only one solution is left for a function, it is selected automatically. If two or three solutions remain a direct comparison will determine the final solution. This process is performed in this section for each function individually.

5.4.1 Operation time

5.4.1.1 *Provision of lifting gas*

Two options are left for this function. In both cases the gas will be provided from gas cylinders. Either helium or hydrogen can be used. The only drawback of helium is its high price. Hydrogen on the other hand is cheaper, but highly explosive if mixed with air. The potential savings with hydrogen, however, do not justify the increased risk of explosions on the buoy. Therefore helium is used.

5.4.2 Data acquisition

5.4.2.1 *Instrumentation for wind assessment*

Even though cup anemometer can be used for offshore wind monitoring they are less suited for the operation in marine climate. Therefore sonic anemometers are selected for the final design. A 2D version is preferable due to their low cost which are comparable to those of cup anemometers.

5.4.2.2 *Detect position and motion of instrument*

For this function only two solutions remain after filtering, a DGPS based detection and an orientation sensor (consisting of a barometer and an accelerometer). Both solutions have comparable cost. A detection via DGPS yields good accuracy but increases the energy demand of the sonde substantially. An orientation sensor has a contrary characteristic, its energy demand is very little but the absolute accuracy is worse. The real accuracy of the orientation sensor, however, could be better. Because of the high resolution of the sensors the relative accuracy (within stable temperatures) can reach those of a DGPS system. This would make them better suitable than a DGPS based system. But without intensive testing in the real operation environment the real accuracy is uncertain and this solution remains an option for further improved of the system. For the unknown accuracy and because an accurate altitude detection is of major importance, a DGPS sensor is the better option for a first design.

5.4.2.3 *Combine the hardware*

Here two solutions remain for selection. Both are based on a self-made microcontroller. Either it can be built with off-the-shelf Arduino components or it is developed from scratch as a customized microcontroller. Since Arduino components are intended for prototyping purposes they are selected for this function. Once a successful microcontroller design has been developed with Arduino, it can be transformed into a custom board during further improvements.

5.4.3 Energy transport

5.4.3.1 Supply aerostat with energy

For the energy supply of the aerostat two solutions remain. Either it can be powered from a mounted solar panel or by conductors in the tether, transporting energy from the buoy. Solar panels are more expensive and potentially heavier than conductors. However, the motions and big forces between buoy and aerostat are a major thread for conductors. Precise knowledge about the application of this technology is not available. For that reason solar panels shall be used, as long as a sufficient energy supply in low-irradiation-months can be achieved.

5.4.3.2 Supply buoy with energy

In this case the choice is between the supply from renewable sources or a diesel generator. The prices are comparable. Requirements in terms of space and weight are also similar. Renewable sources are more ecofriendly, need less maintenance and have less legal requirements. For that reason a combination of solar panels and micro wind turbines is used.

5.4.3.3 Data transmission sonde/buoy

The choice is between Wi-Fi and equipment working on an ISM band, like ZigBee. Due to the range issues with Wi-Fi and the smaller energy consumption, an ISM band transmission is preferable.

5.4.3.4 Data transmission buoy/onshore

For this function three solutions are potentially possible. However, a satellite connection is the only connection that is not site specific. GSM connectivity can not be expected everywhere. The exact costs for a VHF connection are unknown. The erection of onshore masts for a VHF connection also make the system less mobile. Therefore a satellite connection is selected.

5.5 THE FINAL DESIGN

The final design has been selected and is depicted in Table 13. This design will be the basis for the cost analysis in the next chapter. To estimate the cost precisely the assumptions from the preliminary calculations have to be checked and, if needed, adapted. First the energy part is discussed, then the weight estimations. Finally, a basic visualization, showing the different parts of the system, is given.

Table 13: Final design matrix

MAIN FUNCTION	FUNCTION	SOLUTION #1	SOLUTION #2	SOLUTION #3
OPERATION TIME	Maintain lifting force	Tank on board	Take down	**Feed-tube**
	Provision of lifting gas	**Helium cylinder**	Hydrogen cylinder	Elektrolyser
	Keep altitude in strong wind	**Helikite/spheroid**	Winch control	
DATA ACQUISITION	Instrumentation for wind assessment	Cup anemometer	**Sonic anemometer**	
	Detect position and motion of instrument	**DGPS (EGNOS)**	Orientation sensor (barometer + accelerometer)	Optical/Ultrasonic range finder
	Detect cardinal direction of instrument	**Digital compass**		
	Combine the hardware	Hacking	**Arduino**	Custom microcontroller
ENERGY SUPPLY	Aerostat	Battery	Via tether	**Solar panel**
	Sonde	Battery	Via tether	**Solar panel**
	Buoy	Battery	**Renewable source**	Generator
INFORMATION TRANSPORT	Transmission Sonde/Buoy	Wi-Fi	**ISM band**	
	Transmission Aerostat/Buoy	Wi-Fi	**ISM band**	Optical cable
	Transmission Buoy/Shore	GSM/3G	Marine VHF radio	**Satellite**
PLATFORM	Supporting structure	Navigational buoy	**3m buoy**	NOMAD
	Mooring	**All chain mooring**		

5.5.1 Energy

Again the table from the section on energy supply is used. The additional consumptions have been removed as they do not exist anymore:

	Basic consumption			Total consumption
	Type	Peak	Average	
Sonde	Instrumentation:	0,35W	0.35W	0,35W
Aerostat	Position lights:	55W	11W	11W
Buoy	Data logger incl. satellite link:	50W	10W	15.5W
	Position lights:	27.6W	5.5W	

The energy production on the sondes must be designed for 0.35W, for the aerostat it remains at 11W and for the buoy the low energy scenario of 15.5W has to be met.

5.5.2 Weight

The weight of the different components (adding to the payload) are summarized in the following table to check if the size of the aerostat of 43m³ is correct.

Part of system	Item	Weight in kg	Number	Total weight in kg
Aerostat	Solar panel	6.50	1	6.50
	Beacon light	0.05	2	0.10
Tether	Hose	3.60	1	3.60
	Rope	3.20	1	3.20
Sonde	Sonde	1.20	10	12.00
			Total:	25.40

It can be seen, that the preliminary payload calculation was too low. The aerostat needs a gross payload of 38kg (considering the losses as in annex A), but can only carry 27kg. To compensate this either less sondes can be used or a bigger aerostat has to be selected. The biggest single ply aerostat (50m²) is offered by Skydoc™ and has a gross lift of 32kg. This means the amount of sondes has to be reduced as well. Only 21.4kg of payload are allowed with a gross lift of 32kg. This means the number of sondes has to be reduced to 6. This is still in compliance with the fixed points in section 5.1, requiring a minimum of 3 sondes. A final remark, a slightly bigger aerostat accounts for a higher helium consumption too. The loss is 16% bigger in total.

