High Altitude Electrical Power Generation

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Abstract: - This paper investigates the technical feasibility of a system that could be used to collect the solar irradiation at high altitude, convert it into electricity, and then transmit it to the ground via a cable. As a first step to assess the viability of this device, an estimate of the solar irradiation that can be expected at a defined altitude above the ground is presented, based on real atmospheric data. The study demonstrates that locating PV devices at high altitude with the use of an aerostatic platform, could bring a significant advantage in the production of electrical power, if compared with a typical UK ground based PV system. The fundamental equations for a preliminary design of the system are presented together with a first realistic choice of the most relevant engineering parameters that need to be set. An estimate of the cost of the system is provided and the possible risks involved, applications, advantages and disadvantages of the technology are assessed.

Key-Words: - Solar Energy, Aerostat, Photovoltaic, Flying Electrical Generators, Energy Conversion, Solar Radiation

1 Introduction

Ground based Photovoltaic (PV) modules have relatively low energy density which is compounded by the fact that the output of the devices is dependent on the latitude of the installation and in particular by the weather conditions of the location. These factors have particularly hindered the diffusion of this type of devices in countries where the cloud coverage is an important issue to consider, such as in north European countries. For example in the UK, a well designed 1kWp grid connected PV system, will produce around 750-900kWh per year, and assuming a 15% efficiency cells the panels area required would be approximately 7m^2; whereas the same system located in a southern European country could generate about twice as much. As weather conditions can have a strong influence on the output reliability of a ground based PV system, a possible solution could be to install PV systems in areas with high and more constant solar irradiations (e.g. African or Middle Eastern deserts). The main problems of this option are the fact that these areas are remote from most users (in particular UK) and the losses over thousands of miles of cables, together with the political issues involved, would severely reduce the economic advantages.

Another possibility would be to collect solar power in space, as most satellites do in order to power their subsystems. Here a sun pointing surface would receive a constant power of about 1367 W/m^2 that would allow a production of about 12000 kWh per year for the same PV system mentioned above (over an order of magnitude greater than what can be achieved on the ground in the UK). This possibility was considered in the 1970s by Glaser [1], who proposed the large scale collection of solar power using a large satellite platform that would then transmit the energy to the ground using microwave radiation. However, the development of his Satellite Solar Power (SSP) concept was stopped by a mixture of safety concerns (regarding the transmission of energy from the satellite platform to the ground using a microwave beam), as well as technical issues (such as the losses in the energy conversions and transmission), and the very high cost that always denied the economical feasibility of the system.

As an intermediate solution between SSP and Ground Based PV devices we propose the possibility to collect the solar energy using a high altitude aerostatic platform [2], [3], which would support PV devices above the clouds and bring energy to the ground via its mooring line. This approach allows most of the issues related to the weather condition to be overcome, as the platform will be above the clouds except in very extreme weather situations, and it would bring a relevant advantage in the production of energy. At the same time, as the platform is above the densest part of the troposphere, the sun’s radiation will travel through considerably less air mass than if it was on the ground (particularly during the early morning and evening) and this will further improve the energy output.

The choice of transmitting the energy produced to the ground using the mooring line of the aerostatic platform allows to solve most of the problems concerning the safety issues and to limit the electrical losses. The cost for this "augmentation" is mainly constituted by the cost of the aerostatic platform and tether system. The study that we carried out (see ref [3]) considers the economical advantage that this technology could bring, showing that including all these factors it could be possible to make the energy available on the ground at a lower cost than that can be achieved by solar panels based on the ground in northern European countries.

In Sec.2 a first assessment of the possible advantages that can be achieved locating the PV cells at high altitude is presented. The analysis is performed through the elaboration of real datasets that quantify the effect of the clouds on the solar radiation at different altitudes. In Sec.3 the concept is presented together with a preliminary design of a facility to collect solar energy in the medium-high troposphere. The preliminary design includes a first sizing of the system with the selection of the relevant engineering parameters and the assessment of the performance. Particular attention is dedicated to the study of the dynamic behavior of the tethered aerostat, when subjected to the environmental conditions, in which the system is due to operate (wind speed and gusts). In Sec. 4 an analysis of the cost of the system is carried out and the possible risks involved in the operation are considered together with possible market applications.

2 Atmospheric Attenuation of Solar Energy

In this section, a preliminary characterization of the environment in which the system is due to operate is presented. The characterization basically includes an assessment of the solar radiation that can fall on a surface located at different altitudes above the ground, considering the combined effects of the clear atmosphere and the influence due to the presence of clouds. The analysis is based on real data collected for a precise location in the South of the UK (Chilbolton), but the conclusions can be extended to other regions located at Northern latitudes in Europe with similar climates.

The attenuation of a solar beam travelling through the atmosphere is mainly due to the interaction between the radiation and the air molecules in terms of absorption and the scattering. The combined effect of these two kinds of processes can be quantified using the atmospheric extinction parameter α, in the differential equation that governs the attenuation of a light beam of intensity I crossing an infinitesimal distance dz (Lambert-Beers' Law):

$$\frac{dI}{I} = -\alpha \cdot dz \tag{1}$$

The extinction parameter can vary considering different altitudes in the atmosphere above the ground and the instantaneous position of the Sun (that depends on the time of the day).

