July 18, 2011

StratoSolar Photovoltaic system

Introduction: The goal of this document is to present a short introduction to StratoSolar Photovoltaic (PV) technology and economics.

Alternative energy solutions are struggling to be economically viable without subsidy and also demonstrate that they can scale adequately without damaging the environment they are allegedly trying to protect.

It is becoming increasingly clear that no current alternative energy technology is in sight of satisfying these two big constraints, and in a world of fiscal austerity the will to subsidize alternative energy solutions to the degree necessary to take them to economic viability is rapidly disappearing.

The StratoSolar PV solution represents an opportunity to make today's PV technology cost effective without the massive subsidy needed to drive the technology to commercial viability in the 15 to 20 years historical trends would indicate will be necessary. It also makes PV an affordable alternative for locations like Germany and Japan where PV is unlikely to ever be viable without subsidy.

What the StratoSolar PV system does:

- Weather independent, photovoltaic solar power (PV)
- Locations up to latitude 60 produce market competitive electricity
- Electricity in utility scale systems from 10 MW to 1 GW in modular increments
- Cost competitive electricity without subsidy

Key insights:

The idea exploits two environmental facts. Firstly, the stratosphere is a permanent inversion layer in the earth's atmosphere. Inversion layers effectively isolate gas bodies. The calm weather free stratosphere is isolated from the turbulent troposphere below. There is no rain, hail, snow, or moisture in the stratosphere and wind force is much reduced and stable. This means that buoyant platforms suspended in the stratosphere can be permanently stationed there without needing to be winched down in bad weather. It also means that PV panels in the stratosphere don't suffer water or snow or ice based weather effects and can be simpler and cheaper to manufacture.

Secondly, light from the sun at 20km altitude is both strong and constant from dawn to dusk. At 20km a platform is above over 90% of the atmosphere, so sunlight is not significantly scattered or absorbed and there are no clouds to interrupt power generation. This means that on average PV panels produce multiples of the power they can generate on the ground, and just as important, the power is highly predictable and not subject to interruption by clouds or storms.

Why it generates electricity at a reasonable cost:

For solar-power plants, almost the complete operating cost is the loan payment. The StratoSolar PV system has a reasonable operating cost mostly because the solar PV array (which dominates PV cost) has a reasonable capital cost and a high utilization, with a resulting reasonable cost of electricity. The reasons for this are:

- The PV panels are exposed to 1.5 to 3.5X the solar energy of ground-based PV panels
- This means each square meter of PV panel gathers 1.5 to 3.5X the energy of ground-based PV panels
- The PV array uses no land. No land cost, or site development cost.
- The PV array support structure uses very little material due to light structural loads.
- All construction materials are standard, off the shelf, and low cost
- The PV panels are lower cost than ground-based PV panels due to reduced panel packaging cost
- The PV panels are higher efficiency than ground-based PV panels due to lower operating temperature and reduced reflection losses.

The extra capital costs incurred by the StratoSolar approach are the tether/HV cable, the winch, the gasbags and the hydrogen they contain. Adding everything up the capital cost of a StratoSolar plant in dollars per peak Watt ($/Wp) is the same as or lower than the same plant on the ground. (peak Watts is the standard way of defining the power output of PV panels) However the StratoSolar plant captures substantially more energy and generates substantially more kilo Watt hours (kWh) of electricity. Depending on geographic location the overall advantage in the cost of electricity generated in $/kWh over ground-based PV can exceed 3X. See the detailed analysis section below for more detail on this topic. Electricity cost for different locations and capital costs

This is a commercially competitive alternative energy solution. By not covering huge land areas, it saves on an expensive, highly regulated, and uncertain resource that tends to delay construction and limit financing options. It also allows great flexibility in location. The competitive and highly profitable economics should lead to a business that is market financed and does not need government support or subsidy once demonstrated. It is a bonus that this energy is carbon-free, and solves energy security issues.

The idea:

A PV array, permanently positioned in the stratosphere at altitude 10 km to 20 km, gathers sunlight, converts it to electricity and transmits it down a tether/high voltage (HV) cable to the ground where it connects to the electricity distribution grid.

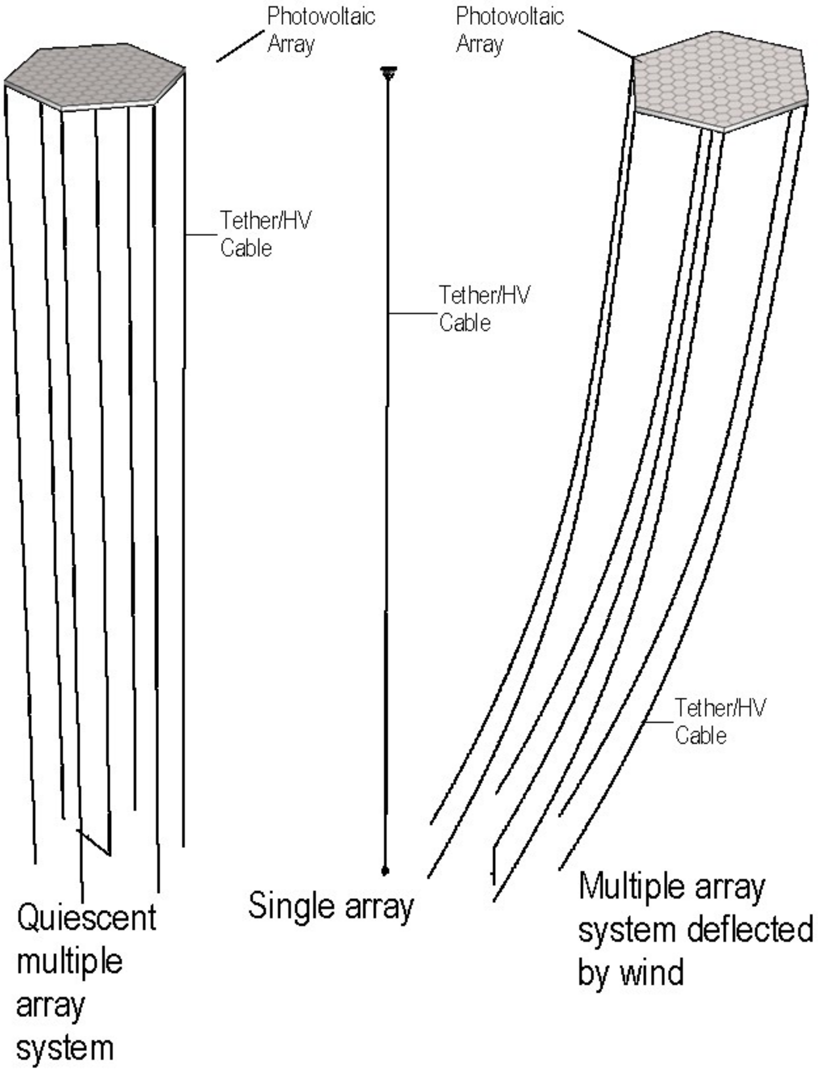

Figure 1

Figure 1 shows an individual PV system in the center. Figure 9 shows a close up view of the platform. The novel element of a StratoSolar power plant is a buoyant tethered platform supporting an array of PV panels floating in the stratosphere. The strong and light tether incorporates a HV power cable that transfers electric power to the ground. Excess buoyancy in the floating platform pre-tensions the tether and allows the platform to resist wind forces.

A rigid truss structure supports the PV array. Buoyancy is from gasbags within the truss framework. Models for the PV array power output are subject to simulation to a high degree of accuracy, with high confidence in the results. While the buoyant structure is novel, there is no new science, and existing engineering design tools are sufficient. The wind and buoyancy forces are well understood from an engineering perspective. There are detailed meteorological models and historical data to provide an accurate statistical profile of the wind and buoyancy forces on the structure and tether. The combination of accurate structural analysis and reliable meteorological data mean that structural viability can be determined to a high confidence level before construction. Accurate models for sunlight and how it varies with location and altitude, daily and seasonally, provide an equally high confidence level for the power output.