5.5.3 Visualization of the system

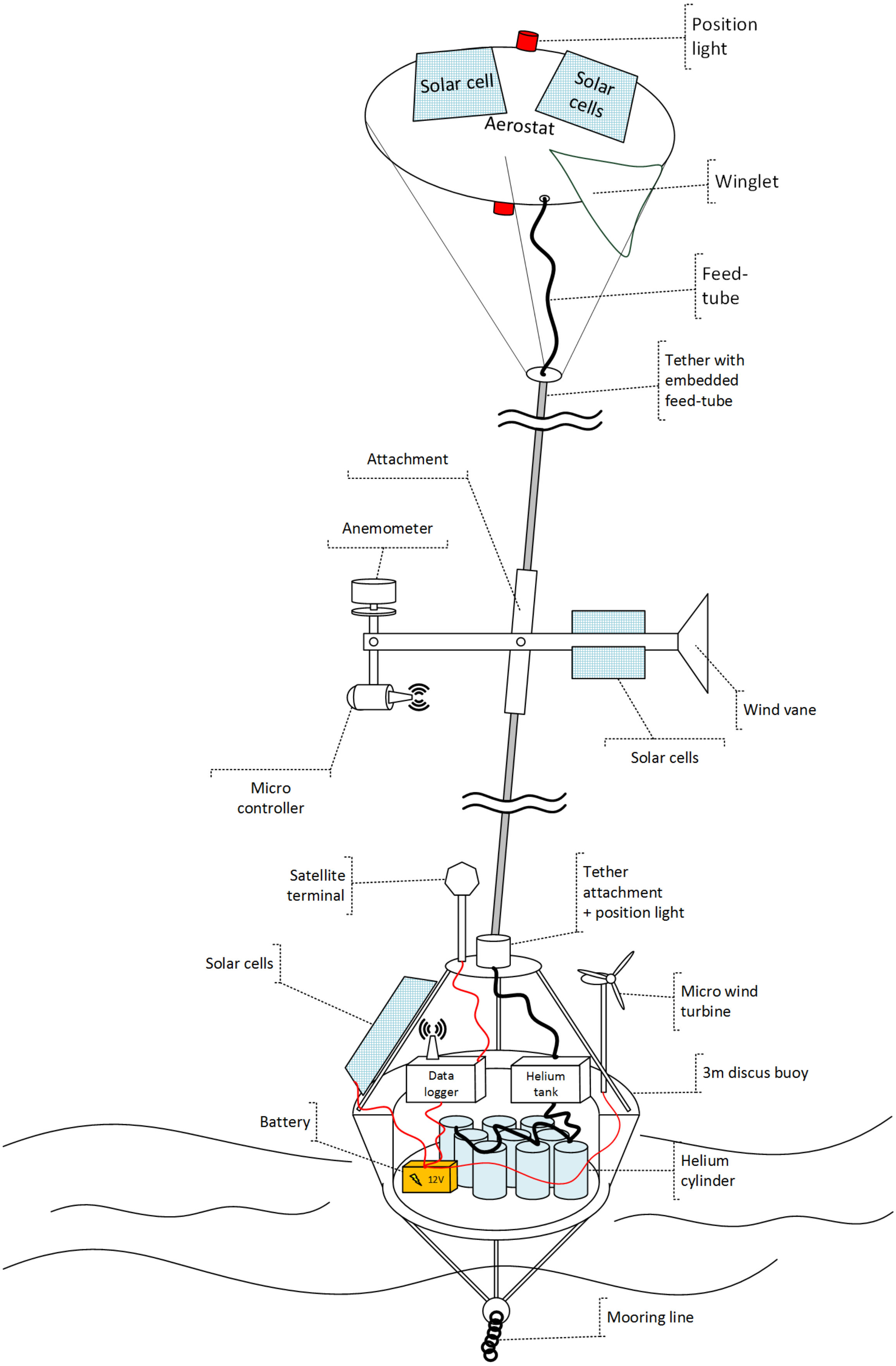

Figure 31: Visualization of the final design (not true to scale)

6 COST ANALYSIS

In this chapter the cost of the selected design are discussed. The cost can be divided into two parts, the fixed and the running cost. Both are discussed separately in the following chapters.

6.1 FIXED COST

The fixed cost of the whole system sum up to almost 180.000€, which is significantly less compared to the market price of a floating lidar system. The pie chart in Figure 32 (left) depicts these costs for each sub-system. It is obvious that the biggest cost item is the buoy hull with 103.000€. It alone consumes already 59% of the total budget, which is remarkable. The actual monitoring equipment accounts for only a 27% share. The cost structure is very similar to that of a floating lidar system in Figure 3, where the buoy accounts for 60% and the monitoring equipment for about 29% of the total cost.

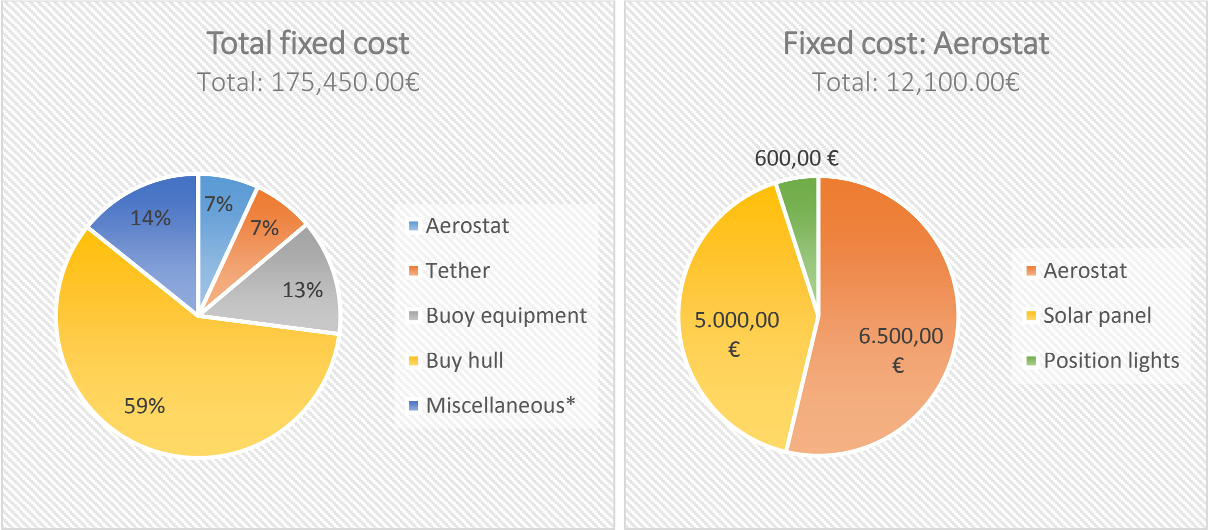

Figure 32: Breakdown of the total fixed cost and the fixed cost of the aerostat (*assumption)

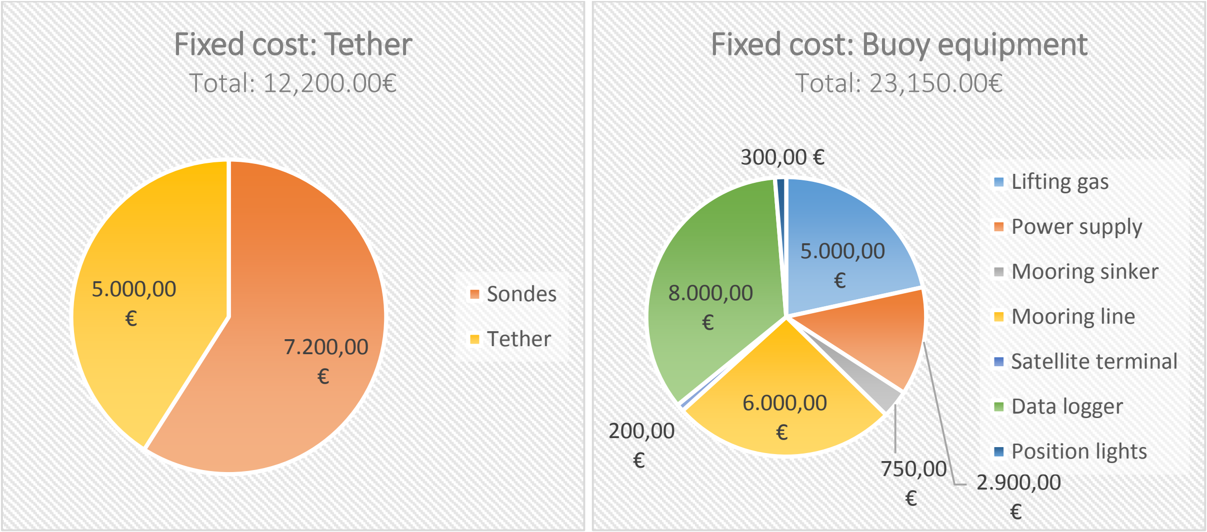

Figure 33: Breakdown of the fixed cost for the tether and the equipment of the buoy

To understand the composition of the other cost items *Aerostat, Tether and Buoy equipment* they are shown in more detail in Figure 32 (right) and Figure 33. It can be seen that the aerostat cost is dominated by the aerostat (6,500€) and the solar panel (5,000€), the positions lights have low costs. Also, the sondes are relatively cheap (1,200€), their total cost depends on the number that is attached to the tether (in this case six). The buoy equipment has three major cost items: The lifting gas (5,000€), the data logger from AXYS that comes with the buoy (8,000€) and the mooring (combined 6,750€). The cost for *Miscellaneous* are not given in detail. They comprise additional equipment - e.g. wirings, casings, auxiliary devices, etc. (assumed 5,000€) - , the assembly (assumed 5.000€) and deployment of the system (15.000€). Especially the deployment is cost intensive. The prices to hire a towing ships are in the ranges from 10,000€/day (Pedro Simoes from Lindley, personal communication, 20.05.2014) to over 18,000€/day (Detrick, R., et al. 2000). Since the 3m-buoy is rather small, the lower price and a one day deployment are assumed. The cost for assembly and additional equipment are assumptions. Crew wages are assumed with 50€/h. For more detail see annex O.

The fixed costs, which were presented in this section, only show the initial expenses for the operation. Nevertheless running cost occur during a long term operation. These cost are discussed in the following chapter.

6.2 RUNNING COST

The running cost comprehend several points. The first is maintenance. After 6 months the buoy will receive maintenance. The lifting gas cylinders have to be replaced, the stored meteorological data must be extracted and possible damages have to be repaired. The second point are the fees for satellite communication. They occur monthly and add to the running cost.

The first scenario (*Running costs 1*, which only comprises the points mentioned above) is broken down in Figure 34 (left) for a half year mission. The boat hire is assumed to be less since a smaller boat (2,000€) can be used for maintenance. The crew wages are for four technicians. Helium refill is unchanged, as the gas cylinders still have to be rented (5,000€). This scenarios covers the essential running costs. However, a second scenario is thinkable and shall be presented as well.