Considering the variation of α due to the altitude, it is possible to assume the atmosphere as composed by i layers characterized by constant extinction α_i so that the light beam travels through segments of length Δz_i as shown in Fig. 1. Therefore it is possible to rewrite the Lambert-Beers' law which allows calculating the radiation intensity I as:

$$I = I_0 e^{\sum -\alpha_i \cdot \Delta z_i} \tag{2}$$

where I_0 is the irradiance before the beam enters the atmosphere and the sum considers all the segments crossed by the light beam down to the altitude h_0 where we want to calculate the beam intensity.

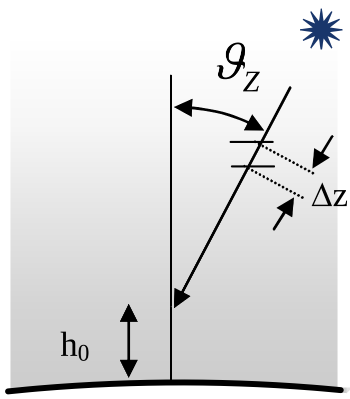

Fig. 1: Sun beam path reaching the altitude h_0

In addition the influence of the real path of a solar beam must be taken into account. In general the solar beam doesn't travel along a vertical path, but it is inclined at an angle θ_z (Sun Zenith Angle) which depends on the Sun position. Therefore it crosses more air mass than if it was travelling along the zenith. This can be accounted for using the relative air mass AM_{REL}, which defines the ratio between the real path and the one along the zenith. For small angles θ_z , AM_{REL} is determined as:

$$AM_{REL}(\vartheta_Z) = \frac{1}{\cos(\vartheta_Z)} \tag{3}$$

For larger angles (that is when the sun is low on the horizon), a more accurate expression can be found in [4]. Therefore it is possible to write the beam intensity that reaches a layer at an altitude h_0 as:

$$I(h_0, \vartheta_Z) = I_0 e^{AM_{REL}(\vartheta_Z)\sum -\alpha_i \cdot \Delta h_i} \tag{4}$$

The sum extends from the top of the atmosphere to a certain atmospheric layer at an altitude h_0 above the ground. In practice, here only the layers up to 50 km altitude have been considered, beyond which the extinction parameter becomes – for our purpose- negligible, and the intensity of the solar radiation (I_0) is assumed constant and equal to 1367 W/m^2.

Starting from the top atmospheric layer, initially the sun beam crosses clear atmosphere (no clouds). Therefore the attenuation at high altitude is quite small and it is only in the last few kilometers that considerable attenuation occurs due to the increasing density of the atmosphere, and very importantly to the possible presence of clouds. Two different datasets have been combined and used to obtain the values of the extinction parameters. The first dataset for clear atmosphere conditions has been published by Elterman [5] and the results obtained using his data in equation (4) have been verified against other methods [6]. However, as mentioned before, clouds produce substantial attenuation, and therefore their effect cannot be neglected.

The second dataset which considers the actual atmosphere (i.e. including the effect of the clouds) at various altitudes was provided by the Cloudnet Project [7]. The data contain extinction parameters obtained from Radar/Lidar measurements at Chilbolton (UK) Observatory. Sample of the data showing the extinction parameter for a typical month and day are shown in Fig 2.

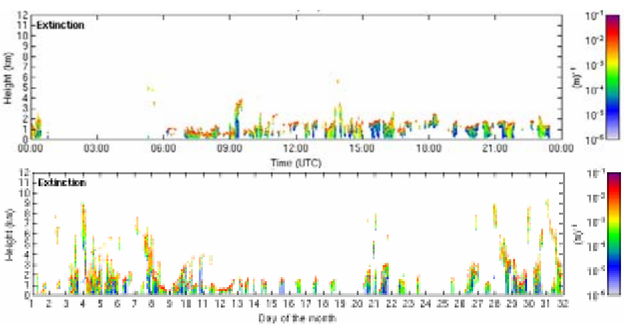

Fig. 2: Extinction parameter. Below, monthly variation (May 2004), above detail of the daily variation (5th of May)

The data from Chilbolton covers only altitudes up to 12km; however clouds above this altitude (although possible, as some clouds can extend up to 20km and more) are relatively rare, and therefore the loss of accuracy considering clear sky above 12km in this context is very small.

Utilizing the data by Elterman for clear sky conditions above 12 km and the Cloudnet data for altitudes between the ground and 12 km, a combined dataset has been created to be used in the equation (4). The equation is applied from the top of atmosphere to the altitude at which the platform to capture solar energy is positioned, to calculate the beam intensity that can reach that atmospheric layer. The beam intensity values can then be averaged during the year, and the results obtained for the altitudes of 6 and 12 km and ground level are shown in Fig. 3.