Figure 1 also shows two views of a large-scale system, the first view on the left with no wind and the second view on the right with a maximum wind load. The large-scale system is a collection of mechanically connected individual modular small-scale systems. For clarity only some of the tethers are shown. The benefits of connecting multiple smaller systems to make a larger system are reduced aerodynamic drag on the PV array and reduced impact on regulated airspace. The array is directionally stable and panels can track the sun. The reduced aerodynamic drag ensures that the structure can withstand the highest wind forces with a large safety margin and is safe to deploy on a permanent basis. It also facilitates modular maintenance and repair, technology upgrades, and incremental overall system expansion. Individual arrays can be winched down in a few hours when wind and weather permits and can use adjacent tethers as guides to ensure safe control.

Operationally there should be no need for people at 20km. There is no need for large “hanger” structures, either for construction or maintenance. During construction and maintenance the array structure is anchored at multiple points to the ground and effectively forms a roof over a protected space. Maintenance on the ground only occurs during good weather and at night to avoid disruption in power output. Plants can safely be raised and lowered in a few hours, and with close attention to weather, the window of exposure to unexpected weather is very small.

Another benefit of the modular approach is the system can grow and be financed incrementally, reducing the risk capital required to develop and demonstrate the system viability.

Beyond electricity generation:

A permanent high altitude platform could serve many additional purposes. Listed below are some examples of possible uses.

- Communications and observation platform
    - Cell phone tower, data networks
    - Radar for weather, commercial, military
    - Science: astronomy, meteorology, earth science
    - Laser communications network
    - Tourism

Solar energy available for selected locations at ground level and at 20km altitude

Latitude	Location	ground kWh/day	Utilization	20km kWh/day	Util	20km 2-axis kWh/day	Util
34.8	Barstow	5.77	24%	8.55	36%	16.38	68%
37.7	San Francisco	4.76	20%	7.70	32%	15.74	66%
34.7	Osaka	4.00	17%				
42.3	Boston	3.86	16%				
41.8	Chicago	3.62	15%	7.37	31%	15.10	63%
46.8	Quebec	3.61	15%				
47.6	Seattle	3.23	13%				
48.7	Stuttgart	3.06	13%	6.85	29%	15.01	63%
53.5	Hamburg	2.67	11%				
59.3	Stockholm	2.64	11%	6.00	25%	14.30	60%
51.5	London	2.66	11%				
53.3	Dublin	2.30	10%				

Table 1 Average daily solar energy kWh/m^2 and associated utilization factor for selected locations

The ground columns in Table 1 show average daily kW.h per square meter of total sunlight for selected locations. This is real data gathered over many years by NREL and others. The data shown is for flat plate horizontal collectors. The 20km columns show StratoSolar data for the selected latitudes generated using atmospheric models. (1) Simple StratoSolar systems will be horizontal flat plate. Varying degrees of tracking are possible, and real systems will have results intermediate between flat plate and 2-axis tracking. StratoSolar data points illustrate that the average daily kW.h diminishes slowly with increasing latitude at 20km altitude. This means that the power output from a StratoSolar PV system is fairly independent of geography, unlike ground based PV systems which as the table shows gather less energy per square meter at higher latitudes and are therefore significantly less cost effective. For example a simple flat plate StratoSolar system at latitude 60 has a higher utilization than the best surface system in the desert. For daily average kWh/m^2 data (the most common data available), the PV utilization factor is simply the kWh/m^2/day divided by 24. This utilization factor applies to PV panels or PV plants whose power is specified in peak Watts (Wp), the industry standard way PV power is rated. Peak Watts is the electricity output for a standard sunlight input of 1kW/m^2. At 20km sunlight can exceed 1.3kW/m^2, which explains utilizations that exceed the theoretical 50% maximum achievable on the ground.

Behavior of systems under wind load:

The graphs in Figure 2 below show the results of simulations of a single module/tether and Figure 3 shows a 100-module PV array system with multiple tethers subjected maximum wind loads in the troposphere and the stratosphere. The vertical axis is altitude in kilometers. The horizontal axis is down-wind deflection in kilometers. The module design assumes the following parameters. The PV array radius is 175 m and depth is 94 m. The radius of the tether is 0.04 m. The large array is 100 of the modules mechanically joined to form a thin disk 3500m in diameter and 94m deep.

The 2D calculation models the tethers as 20 rigid segments connected by pin joints. The calculation is iterative. The wind force on each segment is calculated and depends on the angle of the tether and the altitude. It also depends on the coefficient of drag, wind velocity and air density. Weight for each segment is also calculated. The length of each tether segment lengthens to maintain the platform at 20km altitude and model the tethers "playing out" under wind load. The wind force for each segment changes with altitude and updates iteratively. The desired maximum deflection sets the required amount of buoyancy.

The top four graphs in Figure 2 show progressively stronger wind loads. Larger pictures are in the Appendix. The sequence from left to right is

1) average winds in the troposphere and the stratosphere
2) maximum winds in the troposphere, average wind in the stratosphere
3) average winds in the troposphere, maximum winds in the stratosphere
4) maximum winds in the troposphere, maximum winds in the stratosphere

Average winds are from NASA charts. Worst-case troposphere winds are from NASA and IGRA (2) (3). Worst-case stratospheric wind is from HAA research (4). The graphs show relatively small deflections due to troposphere winds exceeding hurricane force acting on the tethers. The winds in the stratosphere acting on the buoyant platform have the most influence on the maximum deflection of the platform. This shows that where the weather events with the greatest uncertainty occur, we have the biggest margin of safety. Even if the worst-case troposphere wind forces were several times larger than the worst case analyzed, there would be no risk of catastrophic failure.

The goal of the simulation is to verify the practicality and the cost of the solution. The quantities of two materials dominate the wind related costs; the polymer tether cables and hydrogen gas used for buoyancy. For the 360m platform simulation, 62 tonnes of polymer cables are required at $20/kg for a total of $1,245,165. The hydrogen required is 53 tonnes at $6/kg for a total of $319,000.

The graph in Figure 3 shows maximum troposphere and stratosphere winds acting on the large array. T This shows the aerodynamic scaling benefit of the large array. Deflection is smaller under worst-case stratospheric wind.

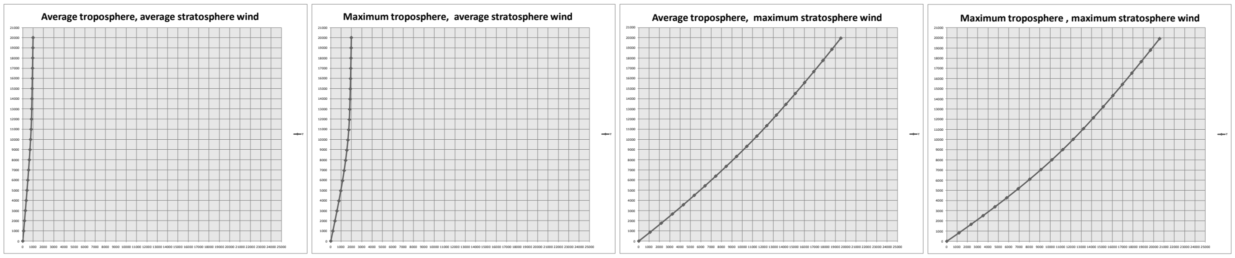

Figure 2 Small 360m platform tether and PV array deflection under wind loads

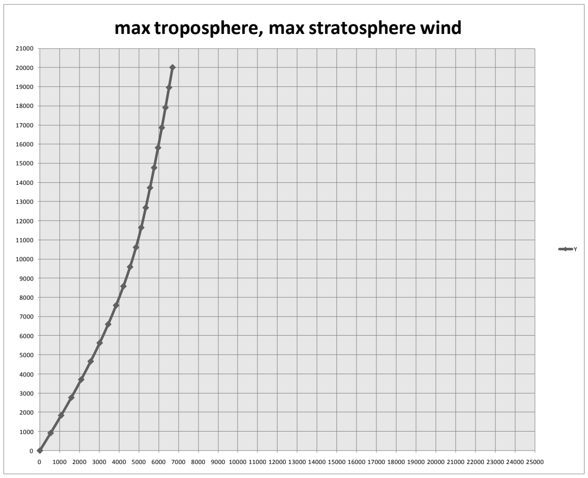

Figure 3 Large 3600m platform tethers and array deflection under maximum wind load

Accurate models for the aerodynamic behaviors of cylinders also allow the calculation of vortex-shedding induced forces (5)on the tether. These are high frequency and low amplitude. Asymmetric aerodynamics of a structure cause the more dangerous “galloping” forces. For example, asymmetric ice buildup causes galloping in the case of power cables.