As the fatigue resistance of the tether and the aerostat are unknown, they may suffer substantially during a 6-month operation and must be replaced. For that case a second (worst case) scenario (*Running Cost 2*) shall be compiled, see Figure 34 (right). The satellite fees and the cost for the helium refill remain unchanged. However, the boat hire and the crew wages increase because a bigger boat is needed to replace the aerostat. It must be able to carry a landing structure and probably needs more crew members (ten instead of four). Also the cost for a new aerostat and a new tether have been added (in total 11,500€). With these adjustments the running costs increase by 17,500€, which is almost a threefold increase.

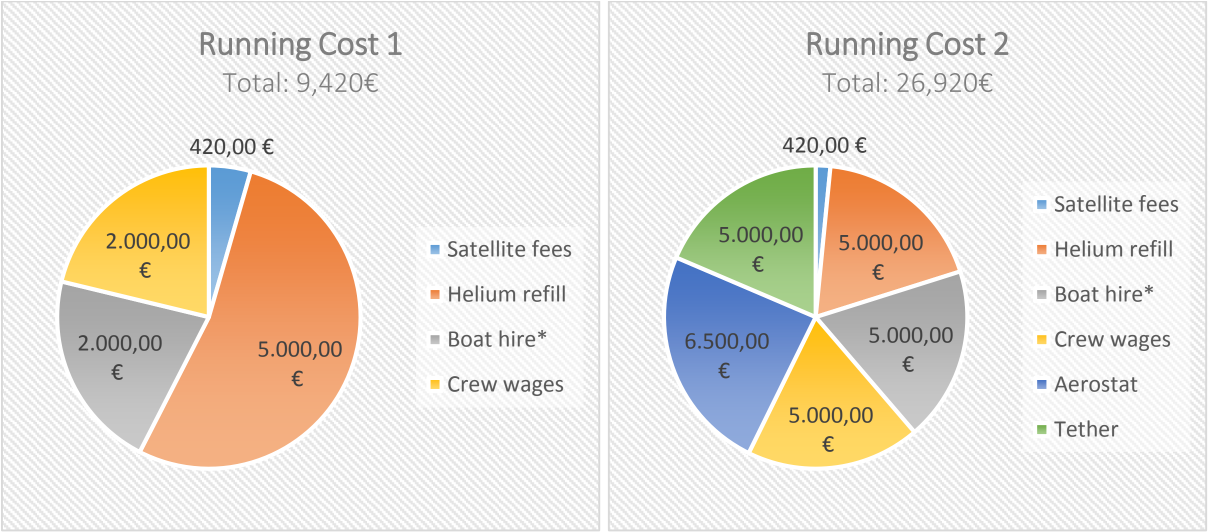

*Figure 34: Two running cost scenario for 6 months period (*assumptions)*

6.3 SAVING POTENTIALS

Looking at the overall cost of the system and considering a profit margin of 50% the systems would have to be sold at around 350.000€, which is about a third of the selling price of a floating lidar system. To become even more attractive in terms of cost it should be possible to offer the system at an even lower price, less than 200.000-250.000€ seem to be possible. To achieve this goal several potentials for cost reduction can be identified. The first, and most important, is the biggest cost item of the system, the buoy hull. Since the design is very basic it could be reproduced in a Portuguese shipyard. Reduced labor cost, no shipping cost and possible economy of scale effects may reduce the cost for the buoy hull substantially. For comparison, a German buoy manufacturer estimated the cost for the 3m buoy at about 20,000€ (André Heller from Weiseler Bojenbau, personal communication, 27.02.2014). Also the connection of standard (navigational) buoys may be an effective way to cut the cost of the total system. The second point is the data logger. Currently a premade data logger from AXYS is used, which has a very high price. A custom data logger could be developed, similar to the tethersonde. Looking at the price for commercial tethersonde and the equipment for a self-developed sonde, big cost reduction potentials can be identified. The third and last point is the lifting gas. As of now the price per cubic meter is around 20-30€. Acquired in bulk quantities the prices are substantially lower. In general discounts can be expected if bigger quantities are acquired, e.g. the CV7 anemometer from LCJ Capteurs was offered with a 30% discount on a 10 units order.

7 CRITICAL POINTS OF THE DESIGN

The intention of this chapter is the identification and discussion of critical aspects of the developed design. Those points are the feed-tube, the survivability of the aerostat and the tether and the motion of the sondes.

7.1 FEED-TUBE

The implementation of a feed-tube for helium replenishment was found to be without any alternative for a long-term mission. Specific data about feed-tubes is still missing as no commercial products are on the market yet. Some companies are working on prototypes (Cortland Cable, Stratocomm Corp., Aerostat Solutions, LLC) but are still in the validation process (Doug Bentley from Cortland Cable, personal communication, 14.02.2014). If those prototypes enter the market and at what point in time remains uncertain. Since the helium replenishment is essential for the system this aspect is critical for a successful realization. As long as commercial products remain unavailable only improvised, self-made or bespoken, feed-tubes can be used for the first prototypes.

7.2 SURVIVABILITY OF THE AEROSTAT

The second critical issue is the behavior and survival capability of the deployed aerostat. Only one manufacturer offers aerostats with the capability to survive hurricane force winds, as already mentioned in section 5.2.1. Other manufacturers criticize these claims to be unfaithful. Whether the aerostats from Skydoc™ have the asserted capabilities can only be answered by long-term testing under the respective weather conditions. Also the behavior of the aerostat has to be examined in those tests. For example, the exact altitude loss with increasing wind speed is of major importance for the future design to determine the exact length of the tether and the sonde positioning.

7.3 SURVIVABILITY OF TETHER

Also the survivability of the tether is doubtful. Tethers in onshore applications possibly suffer from less fatigue as the launching point is not moving. Therefore it is important to know whether the selected tether can survive a long term deployment. The impact of buoy and aerostat displacements on tether fatigue is uncertain. During conversations with experienced staff it was advised to double the necessary tether size to ensure a safe operation. (Randolph Kashino, personal communication, 20.05.2014) An increased tether size, however, implies increasing payload and finally a decreased number of sondes or a bigger aerostat. For those reasons this aspect is critical too and has to be tested, for example in combination with the survivability test for the aerostat.

7.4 MOTION AND ORIENTATION OF THE SONDES

The final point to be discussed is the motion and orientation of the sondes. During the literature review it was concluded that the expected tether vibrations are negligible. Only the motion of the aerostat and the attached tether will induce motions on the sondes. As the sondes can only be powered from solar panels a second source for motions is introduced. The size of the solar panels ($0.07m^2$) is big enough to produce significant forces on the panel by the wind. Therefore an intelligent design is needed to incorporate the cells, e.g. as a wind vane. Anyhow the motions of the sondes can become a critical point.

The second aspect of this point is the orientation of the sonde and the anemometer in particular. As a 2D anemometer a horizontal orientation of the instrument must be safeguarded. Existing tethersonde systems balance the sonde before deployment. Whether this is viable for a long term mission is questionable and must be tested. Alternative design could use for example a mounting similar to *steadycam* devices for cameras.

8 FURTHER DEVELOPMENTS

To overcome the critical points from the previous chapter further developments are necessary. Those shall be discussed in this chapter. Also additional points like the data management, a possible modularization of the system and a development strategy are logical continuations of this work.

8.1 FATIGUE: TETHER/AEROSTAT

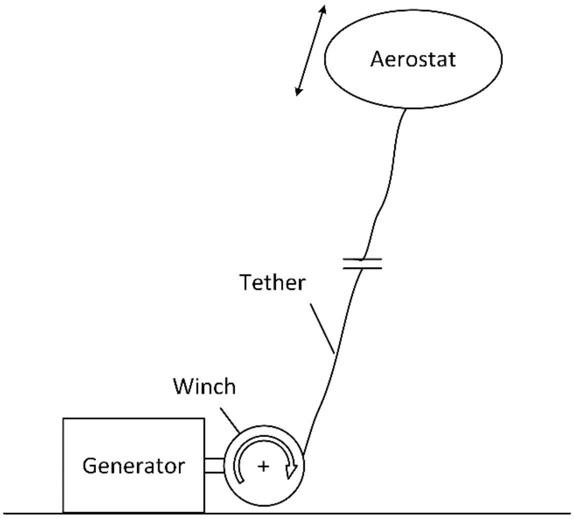

Figure 35: Experimental setup for fatigue testing of aerostat and tether

This section addresses some critical issues from the previous chapter such as the fatigue of the mechanically stressed aerostat and tether. A detailed long-term study should be carried out with a tethered (including the feed-tube) aerostat to understand the over-time wear of those components. Those test should be carried out onshore to limit the costs. The heaving of the buoy has to be appropriately simulated. The aerostat could, for example, be attached to a powerful winch to simulate the wave motions. By adjusting the tether length with a multispeed winch the motions of the buoy can precisely be simulated. Also different tether thicknesses could be tested to develop realistic safety factors for different weather and wave conditions. In addition to the testing of the tether the aerostat should be tested for its survivability in hurricane force storms. For that two scenarios are thinkable. Either the testing point is close to shore and exposed to very high wind speeds, similar to those on the ocean, e.g. in Sagres, or the aerostat is mounted on a fast moving object like a car. In both cases not only the wear of the aerostat should be investigated but also the motions and behavior of the aerostat as a function of the wind speed. Also, the leakage rates of the aerostat, which were claimed by the manufacturer, can be checked. The budget for such an experiment (using a winch) can be assumed to be around 52,000€, see annex P. The time frame should be at least one year, to get reasonable results. A simple visualization is given in Figure 35.