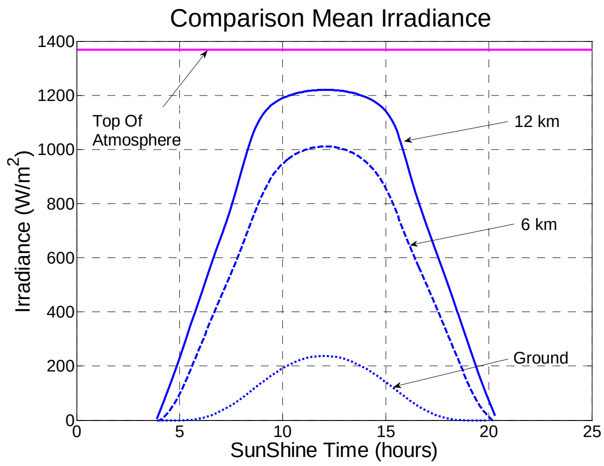

Fig. 3: Daily variation of the yearly mean value of the Irradiance (beam component)

The beam irradiance ([W/m^2]) needs to be integrated during the day (from sunrise to sunset) in order to obtain an estimate of the total year beam irradiation E_B ([Wh/m^2]) that can be collected by the device if located at a defined altitude h:

$$E_B(h) = \int_{SR}^{SS} I_B(h)dt \tag{5}$$

where SS and SR indicate Sunset and Sunrise.

The result is a total year beam irradiation of about 500 kWh/m^2 at ground level (in the UK), whilst the irradiation at 6 and 12 km are approximately 3500 kWh/m^2 and 4800 kWh/m^2 respectively.

The final step is to include the diffused component of the radiation, that at ground level can be even higher than the direct (beam) component.

For the ground level radiation, data is available from various sources, and to obtain the diffused component at the altitude of 6km and 12km the values have been interpolated between ground data and diffused component data coming from satellites in Low Earth Orbits. The interpolation is then carried proportionally to the air mass (assumed to be proportional to the relative pressure) that will be above the specific altitude, and this results in a 15% and 12.5% increase (due to the diffused component) of solar radiation for the altitudes of 6 and 12 km respectively.

Overall the output that can be expected from a typical 1kWp system, at 6km ore 12km altitude is about 4200 and 5500 kWh respectively, whereas a similar system on the ground in the UK typically output between 750 and 900 kWh (although this figures also includes losses for various inefficiencies which could be up to 10-20% and that are difficult to quantify for a high altitude system).

3 Harvesting of High Altitude Solar Energy

In order to exploit the solar energy available in the high atmosphere it is necessary to have a high altitude platform to support appropriate devices to capture this energy (e.g. PV device) and a means to transport the energy to the ground. Aerostats moored to the ground are very cost efficient platforms and they have been used for various applications, providing durable and reliable support for different types of payloads. In general lighter than air systems are used for surveillance, observation and military purpose. For example, along the south of the United States there are already 15 locations with moored aerostats flying at approximately 5-6 km altitude, carrying radar equipment to monitor air traffic entering the U.S. from the south. These aerostats are equipped with an electrically conductive mooring cable that supplies the aerostat (capable of continuous operations for weeks) with electric power from the ground.

It is therefore possible in principle to have a large aerostat to support PV devices and transmit the electric energy to the ground using the mooring line. In the next sections, the technical feasibility of this concept is explored by carrying out a preliminary sizing of the aerostat and mooring cable with the choice of the most important engineering parameters involved. In addition, a more detailed study of the dynamic behavior of the tether subjected to the operational conditions is presented.

3.1 Aerostat for electrical power generation

The first parameter to be set in the design process is the aerostat size that has to be chosen in order to satisfy the operational requirements in terms of lift, weight and energy produced. The aerostat has to be large enough to have sufficient payload capability to lift the weight of the PV devices, the mooring cable and all the subsystems necessary for the operations, and at the same time has to offer a substantial area to be covered by PV devices.

Moreover the external layout of the aerostat has to be set, to take into account all the issues related to the aerodynamic of the system. Most aerostats have streamlined bodies to minimize the drag force produced by the high altitude winds, and to give aerodynamic stability to the system. Many investigations of the flow around this kind of bodies have been performed, both numerical and experimental (with different applications as in [8]). The streamline shape allows the aerostat to behave like a weathervane and line itself up with the wind direction. This can be an advantage in terms of stability. However if the aerostat envelope is partially covered by PV devices, it is clear that to maximize the energy output (which depends on the angle between the solar cell and the incident solar beam), the PV have to be pointed towards the sun. The specific requirement of reducing the aerodynamic moments to allow pointing towards the sun, could conflict with the streamlined body of the aerostat which would tend to line up with the wind direction. Renouncing the streamlined shape for a gimbaled balloon such as the one shown in Fig. 4 would allow to orientate the aerostat and PV devices towards the sun without generating significant aerodynamic moments, and therefore minimizing the power required from the pointing mechanism.

The drawback of this configuration, in aerodynamic terms, is a higher drag force and the presence of vortex induced vibration that would produce oscillations of the aerostat body as a wake of vortexes is shed behind it. An appropriate structural design of the aerostat and cable can take care of the higher drag force [9], and as far as the vortex induced vibrations [10] are concerned, these produce mainly oscillatory displacements and do not produce significant rotations of the aerostat body (that can therefore preserve its sun pointing with sufficient accuracy). These issues have been addressed in detail in [6].