This is a simple static model. It is possible, using engineering software tools, to simulate the system with an accurate meteorological wind model that then drives a simulation of the aerodynamic and dynamic behavior of the structure. This is one of the goals of the funded R&D stage. Accurate computer simulation can test and verify much of the risky engineering.

Electricity cost for different locations and capital costs

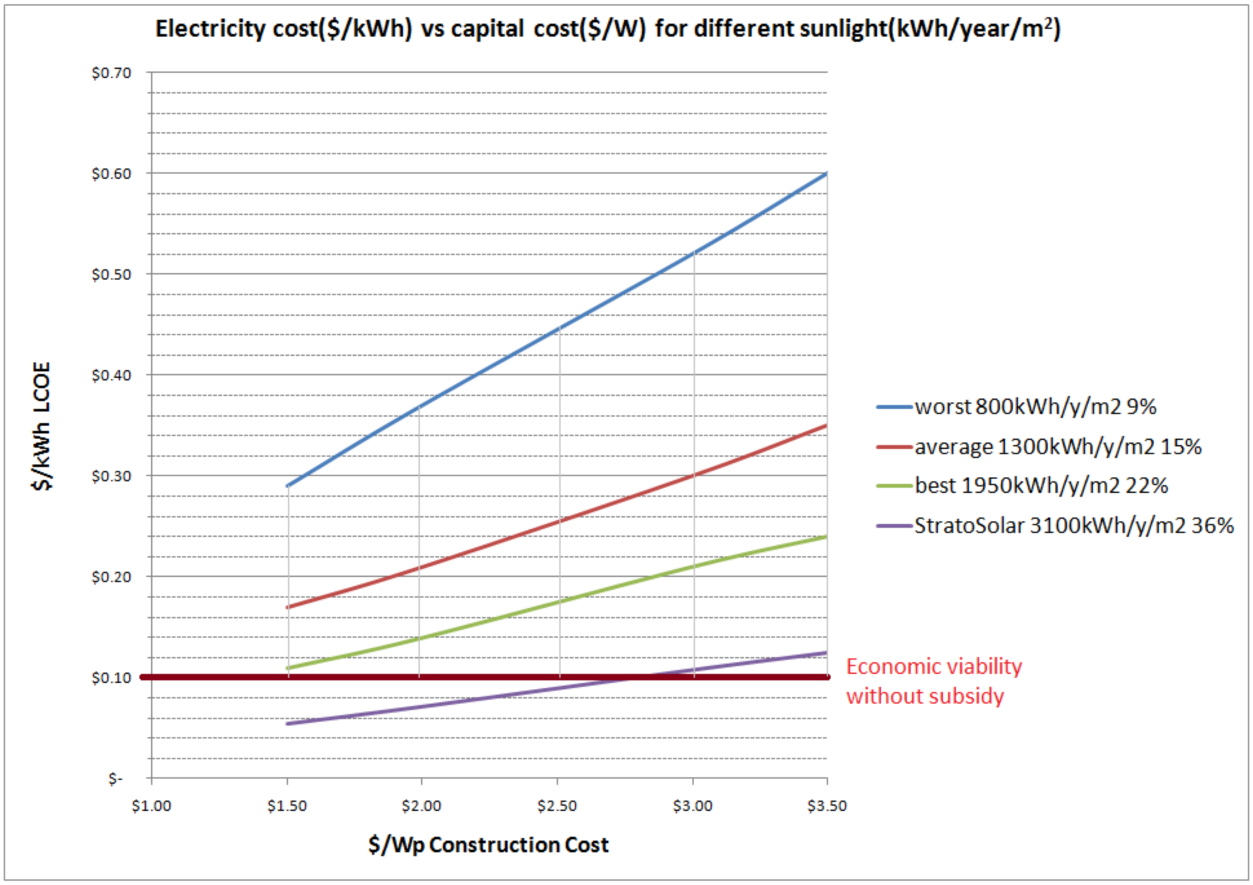

Figure 4 PV electricity cost vs. capital cost for different utilization factors for different locations

Figure 4 shows the relationship between capital cost in $/Wp and the resulting levelized cost of electricity (LCOE) in $/kWh for varying sunlight for different geographic locations. It assumes a 20-year plant life, 8.5% working average cost of capital (WACC) and 2% of capital cost for annual operation and maintenance (O&M).

Worst sunlight is northern Europe, best is US southwest. Sunlight is in average kWh/m^2/year. A common way to refer to this variability in power output is to convert it to a utilization or capacity factor percentage. This is useful when comparing different power plants. Using this metric, worst is about 9%, average is about 15%, best is about 22%, and StratoSolar is about a 36% utilization factor.

Given an expected $/Wp construction cost and a location with known sunlight or its equivalent utilization factor(like Table 1), this chart shows the associated levelized cost of electricity (LCOE) in $/kWh. Displaying the information in this form graphically illustrates a number of important comparisons while only making assumptions concerning financing.

The horizontal line at $0.10 represents electricity that is competitive in the marketplace without subsidy. The vertical distance from this line to the different utilization lines represents the amount of subsidy needed. As can be seen the subsidy can be very large. This subsidy shows up in different ways. In Europe the mechanism is mostly feed-in tariffs that result in higher costs of electricity to consumers. In the US, the mechanism is mostly tax credits and accelerated depreciation ultimately paid by taxpayers.

This chart illustrates several points:

1. The same plant with the same capital cost produces electricity with highly variable cost depending on location. E.g. at the 2010, $3.50/W capital cost, northern Europe generates electricity for about $0.60/kWh, and StratoSolar generates electricity for $0.12/kWh. StratoSolar has the best location (which can be over northern Europe) and lowest cost.
2. The $3.50/Wp capital cost is approximately the 2010 cost. At historical rates of improvement, the $1.50/W cost may occur by 2020 at best. Even in the best desert locations, the resulting ground based PV electricity will still cost $0.12/kWh which will not be competitive without subsidy in 2020.
3. The amount of subsidy required over the next ten years to maintain the historical PV capacity growth rate will become economically difficult to sustain. The historical growth rate would imply 200GWp capacity requiring subsidy in 2020 before breakeven at 1000GWp by 2025.
4. StratoSolar will produce electricity without subsidy with current PV technology $/Wp capital costs and will benefit equally from the PV $/Wp improvement path, producing increasingly lower cost electricity.
5. StratoSolar can do this for northern climes.

Utility scale PV in the desert needs huge additional investment in electricity distribution and backup generation that is not factored into the normal PV $/Wp estimates for construction cost and also has environmental and political problems. This means the trend line in the chart that appears closest to economic viability, is likely too optimistic.

This chart helps illustrate how far currently ground PV is from commercial viability and hints at the enormous cost of subsidy it will take globally to sustain the historical rate of improvement necessary. StratoSolar represents a low cost way to leverage the historical investment in PV technology into commercial viability at locations where PV is unlikely ever to be commercially viable and with today's PV capital cost in $/Wp, which will apply even if the historical rate of $/Wp improvement slows.

Cost of Subsidy:

The historical rate of PV plant cost reduction has been approximately 20% for each doubling in capacity manufactured and installed. Figure 5 below shows a projection of this trend forward at current rates until 2027. The future will not unfold as predictably as this graph would imply, but it does give a general sense of the magnitude of things. This rate of improvement from the current cost base will produce a growing and unsustainable subsidy burden as the GWp capacity rises exponentially while the cost of electricity does not fall below $0.10/kWh until around 2025. The implication is 200GWp capacity needing subsidy by 2020 before breakeven at 1000GWp capacity in 2025.