8.2 SONDE DESIGN / SOFTWARE DESIGN

This development addresses the hardware and the software of the sonde. On the hardware side an intelligent sonde design must be found which incorporates the necessary energy production, compact electric hardware, the instrumentation and a sensible attachment to the tether without compromising the stability and balance of the sonde. The dynamics of the sonde should be tested and prove its stability in harsh wind conditions. Furthermore, the sonde must remain sealed and watertight in rough offshore conditions. Also floatability would be beneficial in case the aerostat breaks loose and the sondes drop into the sea. A visualization of those challenges is given in Figure 36.

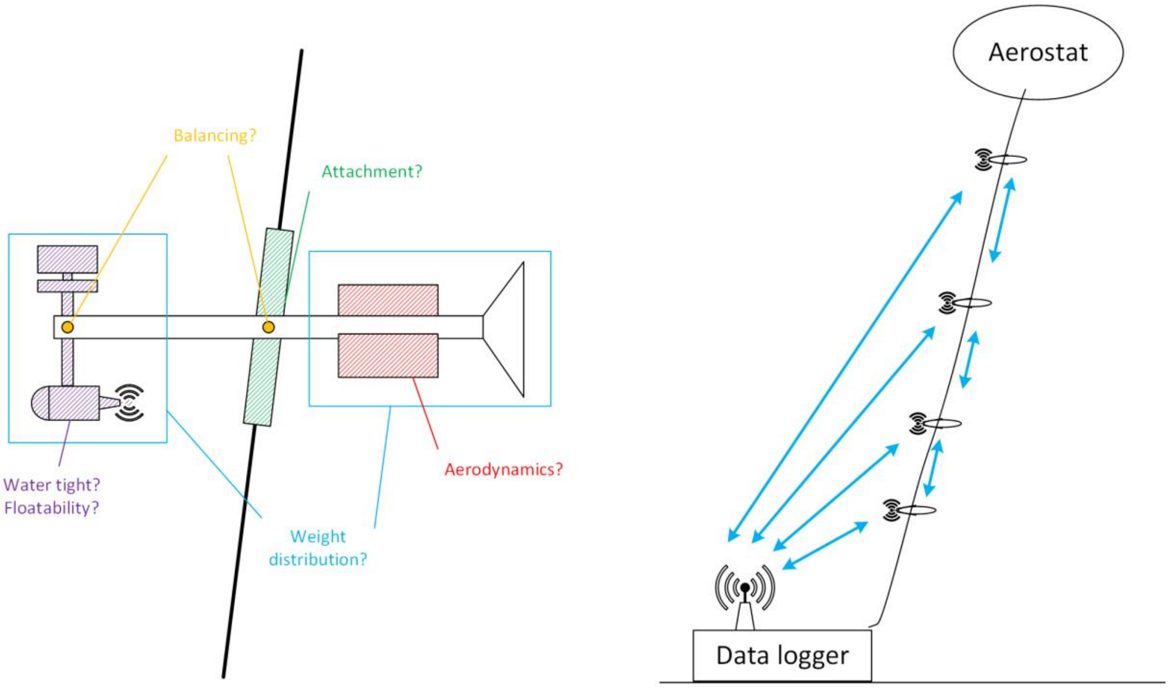

Figure 36: Different challenges of an exemplary sonde design (left), mesh network communication between sondes and data logger (right)

While improving the hardware of the sonde also the software can be optimized. Intelligent sleep routines for the instrumentation, the radio link and the DGPS positioning hardware should be developed to reduce the duty cycles and thus the energy consumption to a minimum. Also a sensible data management should be implemented with, e.g. data filters and watchdogs to ensure the quality of the sensor data. Also the advantages and implications of mesh networking should be discussed, see Figure 36. The budget for such a development will be significantly less, compared to the budget of the fatigue testing as less equipment is necessary. In this case it is assumed to be around 3,500€, not including the man-hours, see annex P. The testing should comprise the simultaneous operation of several sondes communicating with the buoy at the expected distances. For the sonde design one prototype seems sufficient, after preliminary testing (e.g. floatability and water tightness) it should be tested in a wind tunnel for its aerodynamic behavior. Alternatively it can be implemented in the fatigue experiment as wind tunnel testing is costly.

8.3 FEED-TUBE

As long as commercial feed-tubes are not available the development of a feed-tube prototype is inevitable. Even though an embedded solution may be aerodynamically favorable, a tube running in parallel to the tether should be used first, to reduce the development efforts. At the same time a helium provision system has to be developed, which draws helium from the bottles automatically and supplies it at the necessary pressure, for the feed-tube. The cost is difficult to estimate, as no prices could be obtained for the commercial feed-tube solutions. In general the material cost should not exceed several thousand euros.

8.4 MODULARIZATION / LIFE CYCLE COST ANALYSIS

Looking at a relatively expensive but long-lasting platform (buoy hull + buoy equipment) and relatively cheap but strongly stressed parts (aerostat and tether), a modularization of the system seems reasonable; as already pointed out in the cost analysis section. A study on a modular system could include the selection of appropriate connection systems, the identification of recycling potentials (like the sondes or the aerostat solar panel) and appropriate replacement intervals. Finally a detailed life cycle cost analysis e.g. over 10 years could unveil the long term cost of the system.

As this development focuses on the long term no budget has been calculated. For the literature study on the modularization techniques and potential no initial equipment is necessary. The time frame for the life cycle cost analysis would be many years to obtain reliable data. Also the exact procedure seems unpredictable at this point.

8.5 DEVELOPMENT STRATEGY

To ensure a coordinated process of the presented development steps a preliminary development strategy is proposed with them. The time line of the proposed process is depicted in Figure 37. The three subcomponents feed-tube, sonde and aerostat/tether are developed separately in the initial development phase. As soon as a proof of concept has been established a fast integration of the components should be carried out. After this integration a combined testing of the aerostat/tether system with operating sondes will be carried out. Simultaneously to the combined testing of the floating parts of the system, the implementation on the buoy will be carried out. This comprises the power supply integration, the helium storage and provision and the data communication. After completion a first prototype should be ready for initial offshore trials. The development of a modularization strategy is advised as well, as soon as first experiences are made with the aerostat and tether attachments. With the deployment of the first prototype the life cycle cost analysis should be initiated.