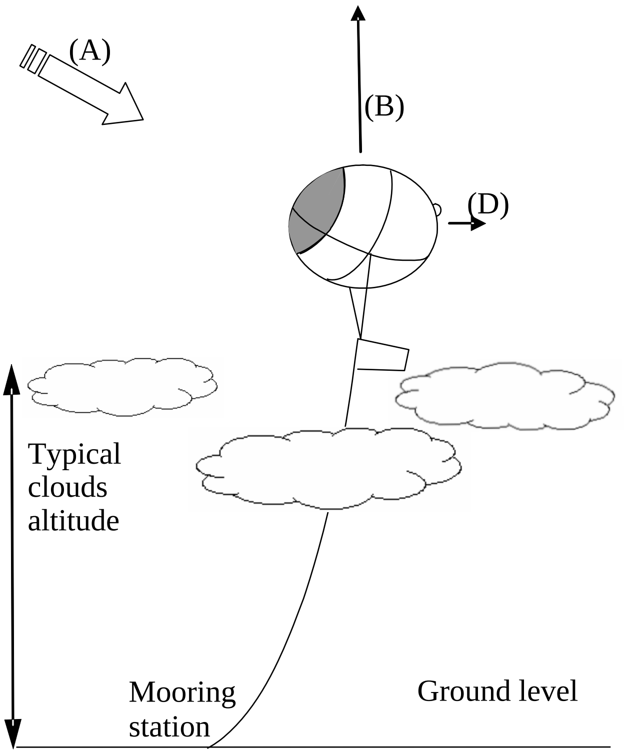

Fig. 4: Schematic configuration of an Aerostat for Electrical Power Generation. The grey area represents PV cells cladding; B lift force (Buoyancy), D drag force, A solar beam direction

3.1.1 Aerostat parametric model

Following the fundamental equations involved in the preliminary design of the system are presented. They mainly focus on the most important parameters that have to be set to size the aerostat and the subsystems, in particular for the design of the mooring tether. Moreover the equations allow to do a first assessment of the performance of the system.

The aerostat has to be able to produce enough lift via its buoyancy to overcome its weight, the weight of the solar cells plus any control system and that of the tether, still leaving enough margin to produce appropriate tension in the tether to avoid excessive sag. The buoyancy produced is directly related to the volume of the aerostat and to the characteristic of the contained gas. Assuming a spherical shape, the lifting force due to the aerostat buoyancy is:

$$L = (\rho_{air} - \rho_{gas}) g \frac{4}{3} \pi R^3 \qquad (6)$$

where R is the radius of the aerostat and ρ_{air} and ρ_{gas} the densities of air and gas (helium or hydrogen can be used) filling the aerostat envelope at the specific conditions of operations (e.g. pressure, altitude), and g is the gravity acceleration (9.81m/s^2). Here it is assumed that there is a negligible pressure differential between inside and outside the aerostat envelope, and that the whole volume of the envelope is occupied by the gas.

The weight of aerostat and PV devices is proportional to the external area of the aerostat, and it can therefore be written in terms of the envelope's surface, using the Radius as variable:

$$W_{aero} = (1.33\delta_{aero} + \delta_{cells}\gamma) g \, 4\pi \mathrm{R}^2 \qquad (7)$$

where δ_{aero} and δ_{cells} are the area density of the envelope material and PV cells respectively, γ is the fraction of the envelope surface that is covered by the PV cells, g is gravity acceleration and R is the radius of the balloon.

The first step to determine the weight of the mooring tether is the assessment of the force this has to be able to withstand, the estimate of the power generated by the PV cells and the electrical losses along the cable. Defined the force in the tether, it is possible to estimate the weight of the load bearing element of the cable, that has to be added to the weight of the conductor that is used to transport the electric energy to the ground. Starting from the latter, the power produced by the PV cells cladding the aerostat is equal to:

$$P_{gen} = 4\pi \mathrm{R}^2 \gamma \eta_{cells} \eta_{area} \Phi \qquad (8)$$

where γ is the fraction of the whole aerostat surface covered by PV cells of efficiency η_{cells}, η_{area} is an efficiency parameter that considers that the cells are on a curved surface and therefore the angle of incidence of the sun beam varies according to the position of the cells and finally Φ is the solar flux at the aerostat operational altitude that is the irradiance discussed in the previous sections.

The size of the required conductor can be estimated from the electrical current (that is the ratio between the power generated by the PV devices on the aerostat and the transmission voltage V), setting a defined value for the losses along the cable. The cross sectional area of the conductor can then be determined as:

$$A_{cond} = r_{Al} \frac{S}{\eta_{trans}} \frac{P_{gen}}{V^2} \qquad (9)$$

where r_{Al} is the resistivity of the aluminium (selected for its higher conductivity over mass ratio), S is the overall length of the conductor, η_{trans} is the ratio between the power lost in the cable and that generated by the PV devices (that is P_{gen}), and V is the transmission voltage.