Figure 6 below illustrates the growth and magnitude of the implied subsidy which adds up to a total of about $250B over about 15 years. If the political will to provide the subsidies that sustain the capacity growth diminishes, then the improvement in the $/Wp capital costs will slow and the unsubsidized market viability of PV will be delayed beyond 2025.

StratoSolar can quickly reduce or eliminate the cost of subsidy and thereby ensure the growth in volume of GWp capacity that will maintain or even increase the rate of cost improvement in PV technology. Getting to economic viability sooner with StratoSolar means the cost of the subsidy is greatly reduced, or given the unlikelihood of sustaining the subsidy, StratoSolar can ensure that historical growth in PV volume will not decline.

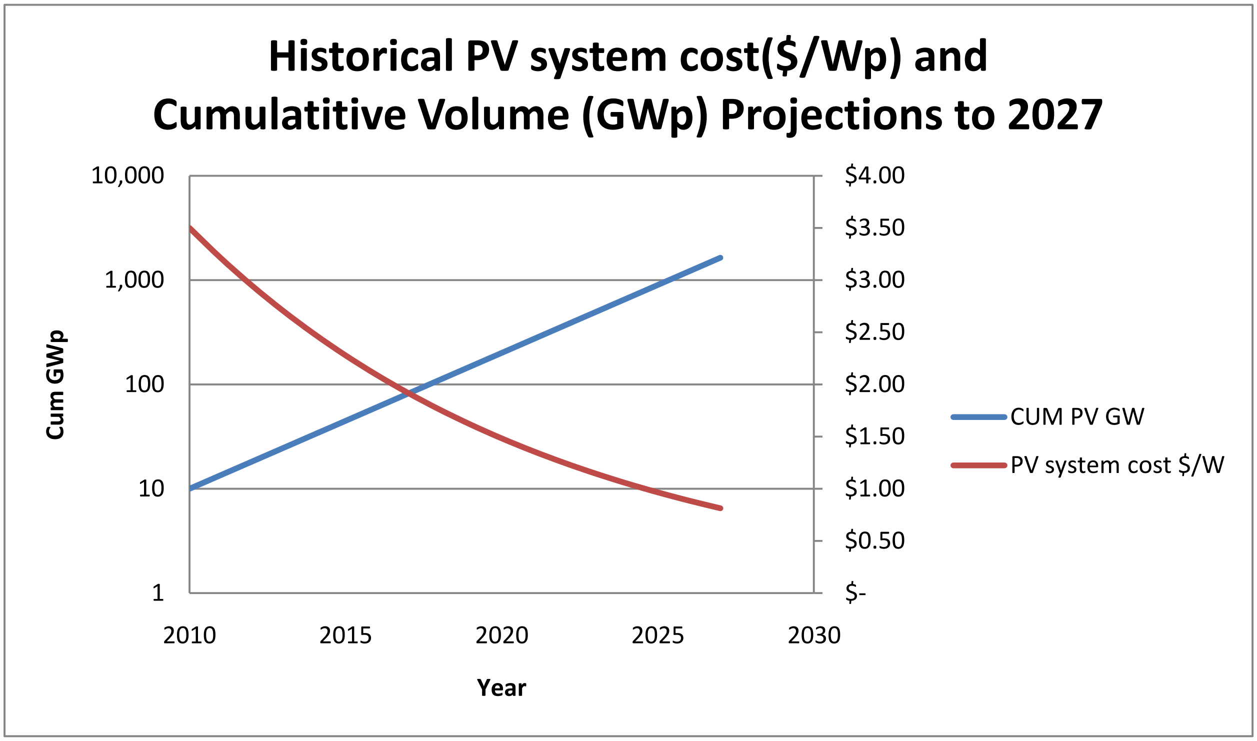

Figure 5 PV system cost and volume projection to 2027

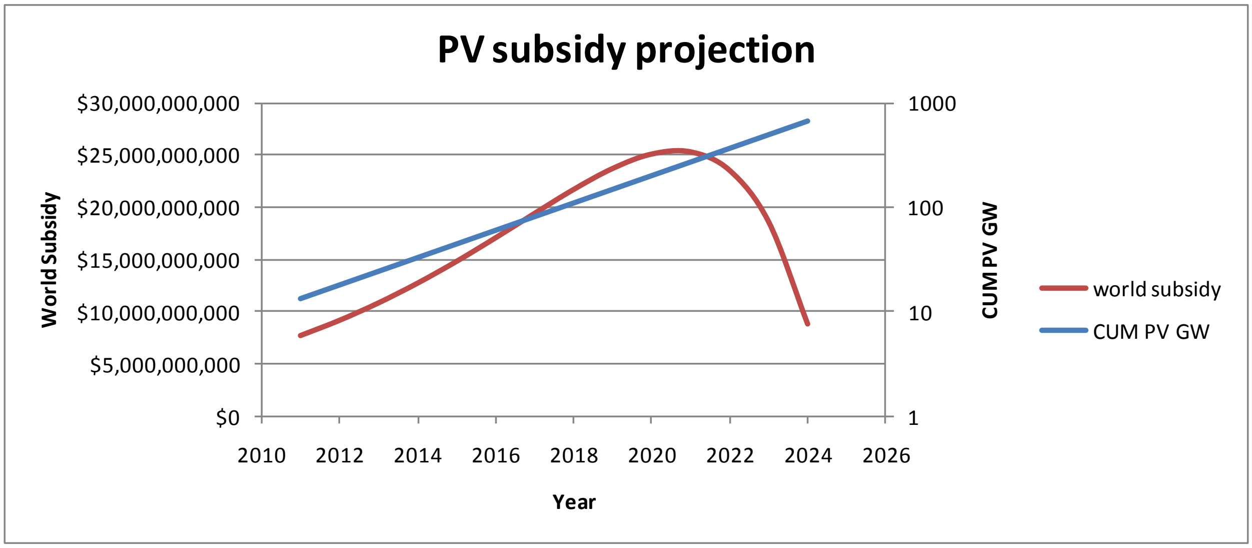

Figure 6 PV subsidy cost projection to 2026

List of abbreviations:

PV	Photovoltaic
DNSI	Direct Normal Solar Insolation
CSP	Concentrated Solar Power
CPC	Compound Parabolic Concentrator
kWh	kilo Watt hours
GWe	Giga Watt electrical
Pa	Pascal
MPa	Mega Pascal
PPA	Power Purchase Agreement
ppm	part per million
PET	Polyethylene Terephthalate
mrad	milli radian
LEC	Levelized Electricity Cost
O&M	Operation and Maintenance
R&D	Research and Development
WACC	Working Average Cost of Capital
OLF	Optical Light Film
Wh	Watt hours
HAA	High Altitude Airship
UV	Ultra Violet
UHMWPE	Ultra-high-molecular-weight polyethylene
LCOE	Levelized cost of electricity
Wp	Peak Watts, a standard measure of PV panel power output