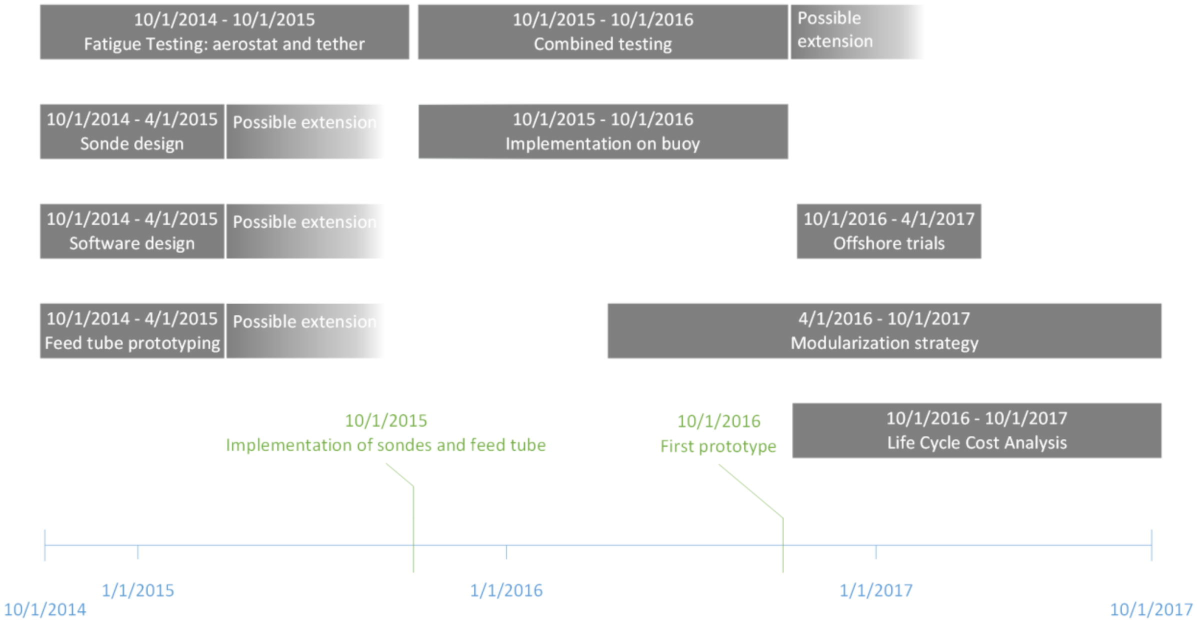

Figure 37: Timeline of the proposed development strategy

9 CONCLUSION

The expansion of offshore wind energy is part of many national programs for the implementation of renewable energies. In addition to wind power plants in shallow waters, recent developments focus on the exploitation of wind resources in deep water areas. The reasons are access to new areas with a potentially more reliable and powerful wind resource, precipitous ocean floors and sensitivities of local residents against offshore wind turbines. This led to the development of floating wind turbine designs. Recent prototypes are in operation at the coasts of e.g. Portugal, Norway and Japan. However, the wind resource assessment in deep sea, which can be exploited by floating wind turbines, remains challenging. Existing technologies, such as meteorological masts or lidar based systems, are very expensive. Moreover, lidar-based systems still lack acceptance by the wind industry. These issues promote the development of new, versatile and cost effective systems to assess the wind resource in deep water areas.

A preliminary design for such an alternative system, for offshore wind resource assessment, has been developed in this work. Solutions to meet the diverse requirements of such a system have been proposed and evaluated. The solutions have been summarized in a morphological matrix and filtered with respect to operational feasibility, costs and expected R&D efforts. Eventually a final design was selected and visualized.

The final design features a wind resistant aerostat (shaped like a spheroid), which is launched from a buoy to carry the instrumentation along the tether. The leaking lifting gas of the aerostat is replenished from stored helium cylinders on the buoy. A feed-tube, incorporated into the tether, transports the lifting gas up to the aerostat. The tether itself carries six tethersondes measuring the wind speed. These sondes are powered from solar panels and carry ultrasonic anemometers. Electricity for the buoy is provided by a solar panel and a micro wind turbine. The position lights on the aerostat are powered by solar panels too. The communication between tethersondes and buoy is realized by radio communication on an ISM band. The communication to shore is established via a satellite data link. As a platform the 3m discus buoy is used with a chain mooring. The cost for the system have been estimated to be approximately 175.000€, with the buoy hull being the most expensive part accounting for more than half of the costs.

To realize such a system successfully several critical aspects of the design have to be overcome. The first is the absence of a mature and commercially available feed-tube system. As of now only prototypes have been developed. Furthermore the survivability of the aerostat and the tether remains questionable, especially during a long operation in harsh weather conditions. In addition, the motions of the tethersonde may be critical.

Finally, future developments to overcome those issues at hand are proposed. Those are: intensive testing of the mechanical stability and fatigue of the tether and aerostat over a long term, prototype development of a feed-tube, the development of an intelligent tethersonde design and a modularization strategy to analyze the lifecycle cost. These proposals are accompanied by a general development strategy to accelerate the overall realization process.

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11 ANNEX

A. PRELIMINARY AEROSTAT CALCULATION

Assumed payload:	10 sondes with 1kg payload each		10kg
	Additional load (e.g. tether, beacon light etc.)	+	5kg
	Total payload	=	15kg
Necessary carrying capabilities:			
	Payload loss due to rain		20-30%
	Buoyancy loss with altitude	+	1%/100m
	Total payload loss	=	33%
	Minimum carrying capability = Total payload / (1- Total payload loss)	=	22. 4kg

Aerostat size selection:

Manufacturer	Model	Size	Net lift	
Skydoc™	#20	37m³	24,0kg	× too close to 22.4kg
	#21	**43m³**	**27,7kg**	**✓ selected!**
Allsopp	Desert Star	64m³	30,0kg	× double ply
Kingfisher	K16N-HC	48m³	30,0kg	× double ply

B. LIFTING GAS REPLENISHMENT

Necessary pull & winch speed

The necessary pull was given from the manufacturer. However it should be double checked to see if the magnitude is right. Therefore a preliminary pull calculation is performed according to the work of (Coulombe-Pontbriand and Nahon 2009). The force of the tether F_T can be calculated with:

$$F_T = c_D * \frac{1}{2} * A * \rho * u^2$$

With $\rho = 1.225 kg/m^3$ being the air density, c_D the drag coefficient, $A = 14.9m$ the cross section seen by the wind and u the wind speed. The drag coefficient was found to be around 0.56 for a tethered sphere (Coulombe-Pontbriand and Nahon 2009). With a maximum wind speed of 90mph (40m/s), as used by (Steffen 2014), the drag force is 8177N. This value is close and even below 1t=10000N. Even though the drag coefficient and the wind cross section may differ for a spheroid, the specification by the manufacturer can be confirmed.

The power P of the winch equals to

$$P = F * v$$

with F being the pull and v the speed of the winch. With a maximum power of 1kW and a necessary pull of approximately 10,000N the speed is limited to 0.1m/s.

Battery capacity

To power a 1kW winch for 1h operation plus reserves e.g. a 2kWh battery is necessary. Using marine batteries from Lifeline a 2kWh battery needs about $0.03m^3$ of space, weights about 60kg and costs around 900€ (Setronic 2013).

Several marine batteries (12V) are summarized in the following table:

Model	Battery type	Capacity in Ah	Size in m (LxWxH)	Weight in kg	Price in €
Lifeline GPL-30HT	Lead-acid	150	0.28x0.16x0.30	43.5	669.00
Lifeline GPL-4DL	Lead-acid	210	0.52x0.22x0.26	61.2	899.00
Lifeline GPL-8DL	Lead-acid	255	0.52x0.28x0.25	73.6	1039.00
Mastervolt 12/160	Lead-acid	160	0.48x0.17x0.25	42.3	501.00
Mastervolt 12/225	Lead-acid	225	0.52x0.24x0.24	63.5	674.00
Mastervolt 12/270	Lead-acid	270	0.52x0.27x0.24	73	800.00

Source: Manufacturers information

Weight of tether

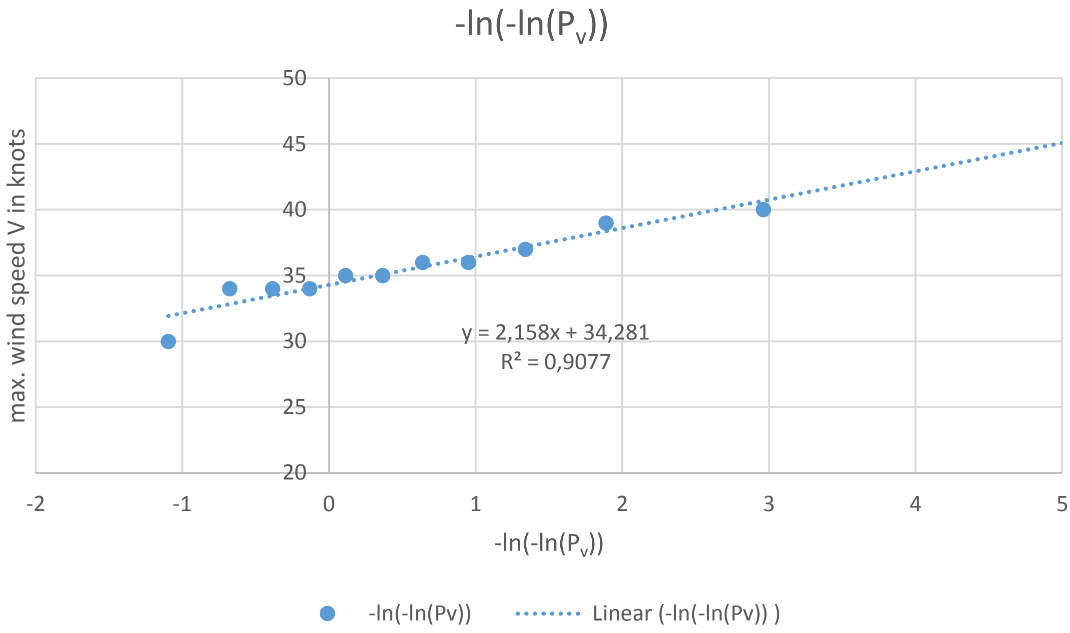
Hose (FESTO, polyurethane, 4mm/2.6mm, 500m coil)	0.009kg/m
Rope (Cortland cable, polyethylene, 5mm, 2.5t tensile strength)	0.008kg/m
Conductor (Stranded copper, polyurethane sheath, 2x0.7mm)	0.007kg/m
Total weight =	0.024kg/m

With a tether length of approximately 400m this sums up to 9.5kg with copper wire and 6.8kg without.