The size of the load bearing part of the cable can be calculated from the maximum longitudinal force that it will be able to withstand:

$$T = \sqrt{(B - W_{Aero})^2 + D^2} \qquad (10)$$

where B is the buoyancy produced by the aerostat, D is the aerostat drag force, and W_{aero} is the total weight of the aerostat, including PV devices and any other subsystem necessary for the operations (i.e. tracking mechanism). Once the maximum load is known, knowing the specific strength of the material used for the cable, it is possible to calculate its cross section. Finally knowing the cross sections of the load bearing part of the cable and that of the conductor, their length and specific material weight, it is possible to calculate the total weight of the cable.

3.1.2 Aerostat sizing

In order to carry out a preliminary sizing of the main elements composing the apparatus it is necessary to have a reasonably good knowledge of the environment, in which the system is due to operate. In particular it is important to obtain a good estimate of the wind speed at the operational altitude, to define an accurate value of the aerodynamic forces acting on the system. Moreover realistic values for all the engineering parameters characterizing the various subsystems, such as typical area density for the aerostat envelope materials and PV cladding need to be properly set, to get a preliminary design of the concept.

Concerning the wind, the data used in this study was provided by the Natural Environment Research Council (NERC), from the Mesosphere-Stratosphere-Troposphere (MST) Radar station located at Capel Dewi in UK. The dataset can provide a wind speed profile at various altitudes, up to a height of 20 km above the ground, with a vertical resolution of 300 m. For our actual purposes an altitude range up to about 10 km was taken into account for the analysis. The year mean and the 3 sigma values have been determined for the different layers above the ground (Fig.5). Considering a possible operational altitude of 6km, the year mean value of the wind speed obtained is 20m/s and the 3 sigma value results 55m/s. Starting from these values it is possible to estimate the aerodynamic drag, considering the projected surface of the spherical aerostat.

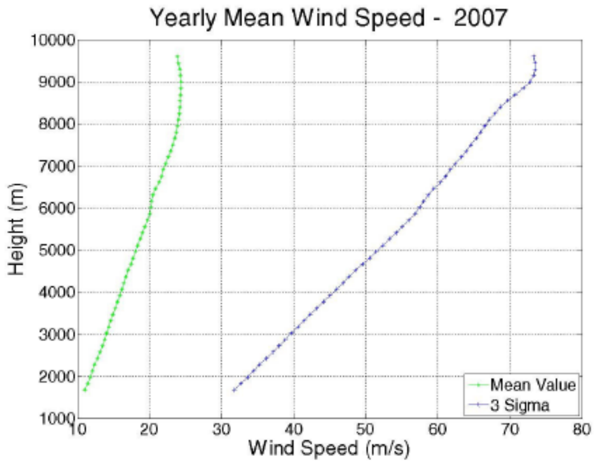

Fig. 5: Wind Speed profile – Year Mean and 3 Sigma Value

To calculate the total weight of the lighter than air platform (including the PV cladding), it is necessary to give an estimate of the specific weight of the envelope fabric and of the PV cells. Typical values for the aerostat envelope specific weight according to size can be found in [11], or they can be provided by fabric manufacturers. The weight per unit area for the PV devices are known from literature and in this particular study we have considered Crystalline Silicon PV devices with 1kg/m^2 area density and 15% efficiency.

As described above, the size of the aerostat has to be properly selected in order to produce enough disposable lift to be able to produce enough lift to maintain all the subsystems at the operational altitude and to keep the mooring cable relatively taut, avoiding excessive sag.

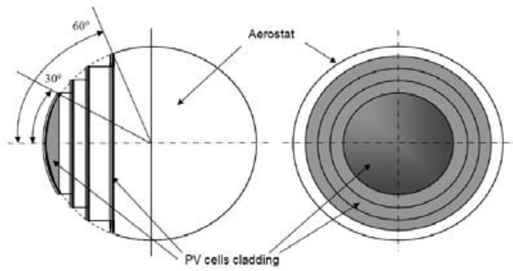

Fig. 6: PV cells cladding

Considering these factors in our preliminary study we have found that a 35m R sphere (that means an area of the external surface of about 15,400 m^2 and an aerostat volume of 179,000 m^3) should be able to generate a gross lift of about 1 MN, enough to overcome the weight of its own envelope, of the PV cells cladding and of the tether. In terms of energy, the aerostat should generate a peak power of 0.5MW, using a cladding like the one presented in Fig 6. However the energy output can be increased using PV cells with higher efficiency than the one considered in this preliminary study. Another important parameter that needs to be set to maximize the power production of the system is the transmission voltage, which should be enough high in order to limit the electrical losses along the tether. The transmission voltage has been preliminarily set at 3kV and this should keep the losses in the mooring cable at about 5%.

3.1.3 Tether Dynamics

An important issue to be addressed in the development of the design, is the dynamic behavior of the system when subjected to the operational conditions in terms of constant wind speed and possible gusts that might occur. Following a preliminary analysis of the effect of the aerodynamic forces on the system is presented, with particular attention to the interaction between the mooring tether and the aerostat.