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Appendix

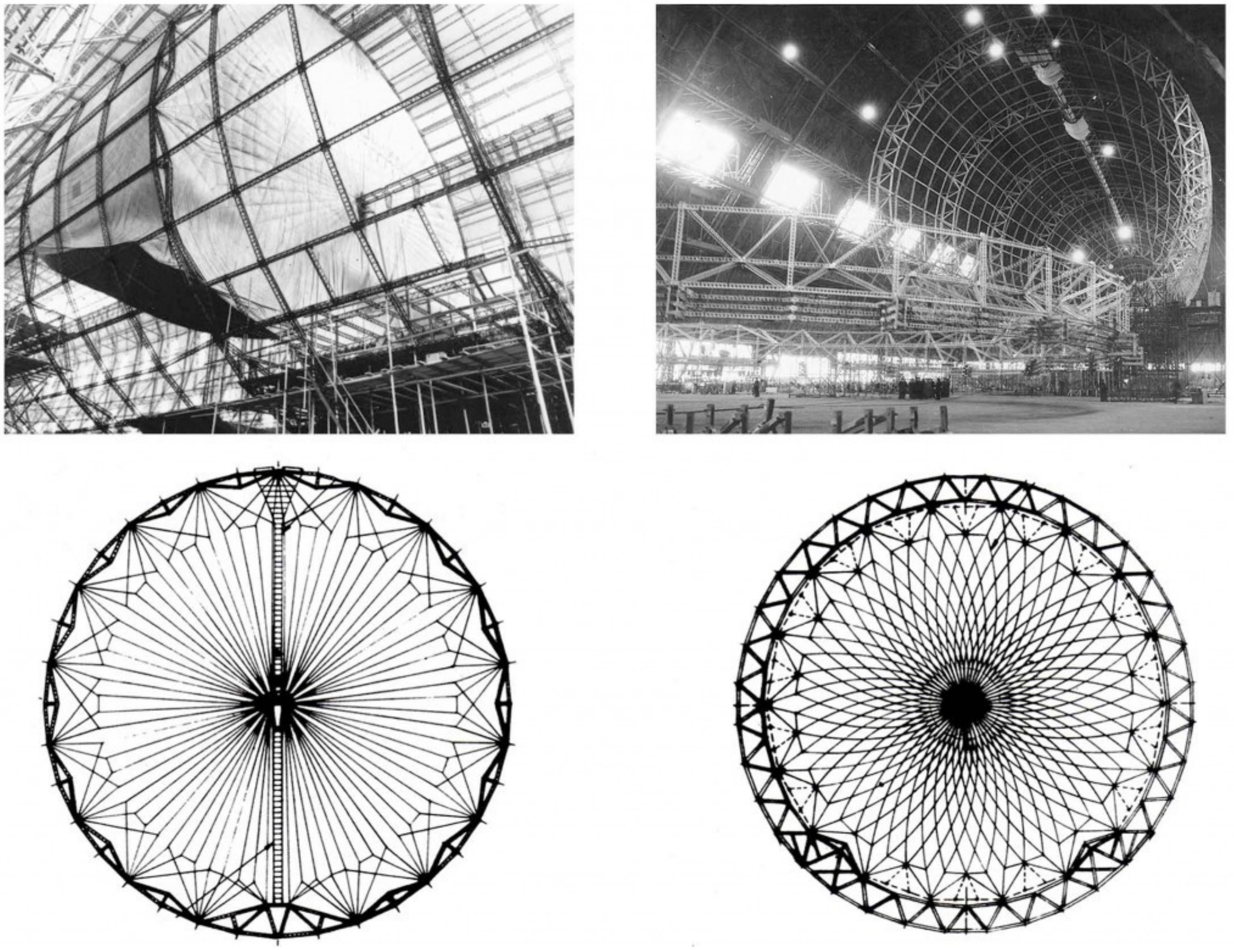

Figure 7 Internal structure of the Hindenburg and the Macon

Figure 8 Air force tethered aerostat radar

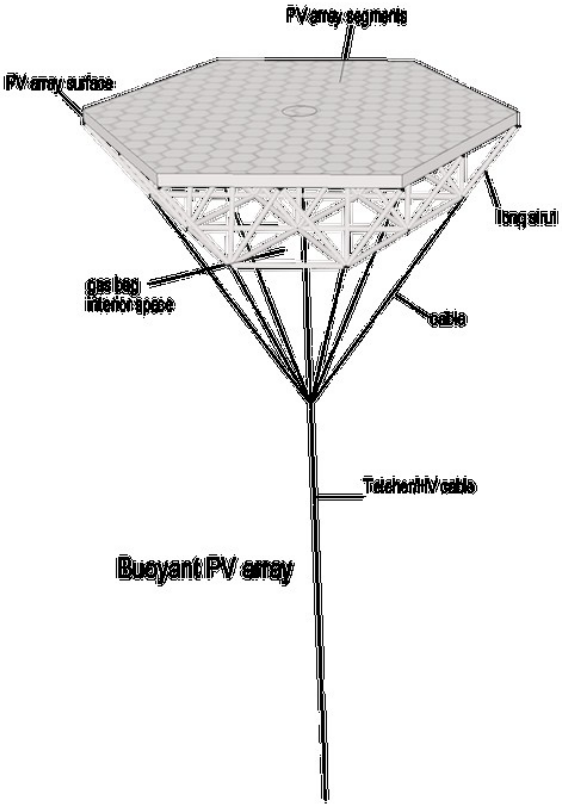

Figure 9 360m buoyant PV array

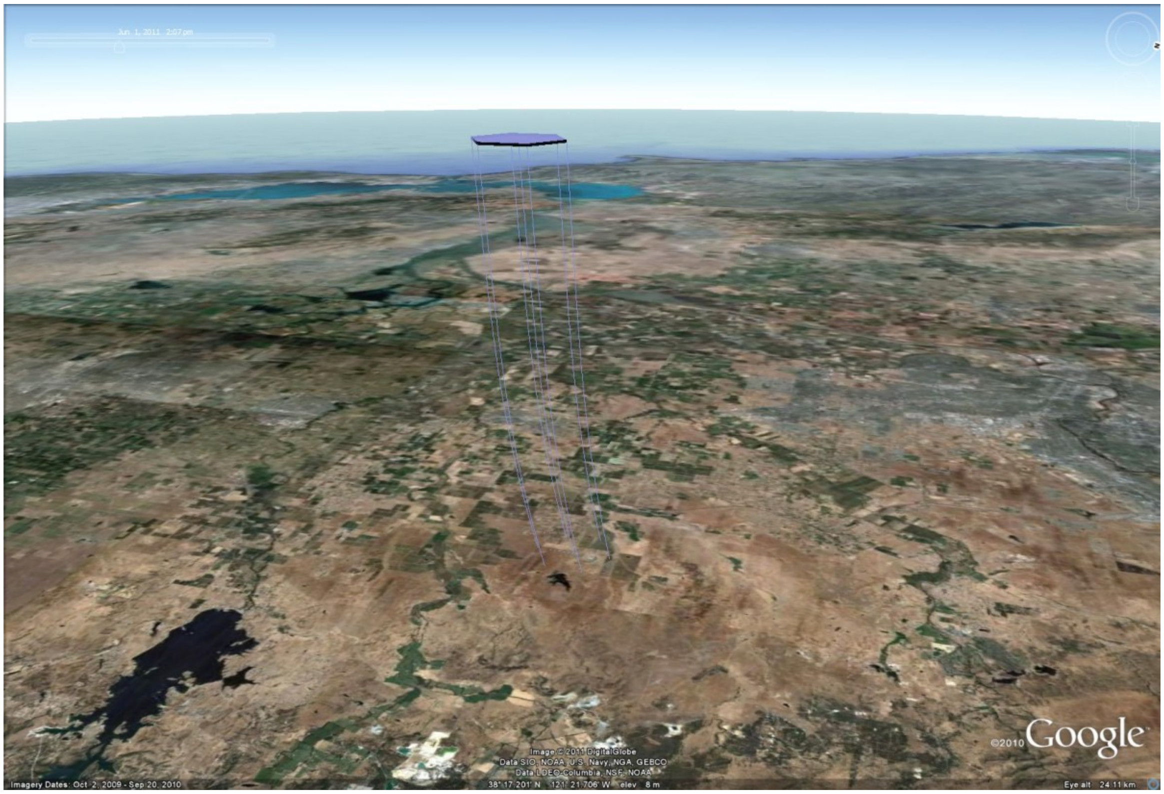

Figure 10 View of a 3,600m PV array from a high-flying aircraft

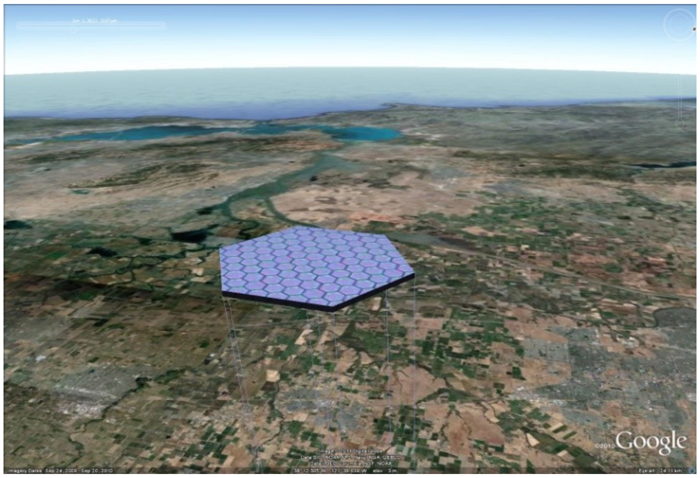