C. MAINTAINING ALTITUDE IN STRONG WINDS

Expected wind speeds

The wind speeds can be expected using a Gumbel distribution. The maximum annual wind speeds from the weather station in Sagres were used to compute the function. The data was obtained from www.windguru.cz. The computed Gumbel distribution is shown in the following graph with a linear trend:



For a 100-year storm[15] the *-ln(-ln(*P_v*))*-parameter equals to 4.6 which translates into a wind speed of 44 knots. This is equal to 81km/h. Assuming the wind speeds to be measured 10m above sea level it can be extrapolated to the potential height of the balloon of 400m using the equations from section 3.3.2. The calculated value is 120km/h using a shear coefficient of α=0.11.

D. LIFTING GAS PROVISION

Gas cylinder

The following table gives the specific information about gas cylinders:

Cylinder type	Gas type	Gas volume in m³	Geometrical volume in l	Pressure in bar	Weight in kg	Gas price in €/m³	Rental price in €/month
B50	Helium	9.1	50	200	65	21.30	16.20
B20	Helium	3.6	20	200	31	25.80	12.90
GENIE	Helium	3.6	20	200	21	31.00	26.60
GENIE	Helium	5.4	20	300*	22	31.00	26.60
B50	Hydrogen	8.9	50	200	65	6.50	16.20

Source: Manufacturers information

*not yet possible in Portugal (José Dias from Linde, personal communication, 19.05.2014)

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[15] A storm with a magnitude occurring only once in 100 years' time.

The next table shows the cost for gas for a 180 days mission. This includes the compensation of leaking gas (43m^{3}x0.0071m^3/dayx180days= 54m^3) and the initial filling of a 43m^3 aerostat:

Cylinder type	Gas type	Gas volume in m³	Gas price in €/m³	Rental price in €/month	Cost for initial filling in €	Necessary number of bottles on buoy	Cost for replenishment inc. rent in €	Total cost in €
B50	Helium	9.10	21.30	16.20	916.00	6	1733.40	2649.00
B20	Helium	3.60	25.80	12.90	1109.00	15	2554.20	3664.00
GENIE	Helium	3.60	31.00	26.60	1333.00	15	4068.00	5401.00
GENIE	Helium	5.40	31.00	26.60	1333.00	10	3270.00	4603.00
B50	Hydrogen	8.90	6.50	16.20	280.00	6	934.20	1214.00

E. MOTION AND POSITION DETECTION

The wind shear exponent is calculated as follows:

$$\bar{\alpha} = \frac{\log \overline{v_2} - \log \overline{v_1}}{\log h_2 - \log h_1}$$

To estimate the error in the wind measurement the following reference values are used:

$$h_1 = 20m \qquad v_1 = 7m/s$$

$$h_2 = 200m \qquad v_2 = 10m/s$$

The respective shear coefficient is α=0.155. If the wind speed is estimated at 100m it is equal to v_3=8.98m/s.

DGPS

With an error in altitude detection of 1.7m the values change as follows for the worst case:

$$h_{1^*} = 18.3m \quad v_1 = 7m/s$$

$$h_{2^*} = 201.7m \quad v_2 = 10m/s$$

The respective shear coefficient is $\alpha^* = 0.149$ and $v_3^* = 9.02$. Thus, the relative error of the estimated wind speed is 0.44%.

The following table lists some DGPS modules:

Model	Sensitivity in dB	Fix rate in Hz	EGNOS support	Consumption	Price in [€]
ElecFreaks Fastrax UP501	-165	10	Yes.	25 mA @3V	n/s
DFRduino LEA-5H	-160	2	Yes.	n/s @3.6V	62€

Source: Manufacturers information

Orientation sensor

The same calculation can be done with an accuracy of range of 1-8m. The biggest error occurs for:

$$h_{1^*} = 12m \qquad v_1 = 7m/s$$

$$h_{2^*} = 208m \qquad v_2 = 10m/s$$

The smaller error is calculated with:

$$h_{1^*} = 19m \qquad v_1 = 7m/s$$

$$h_{2^*} = 201m \qquad v_2 = 10m/s$$

In this case the shear coefficient are in the range of $\alpha^* = 0.125$-0.151 and the relative error of the estimated wind speed is between 0.26-2.1%.

Find different high performance pressure sensor chips in the following table:

Model	Range in hPa	Resolution in Pa	Absolute accuracy in hPa	Relative accuracy in hPa	Consumption	Price in [€]
Bosch BMP280	300-1100	0.18	±1	±0.12	2.74 µA @3.6V	<5
Epcos T5400 series	300-1100	2.9	±2	±0.15	790 µA @3.6V	<1
MEAS MS5607-02BA03	10-1200	2.4	±2.5	±1.5	1 µA @3.6V	16

Source: Manufacturers information

Optical/Ultrasonic range finder

Specifications of typical industrial laser sensors for long range detection:

Model	Range in [m]	Accuracy in [m]	Power consumption	Weight in [kg]	Price in [€]
Acuity AR3000	200-300m	<0.01	170-550mA @10-30VDC	0.85	3,500
Laser Technology TruSense S-Series	1600m	1	150mA @8-11VDC	0.14	950

Source: Manufacturers information

F. COMBINATION OF COMPONENTS

Arduino

A setup with similar sensors to those of a commercial *Tethersonde* are listed in the following table. Only parts from www.seeeduino.com have been used to ensure compatibility.

Component	Weight in g	Power supply	Consumption in mW	Price in €
Stalker	30	23mA @ 3,3V	75.90	29.00
Energy Shield	40	-	*85% efficiency*	22.00
3 x Solar cell	200	540mA @ 5.5V	-	26.00
2x Battery 2200mAh	82	3.7V	-	15.00
Barometer	2	0,1mA @ 5,5V	0.55	11.00
Temperature, Humidity	5	1,5mA @ 6V	9.00	11.00
Compass, Accel.-meter	5	47µA @ 3,3V	0.30	15.00
Resistances, cables etc.	50	-	-	10.00
2km radio link	12	<100mA @ 5V	80.00	13.00
GPS shield (EGNOS)	50	25mW @ 3V	75.00	62.00
Total:	**476**		240.75	**214.00**

The anemometer, the casing and assembly cost have to be added:

Component	Weight in g	Power supply	Consumption in mW	Price in €
LCJ Capteurs - C7	200	8mA @ 12V	96	616.00
Casing	500*	-	-	100.00*
Assembly	-	-	-	250.00*
Total:	**1176**		336.75	**1180.00**

Source: Manufacturers information
**assumptions*

G. ENERGY SUPPLY AEROSTAT

Battery

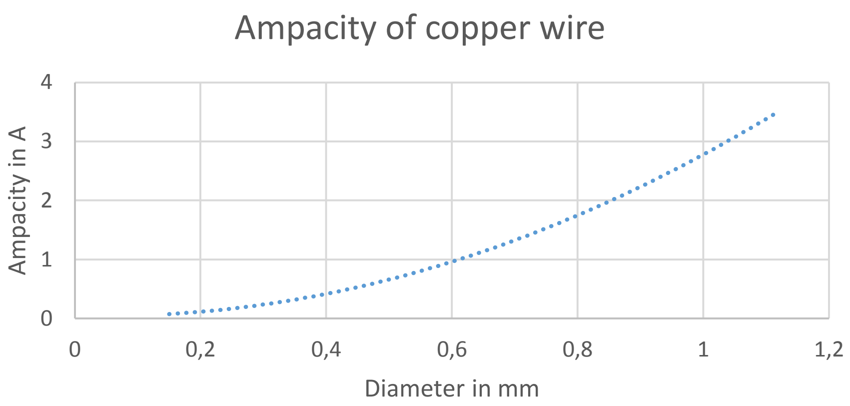
The weight of the battery can be calculated with

$$W = P * \frac{h}{e} = 11W * \frac{180\ d * 24\ \frac{h}{d}}{155\ \frac{Wh}{kg}} = 306.6kg$$

with W being the weight, P the power demand, h the operation time and e the practical specific energy.

Tether

Diagram of the ampere capacity for stranded copper, the data is derived from common copper wire data sheets:



Solar panel

Preliminary solar panel size calculation:

Radiation (Porto in January 2013) 1kWh/m²/day = 41.6 W/m²

Efficiency of a light weight and flexible solar cell:

	Amorphous Si	**Mono-crystalline Si**
Intrinsic efficiency	5%	20%
Panel degradation	0.99	0.99
Pointing efficiency	0.9	0.9
Battery charger	0.85	0.85
Battery efficiency	0.85	0.85
Total efficiency =	**3.4%**	**12.9%**

Average power consumption: 11W

Thus, the needed minimum area is (depending on the cell type):

$$A = \frac{11W}{41.6\frac{W}{m^2} * 3.4(12.9)\%} = 7.7m^2\ (2m^2)$$

A selection of flexible marine solar modules is given in the following table:

Module	**Type**	**Power in W_{peak}**	**Size in m²**	**Power supply (MPP)**	***Weight in kg***	***Price in €***
Solara M-serie	Mono-crystalline Si	70	0.54	3.8A @19V	5.9	759.00
PowerFilm SolarCharger	Amorphous Si	120	2.9	7.2A @15.4V	2.95	2,370.00
Sunware TX-22052	Mono-crystalline Si	100	0.9	5.5A @ 22.8V	8.8	1,198.00

Source: Manufacturers information

Considering this selection the modules are in the range of 250-300W, independently of the solar cell type. The amorphous silicon type is advantageous in terms of weight, but requires more surface to obtain the same power due to the lower efficiency.