Previous works have considered the problem of defining the response of tethered spheres to aerodynamic loads [10] in uniform flows with Reynolds number up to the supercritical region. These analyses are focused on the study of the amplitude of the displacements due to the vortex induced vibrations, supporting the theoretical model with very extensive experimental results and considering the effects of parameters like mass ratio and mass damping. The research presented here includes the specific effect of the tether sagging due to its own weight and considers the non linear dynamics that can affect considerably the behavior of the balloon (in particular when the response to transient loads, such as gusts, needs to be determined). The work is based on the development of an algorithm that includes an FE model and allows to carry out the solution in the time domain and to update at each time step the loads due to the interaction between the body and the fluid flow.

The system is modeled using commercial FE software (Ansys). In particular the tether is built dividing the total length into N beam elements with a defined density and bending stiffness. The loads along the tether are defined with the use of a load matrix $\mathbf{F}_t$. The aerostat is modeled with a point mass of defined inertia connected to the last beam element. The load in this case is defined with a vector $\mathbf{f}_A$ which represents the forces due to aerodynamics and the buoyancy of the balloon. The solution is calculated by the FE code imbedded in a loop, which implements a transient analysis (including stress stiffening), at each time step and updates the input for the next solution. Both $\mathbf{f}_A$ and $\mathbf{F}_t$ are updated to take into account the possible variation of the external load on the system (wind speed and direction). The loop is summarized in Fig.7.

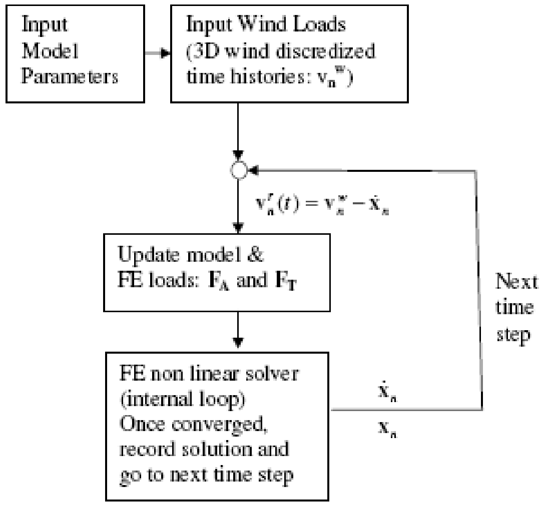

Fig. 7: Solution scheme summary flow chart

For the moment, the forces are calculated directly from the relative velocity between the fluid and the structure. Since the curvature of each tether element is significantly smaller than the element length or cross section, the tether can be considered consisting of straight cylinders with varying inclination with respect to the incoming flow as shown in Fig.8.

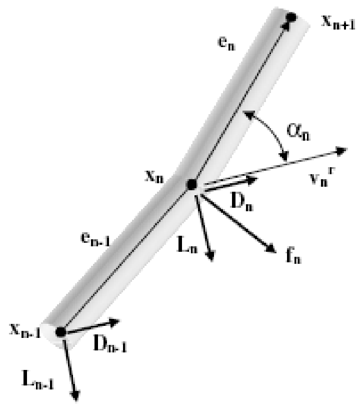

Fig. 8: Tether elements and wind vector

The aerodynamic forces acting on each element can be therefore determined using the 2D lift and drag coefficients presented in [12].

The results obtained from the FE model were validated against theoretical results, for two different types of analysis. The first analysis concerns the quasi static response of the system, and the input used is a constant wind speed. The theoretical model required an extension of the standard catenary equations, to include the horizontal loads and the stretch of the cable. The deformed shape of the tether obtained with the FE model and the one derived from the theory, were compared showing excellent agreement.

The second validation was used to verify the dynamic response of the tethered balloon. In this second case, the period of the oscillations of the system around a position of equilibrium were compared to the period of the oscillations of an inverted pendulum with equivalent characteristics (See Fig.9).

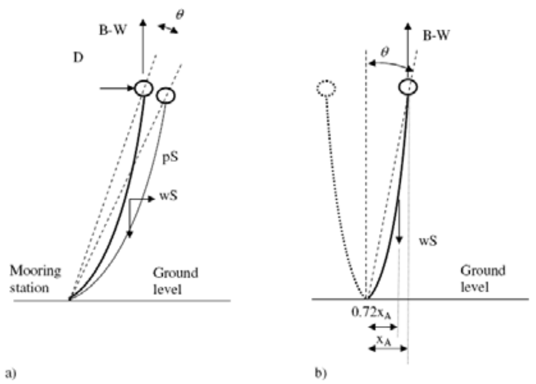

Fig. 9: Small oscillations a) with wind b) no wind

As in the case of the static validation, the comparison between the results obtained from the FE model and the theory showed excellent agreement.