Figure 11 View of a 3,600m PV array from a high-flying aircraft

Figure 12 View of a 3,600m PV array from 10km

Figure 13 View of a 3,600m PV array from 100km

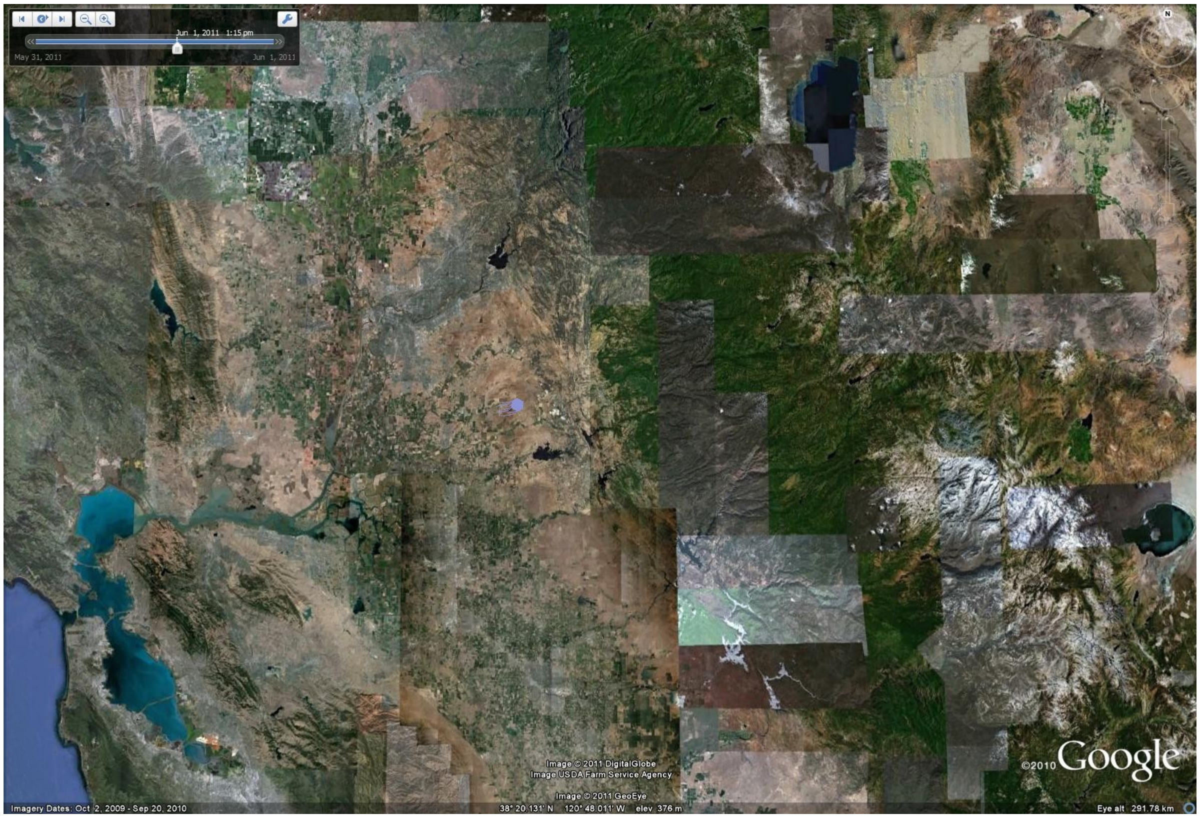

Figure 14 View of a 3,600m PV array from low earth orbit

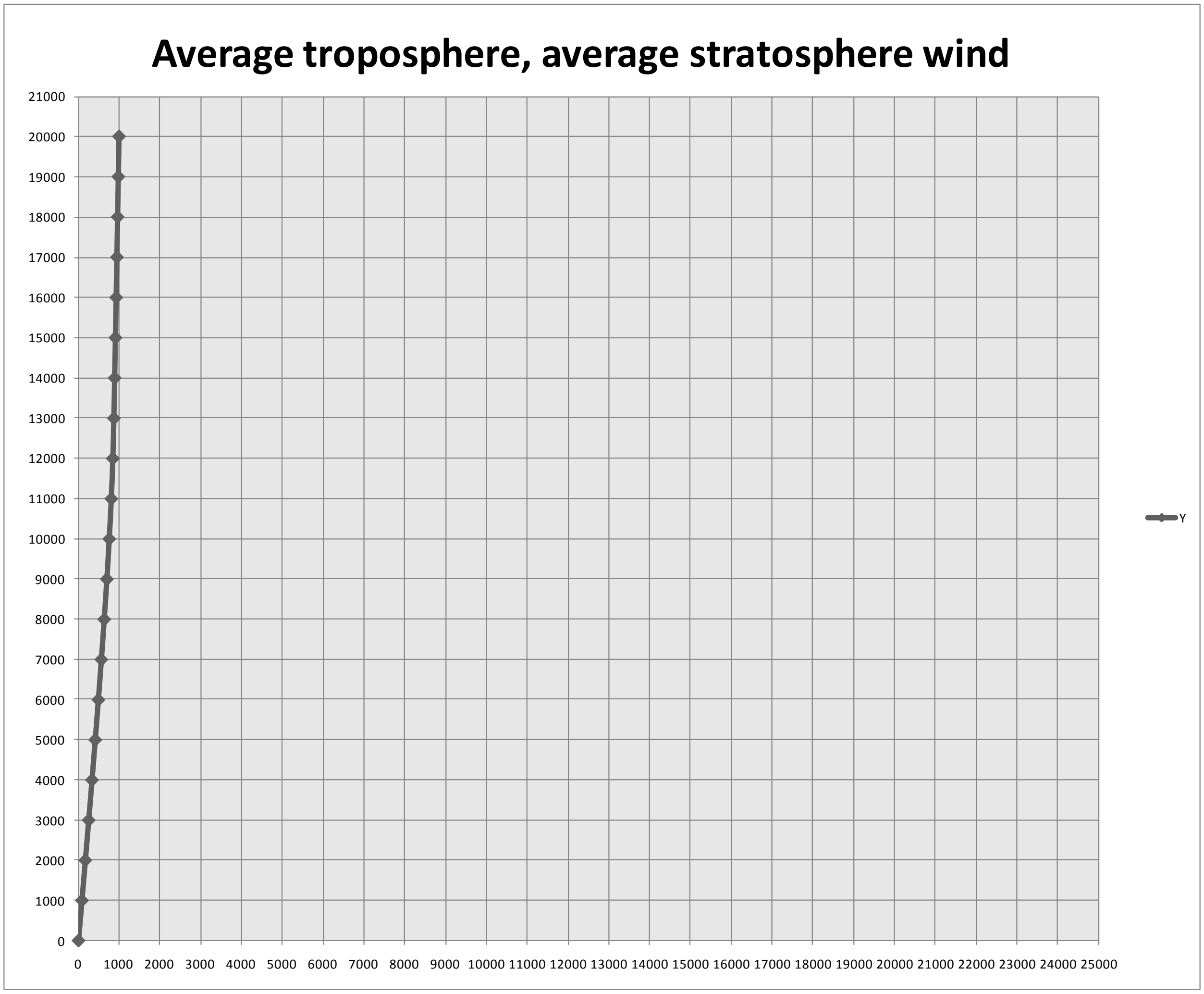

Figure 15 Small 360m tether and platform deflection for average wind on the tether and average wind on the platform