H. ENERGY SUPPLY SONDE

Solar panel

The same calculation as in the previous section can be done for the solar panel of the sonde. A solar cell efficiency of 17% and an average power demand of 350mW are used. The necessary size of the solar cells are 0.07m². Again some solar cells are presented to estimate the power, the weight and cost.

Module	Type	Power in W_{peak}	Size in m²	Power supply (MPP)	*Weight in kg*	*Price in €*
2W Solar Panel 80X180	Mono-crystalline Si	2	0.014	360mA @5.5V	0.045	6.00
2.5W Solar Panel 116X160	Mono-crystalline Si	2.5	0.019	450mA @5.5V	0.05	7.50
3W Solar Panel 138X160	Mono-crystalline Si	3	0.022	540mA @ 5.5V	0.065	9.00

Source: Manufacturers information

The necessary power of the solar cell has to be between 9-10W.

I. ENERGY SUPPLY BUOY

Renewable sources

The cost for the equipment for renewable energy production on the buoy can be assumed from the following tables, which lists typical marine equipment for power production. First marine micro wind turbines (MWT):

Module	Rotor diameter	Rated power in W	Start up speed in m/s	Power supply (rated power)	Weight in kg	Price in €
Sunforce – 400W Wind Generator (Marine)	1.17m	400	3.0	13.6-17.0V	6	420.00

Silentwind - Windgenerator 12V	1.15m	420	2.2	12.0VDC	6.8	1300.00
Zephyr – Airdolphin Marine 1000W	1.8m	1000	2.5	24V	17.5	3000.00

Source: Manufacturers information

Then marine solar panels:

Module	Type	Power in W_{peak}	Size in m²	Power supply (MPP)	Weight in kg	Price in €
Solara M-serie	Mono-crystalline Si	70	0.54	3.8A @19V	5.9	759.00
Sunware SW-3065	Mono-crystalline Si	48	0.42	2.2A @22V	4.5	599.00
Sunware SW-3066	Mono-crystalline Si	70	0.56	3.2A @22V	6.1	759.00

Source: Manufacturers information

Marine batteries have already been presented in annex B. The next step is now to find a suitable setup for the two reference values 15.5W and 85W. From the previous calculations in annex G it can be concluded that a pure solar solution would require 2.7m² and 15.5m² respectively. This equals to 350W and 2000kW in installed power. Whereas 350W may fit on a rather big buoy (e.g. the Nomad), 2000kW are not feasible. For that reason the addition of micro wind turbines is considered. For that reason the output of a micro wind turbine is calculated from its power curve and the average wind speed at a typical coast site in Portugal. The calculation is done for the months with the lowest energy production. These are the months with little wind speeds (August, September and October) because the peak power of the MWT is much bigger compared to the solar panels. The power curve of the Silentwind MWT is used for this calculation. Its power curve is depicted in and Figure 38. The average wind speed of approximately 5m/s is obtained from www.windguru.cz and represents the wind occurrence in Sagres.

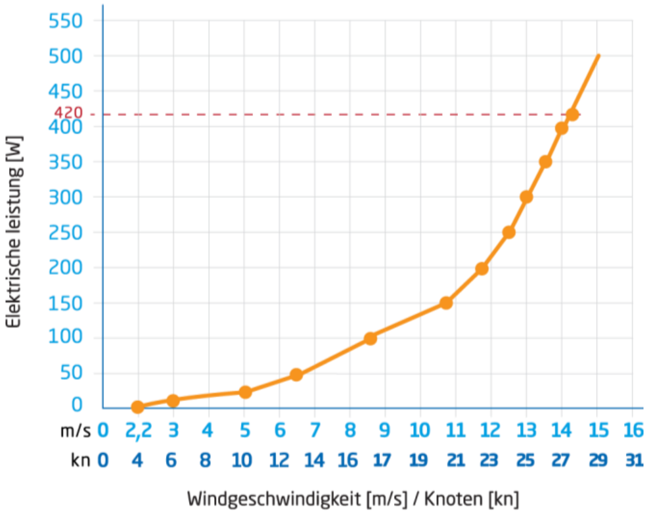


Figure 38: Power curve of the Silentwind MWT

The energy production for this wind speed is in the rage of 20-30W per turbine. For the same time of the year the daily average irradiation in Portugal is around 4500Wh/m² which corresponds to 187.5W/m²; thus it is 4.5 times bigger than in the month with the lowest radiation. The average power per panels can be calculated from the higher irradiation, the efficiency of the panels and their size. The values are shown in the following table:

Module	Power in W_{peak}	Size in m²	Price in €	Average Power in W	Cost per average power in €/W
Solara M-serie	70	0.54	759.00	13.0	58.40
Sunware SW-3065	48	0.42	599.00	10.2	58.20
Sunware SW-3066	70	0.56	759.00	13.6	55.81
Silentwind	420	-	1300.00	25	52.00

Source: Manufacturers information

It can be concluded that the cost per average power at the “bottle neck” point are almost equal. Therefore it seems to be reasonable to use both technologies equally. The selected equipment is shown in the next table, including a 24h backup battery:

Case 1: 15.5W	Module	Power in W_{peak}	Size in m²	Price in €	Weight in kg	Average Power in W
	Solara M-serie	70	0.54	759.00	5.9	13.0
1	Sunware SW-3065	48	0.42	599.00	4.5	10.2
	Sunware SW-3066	70	0.56	759.00	6.1	13.6
15	Lithium-Polymer Battery 24.4Wh	-	-	15.30	0.5	

1	Silentwind	420	-	1300.00	6.8	25
Total:				**3600.00**	**11.8**	**35.2**

Case 1: 85.5W	Module	Power in W_{peak}	Size in m²	Price in €	Weight in kg	Average Power in W
	Solara M-serie	70	0.54	759.00	5.9	13.0
	Sunware SW-3065	48	0.42	599.00	4.5	10.2
3	Sunware SW-3066	70	0.56	759.00	6.1	13.6
84	Lithium-Polymer Battery 24.4Wh	-	-	15.30		
2	Silentwind	420	-	1300.00	6.8	25
Total:				**6163.00**	**31.1**	**90.8**

Generator

The necessary fuel can be calculated from the average power consumption of the buoy, the rated power of the engine and the fuel consumption of the engine. The average consumption is equal to 15.5W or 500W to cover both maxima. The fuel consumption of the engine is 2.4l/h at 3600rpm and the rated power at 3600rpm is 6.3kW. It is assumed the engine charges the batteries at rated speed and is switched off in the meantime. Thus, the necessary fuel on board is:

$$F_{min} = 2.4\frac{l}{h} * \frac{15.5W * 24h * 180}{6300W} = 25.5l$$

$$F_{max} = 2.4\frac{l}{h} * \frac{500W * 24h * 180}{6300W} = 822l$$

J. DATA TRANSMISSION

Data amount sonde/buoy

The accumulating data can be calculated as follows:

Quantity	Sampling rate in s	Precision in Bytes	Example	Data rate in Bytes/s
Wind speed	1	5	034.1(m/s)	5
Wind direction	1	5	281.3(°)	5
Position X	1	9	52.520817	9
Position Y	1	9	52.520817	9
Position Z	1	5	143.4(m)	5
Temperature	60	2	15(°C)	0.03
Pressure	60	6	1013.2(HPa)	0.1

Rel. humidity	60	2	50(%)	0.03
Total				33.2

With this numbers data accumulation at 33.2Bytes/s, which is adjusted upward to 48Byte. The data accumulation on the buoy is consequently approximately 0.5kBytes per second. For half a year (180 days) this sums up to roughly 7.8GB. With compression software this can be reduced, though. With a standard data rate of e.g. 10kbps the data has to be send down from the sondes every 30seconds.