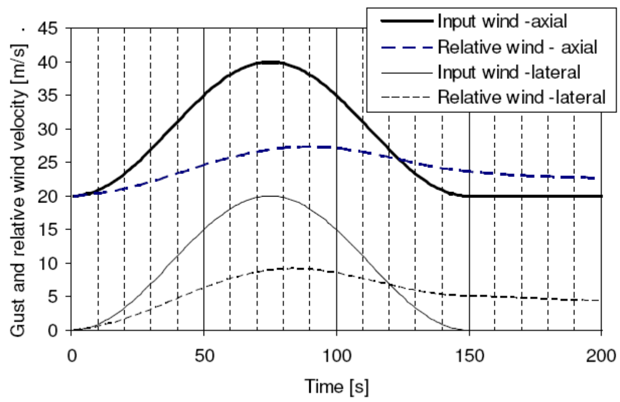

Fig. 10: Wind profile and relative wind velocity in the direction of the gust

Once the model was validated, different simulations were performed for different loading conditions, which are presented in Fig.10.

The first loading condition is represented by a gust of 20 m/s in the same direction of a 20 m/s constant wind flow, while for the second loading condition a 20 m/s gust applied in a horizontal direction transverse to the 20 m/s wind flow was considered. For both the cases, since the system is overdamped, a 150 seconds duration gust was considered.

For what concerns the first loading case, the maximum displacements occurred along the tether line show that the dynamic response is considerably smaller than the steady state response determined during the validation described above. Observing the rotations plotted in Fig.11, it is possible to note that the maximum angle obtained is of about 7.6 degrees, due to the overdamped nature of the response. For the specific case of aerostats for solar power generation, this rotation angle would cause a decrease of the PV device output of less than 1%, since it depends on the cosine of the angle between the solar beam and the cell surface.

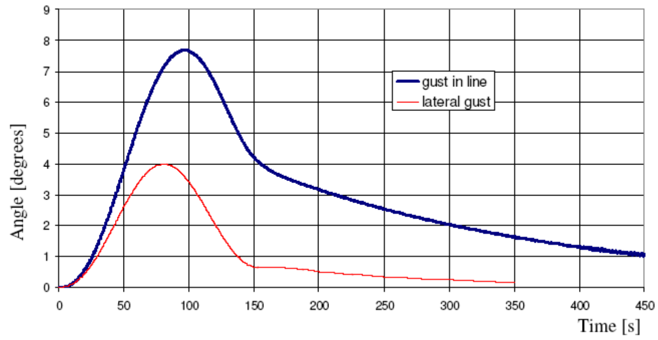

Fig. 11: Rotation of the aerostat produced by a 20 m/s gust summed to a 20 m/s constant wind speed

Considering the second loading condition, the response to the lateral gust presented in Fig.12 and Fig.13 shows that the resulting displacement is along the three axes simultaneously, although the main displacement is along the direction perpendicular to the initial wind direction. This is due to the fact that the tether has the effect of coupling the displacement from the other two directions.

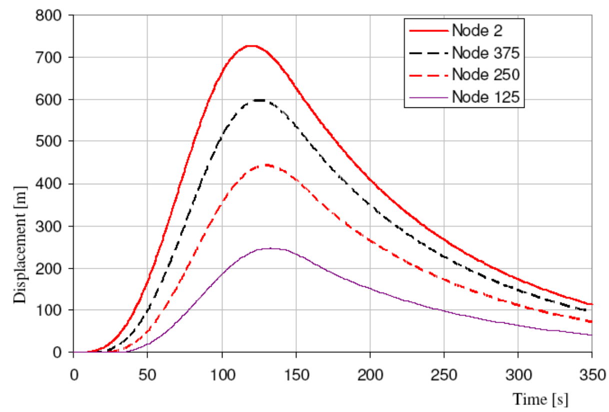

Fig. 12: Out of plane response of aerostat and tether line nodes subjected to a gust (20m/s, 150 sec duration) perpendicular to a constant wind (20 m/s)

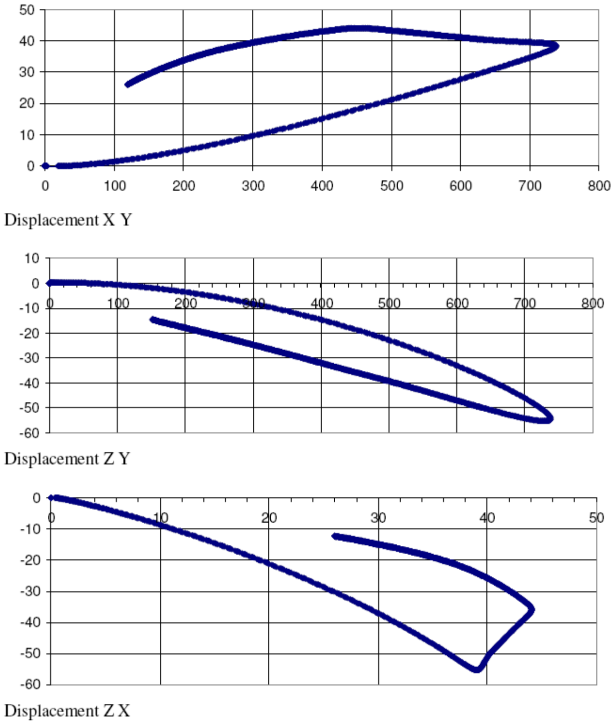

Fig. 13: Trace of the aerostat displacements in the 3 planes, when subjected to a 20 m/s gust transverse to a 20 m/s constant wind speed

The analysis demonstrates the importance to carry out a dynamic study of the behavior of the system, in order to avoid an overestimate of the response. The results obtained show that displacements and rotations give consistently lower values than the static solution, due to the high level of damping (especially the aerodynamic damping produced by the tether). Therefore, the static response can be appropriate for an initial stage of the design, but it might not be accurate enough for the detailed design phase.