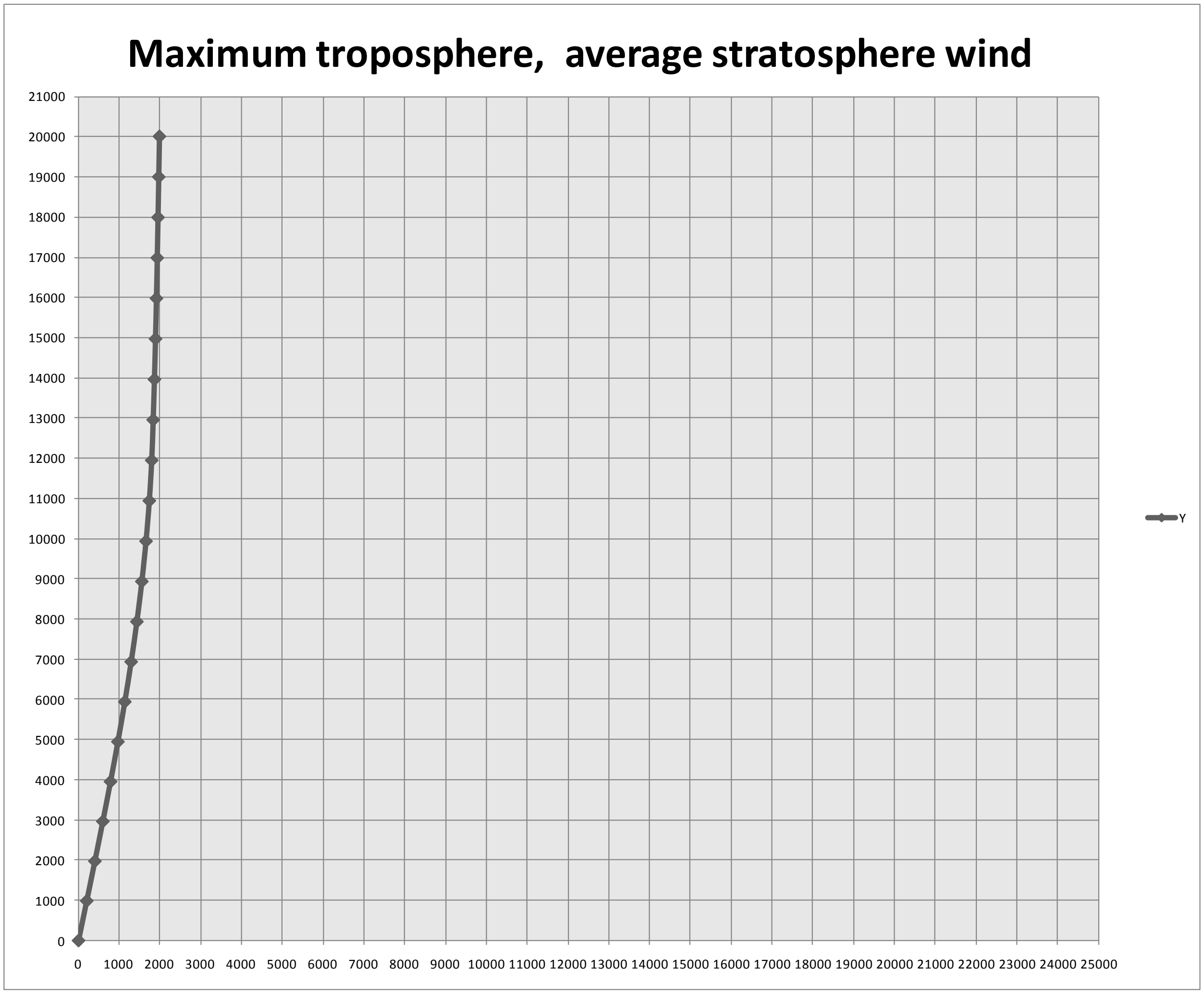

Figure 16 Small 360m tether and platform deflection for maximum wind on the tether and average wind on the platform

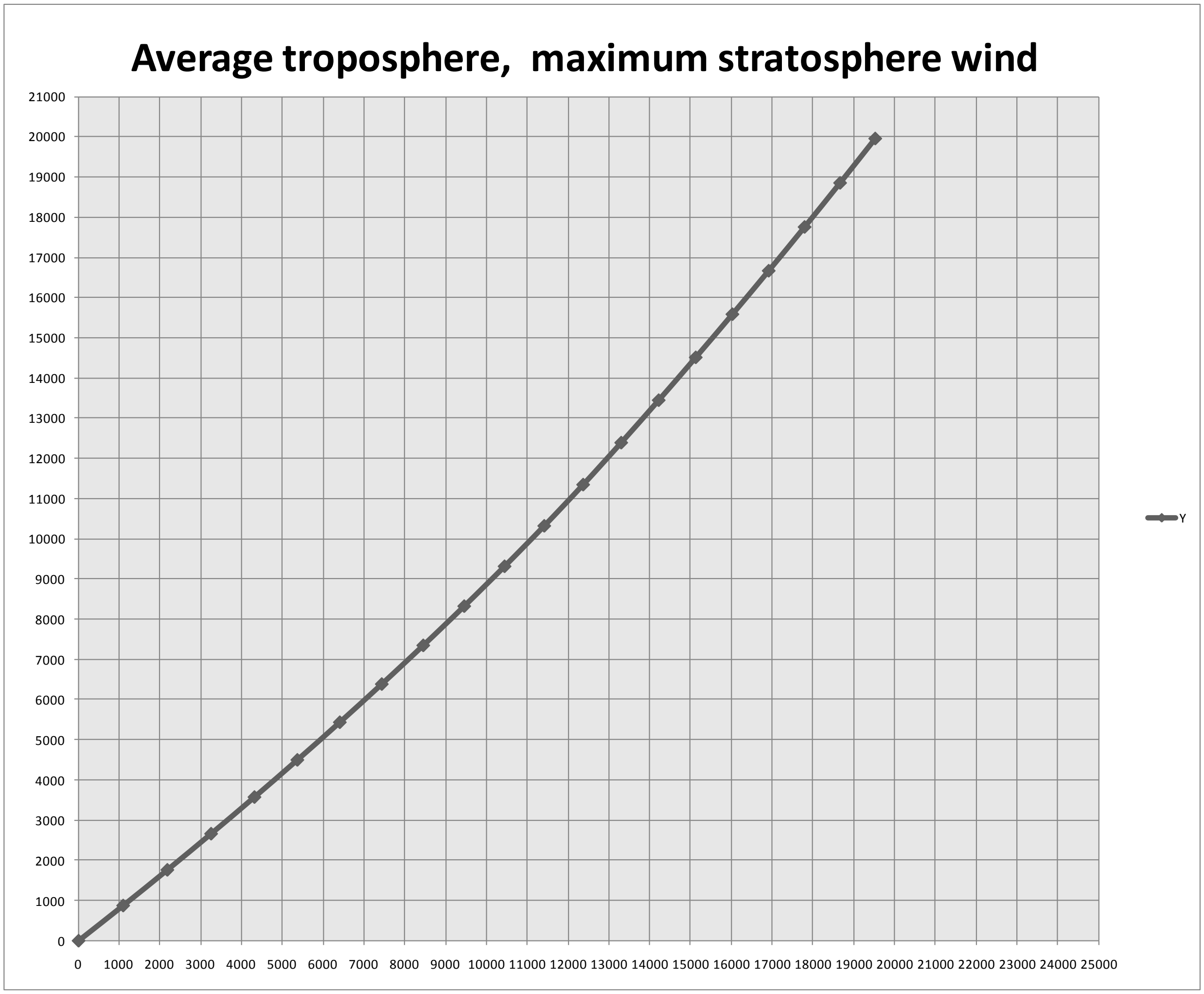

Figure 17 Small 360m tether and platform deflection for average winds on the tether and maximum wind on the platform