Data amount buoy/shore

To reduce the amount of data not all quantities are sent to shore. Only four quantities are sent to shore averaged over 30min: wind speed, wind direction, height of the measurement and turbulence intensity. To further reduce the data the quantities temperature, pressure and rel. humidity are only sent every hour. The precision can be reduced for all quantities as well. This reduces the amount of data to 1200Bytes per day, which again is adjusted upward to 1.5kBytes per day. See the adjusted table below for details:

Quantity	Sampling rate in 1/day	Precision in Bytes	Example	Data rate in Bytes/day
Wind speed	48	5	034.1(m/s)	240
Wind direction	48	5	281.3(°)	240
Height of sonde	48	5	289.3(m)	240
Turbulence intensity	48	5	018.3(%)	240
Temperature	24	2	15(°C)	48
Pressure	24	6	1013.2(HPa)	144
Rel. humidity	24	2	50(%)	48
Total				1,200

K. DATA TRANSMISSION SONDE/BUOY

ISM Band

The following table lists some modules for data transmissions on an ISM band:

Module	Data rate in kbps	Range in-/outdoor in m	Frequency band in MHz	Power consumption	Price in €
XBee® 868LP	10-80	14/640	863-870	62mA @3.6V	160.50
2KM Long Range RF link	5	*n/s/2000*	*433.92*	2.5mA @3.6V	15.00
Mesh Bee - Zigbee Pro Module (JN5168)	4.8-115.2	30/100	2400	17mA @3.6V	15.00

Source: Manufacturers information

The power consumption are given for transmission mode. Therefore they are smaller on average since the consumption during sleeping mode is very low, typically a few µA.

L. DATA TRANSMISSION AEROSTAT/BUOY

Optical cable

Two quotes for an optical cable option in the tether were obtained. They are listed below:

Company	Specification	Tether cost in €
Skydoc™	2 multi-mode fiber optic strands	4,980.00
Aerial Products	Fiber optic option	5,164.50

Source: Manufacturers information

M. DATA TRANSMISSION BUOY/SHORE

Marine VHF radio

The distance to the horizon can be estimated with:

$$D = \sqrt{2 * R_{earth} * h}$$

The following table shows some examples for the maximum transmission distance. The transmission distance is the sum of the two distances for each object to the horizon, see

Location A (aerial height)	Location B (aerial height)	Transmission distance
Buoy (2m)	Shore (2m)	5km + 5km = 10km
Buoy (2m)	Shore – Hill (200m)	5km + 50km = 55km
Buoy – Aerostat (200m)	Shore (2m)	50km + 5km = 55km
Buoy – Aerostat (200m)	Shore – Hill (200m)	50km + 50km = 100km

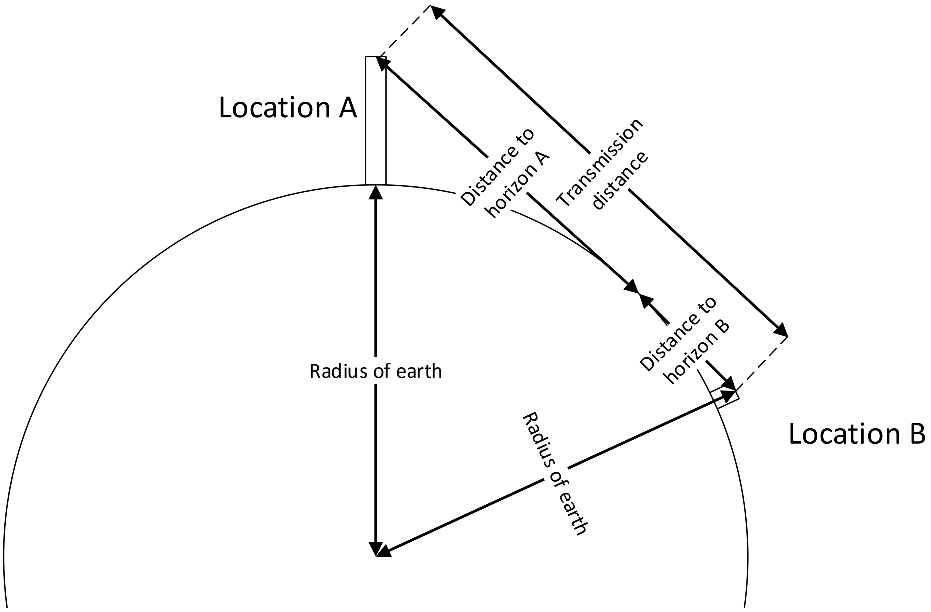


Figure 39: Transmission distance

Satellite

With a data amount of 1.2kB per day a total of 36kB has to be sent to shore monthly. A selection of tariffs from the most common satellite telemetry companies are summarized in the following table:

Provider	Service plan	Service cost in €/month	Data allotment in kB/month	Overage fee in €/kB	Total price in €/36kB
Inmarsat	25k pool plan	26.65	25	0.65	33.77
Inmarsat	100k pool plan	66.17	100	0.37	66.17
Iridium	Plan SBD 0	12.82	0	0.85	41.47*
Iridium	Plan SBD 12	16.54	10	0.77	47.64*

Source: Manufacturers information
*including a 11€ service fee for e.g. GPS tracking, *geofencing* etc.

The prices for typical outdoor satellite terminals for the respective services are as follows:

Model	Network	Price in €
AeroAntenna AT1621-142	Iridium	200.00€
IDP 690 Maritime Terminal	Inmarsat	450.00€

Source: Manufacturers information

N. BUOY AND MOORING

Connection of navigational buoys

To estimate the cost of a solution with connected navigational buoys, the total payload has to be calculated:

Energy supply incl. batteries		150kg
6 Gas cylinders, 65kg each	+	390kg
Connection construction ($1m^2$ cube + connections) fabricated from sheet aluminum ½ inch thick	+	250-300kg
Total:	≈	**850kg**

The maximum payloads for a selection of navigational buoys (from Lindley) are as follows (*assumptions):

B1250T (10,000€, 1.25m diameter, 1.8m height)	200kg
B1600S (15,000€*, 1.60m diameter, 1.8m height)	400kg
C1250T (25,000€*, 1,25m diameter, 3.5m height)	600kg

For stability reasons at least three or four buoy are necessary. More payload may be possible if the navigation devices are removed from the buoys. Therefore three B1600S or four B1250T buoys could be sufficient to carry the payload. Assuming 10,000€ for the connecting structure the overall cost would be in the range of 50,000-55,000€.

Chain weight

The weight of a chain can easily be determined using the weight of the chain per meter, some examples are given in the following table. The net weight considers the fact that the chain is submerged in water and subtracts the buoyance.

Wire diameter in inch	Proof load in kg	Gross weight in kg/m	Net weight in kg/m
1	13,100	12.86	11.12
1 ½	29,700	29.11	25.32

O. COST

The cost items used for the cost analysis are listed again in the following table. Assumed values are indicated with a "*".

Fixed cost

Item	#	Cost per Item	Total Item	Total Subsystem
Aerostat	1	6.500,00 €	6.500,00 €	

Solar panel	1	5.000,00 €	5.000,00 €	
Position lights	2	300,00 €	600,00 €	**= 12.100,00 €**
Sondes	6	1.200,00 €	7.200,00 €	
Tether	1	5.000,00 €	5.000,00 €	**= 11.000,00 €**
Lifting gas	1	5.000,00 €	5.000,00 €	
Power supply	1	2.900,00 €	2.900,00 €	
Mooring sinker	1	750,00 €	750,00 €	
Mooring line	100	60,00 €	6.000,00 €	
Satellite terminal	1	200,00 €	200,00 €	
Data logger	1	8.000,00 €	8.000,00 €	
Position lights	1	300,00 €	300,00 €	**= 23.150,00 €**
Buoy hull	1	100.000,00 €	100.000,00 €	**= 100.000,00 €**
Crew wages	10x10	50,00 €	15.000,00 €	
Boat hire*	10	1.000,00€	10.000,00€	
Miscellaneous*	1	10.000,00 €	10.000,00 €	**= 25.000,00 €**
			Total Cost	**= 171.250,00 €**

Running cost

Item	#	Cost per Item	Total Item
Monthly satellite fees	6	70,00 €	420,00 €
Helium refill	1	1.400,00 €	1.400,00 €
Boat hire*	1	5.000,00 €	5.000,00 €
Crew wages	10x10	50,00 €	5.000,00 €
Aerostat	1	6.500,00 €	6.500,00 €
Tether	1	5.000,00 €	5.000,00 €
		Total cost:	23,320.00€

P. FURTHER DEVELOPMENTS

Budget for the fatigue testing of aerostat and tether:

Item	#	Cost per Item	Total Item
Aerostat	1	6,500€	6,500€
Tether	1	5,000€	5,000€
Long tether winch + 6,3kW Diesel engine	1	10,000€	10,000€
Fuel	8760	1.7€/h	15,000€
Helium	1	6,400€	6,400€
Daily check of ½ h	365	25€	9,000 €
		Total cost:	51,900.00€

Budget for the sonde design:

Item	#	Cost per Item	Total Item
Arduino components	6	250€	250€
Anemometer	1	650€	650€
Materials	1	1000€	1000€
		Total cost:	<3,500€