4 Commercial exploitation

There are two main factors that need to be considered to assess the potential of this concept for commercial exploitation. The first one is the cost of the system and its operation, that ultimately define the cost of the electricity produced. The second is related to the risk, intended not only as technical risk in the project (or its operations) but also risks related to the necessity to comply with a country's regulatory framework in this area which will necessarily pose some limitations to the deployment of this type of devices. Finally the market has to be assessed to confirm the potential for commercialization against existing and future competitors.

4.1 Cost

The assessment of the cost of this facility is quite difficult as the design is still at its concept stage, and only a preliminary sizing of the components has been carried out. Therefore at this stage the only method to predict the cost of the facility is through extrapolation of the cost of "similar" systems, currently in operation. Starting from the Aerostatic platform, the first difficulty is that cost data available from the Aerostat manufacturing industry is very limited. The aerostat weight seems to have a good correlation with cost, and based on a preliminary survey of aerostats currently on the market it is estimated that 2M$ (excluding gas and PV cells) should cover the envelope cost. The cost of the PV cells and that of the helium are calculated from their specific costs, taken here as 4$ per W for the cells and 5$ / m^3 for the helium respectively. Also the cost of the tether has been accounted for using the specific cost of the materials (Aluminium for the conductor, and Kevlar for the strengthening fibers). Overall the complete system should cost in the region of 4.5M$ and produce about $1.7 \cdot 10^6$ kWh per year.

4.2 Risk

The technologies underpinning the concept are relatively mature and the technical risks can be mitigated in the detailed design of the facility. The main risks involved in the development of the project concern issues related to extreme weather conditions, in particular lighting that can occur when the system is in operation. Another significant risk is the possible interference between the presence of the tether and the general aviation traffic.

However, at this preliminary stage, as the objective is to prove the technical feasibility of the system, we can simply look at the experience of the tethered aerostats used along the south border of the USA. These aerostats are able to withstand very strong winds and lightning strikes, and have been in operation for some time. Therefore we can conclude that although there are some undeniable risks during the operations related to the weather conditions, these can be managed, and they will be considered more in depth in the following phases of the design process.

Concerning the regulatory framework, deployment below 19000ft, i.e. below the internationally controlled air space simplifies the legal issues related with the deployment. Again the experience provided by the tethered aerostats currently in operation, can be used as a starting point for the solution of this problem in the following phases of the project.

4.3 Market Applications

In most high latitude countries such as the UK and north European nations the main player as supplier of electricity from renewable sources is wind power. Although in terms of cost at this stage it is difficult to demonstrate that harvesting solar energy at high altitude is more economical then wind power, there are some factors that could make this method to generate electricity preferable. Firstly provided that the aerostat is mechanically/electrically reliable, the energy output should be very reliable too, as above the clouds the quantity of solar energy available is indeed very predictable. On the contrary wind turbine production can be very unreliable as dependent on the presence of wind [13], [14], [15]. Also the daily cycle of solar energy production is better correlated with consumption needs than wind turbine production.

Moreover this kind of system can be extremely useful in conditions where the electrical energy production must have a minimum impact on the ground. The deployment of an aerostat for electrical power generation can be the only way to harness solar energy in emergency situations (natural disaster relief, flooded areas), and it is possible to imagine that these devices could be employed not only in countries with cloud coverage problems, but also in areas where the land resource is scarce.

5 Conclusions

In high latitude countries, the solar energy reaching the ground is significantly lower than that reaching their medium to high troposphere . This is in part due to the prevalent weather conditions and in part to the low angle of the sun above the horizon. These factors have significantly hindered the large scale use of PV devices in these countries.

Using experimental data the energy that can reach a surface located at 6km and 12 km has been calculated, showing levels several folds higher than on the ground. The collection of solar energy at these altitudes could produce 4 to 6 times more energy than that produced by typical UK ground based systems.

A concept to exploit the high level of solar energy available in the high atmosphere has been presented. The concept is based on lighter than air technology and proposes the development of an aerostatic platform to locate the PV cells at high altitude in order to maximize their output.

Realistic values for the relevant engineering parameters have been set, to describe the technical properties of the materials and provide a preliminary sizing of the different subsystems involved. Particular attention has been paid to the dynamic behaviour of the tether, when subjected to the wind conditions in which the system is expected to operate. The preliminary analysis shows that the device is indeed feasible from a technical point of view. To prove the economical feasibility a preliminary costing of a device has been carried out based on similar systems currently available on the market. Finally the technical and commercial risks related to the deployment of this concept have been briefly discussed and assessed, considering in particular issues concerning extreme weather conditions and regulatory problems related to the possible interference with air traffic.

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