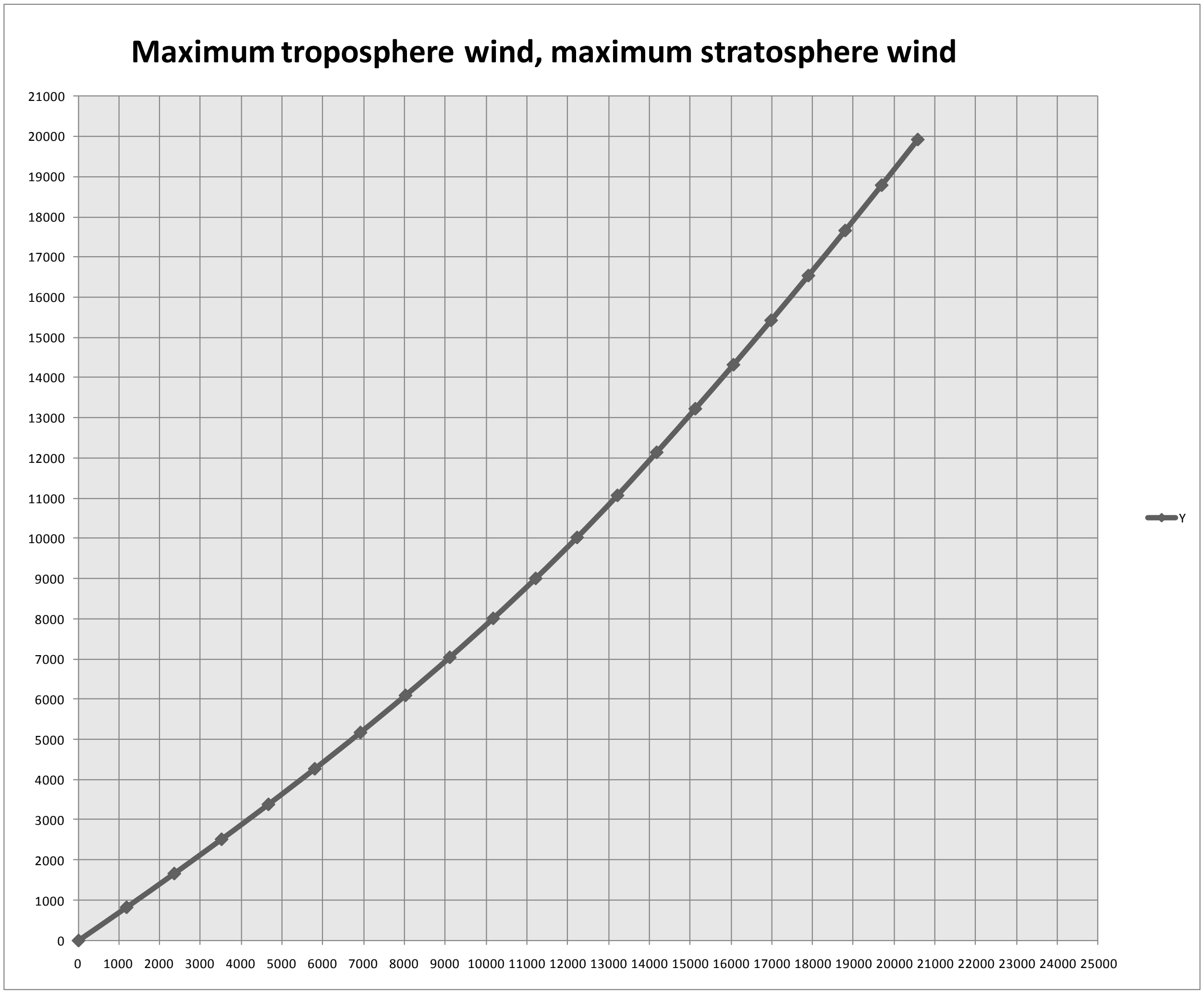

Figure 18 Small 360m tether and platform deflection for maximum wind on the tether and maximum wind on the platform

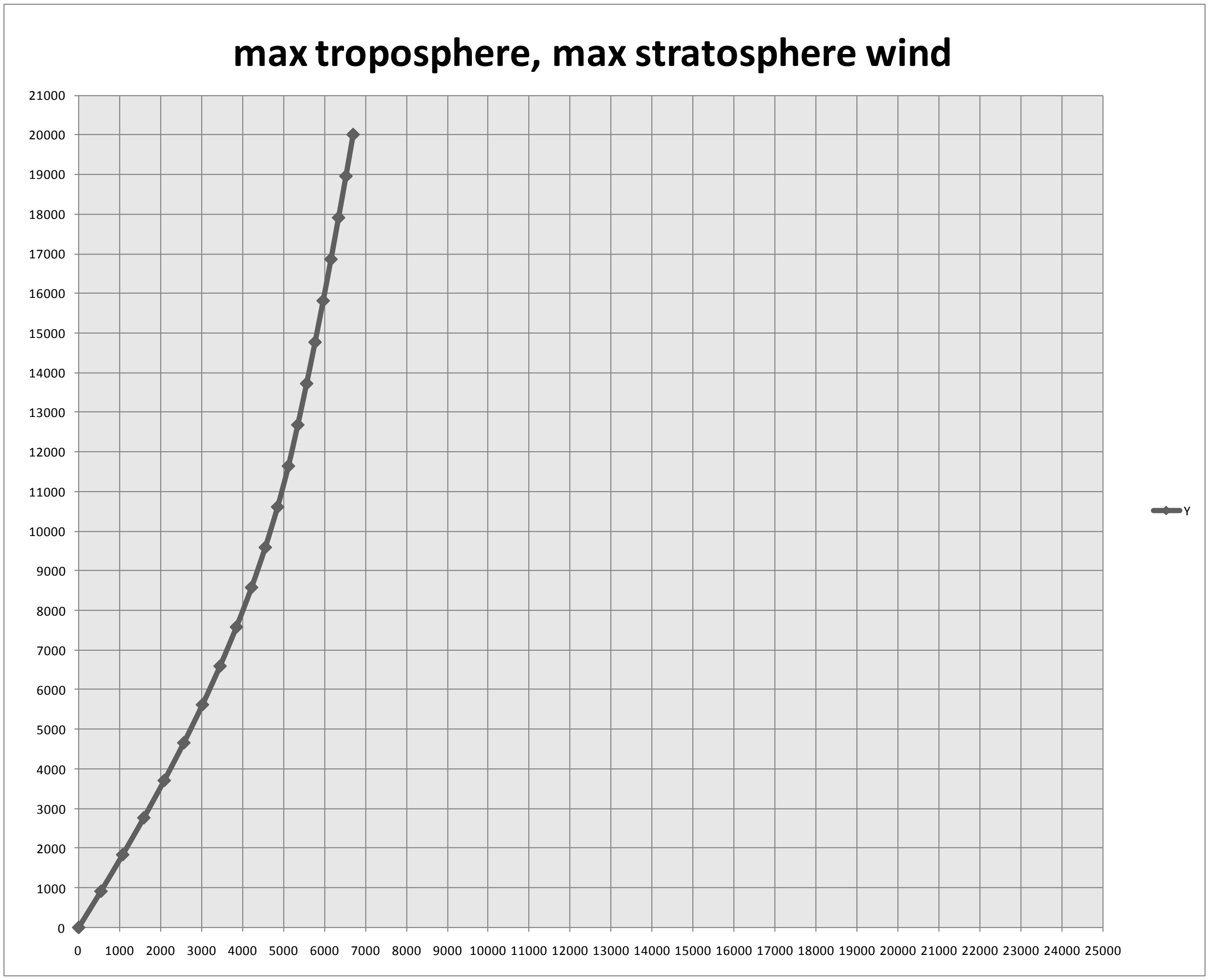

Figure 19 Large 3600m tether and platform deflection for maximum wind on the tether and maximum wind on the platform