The Space Power Grid Approach to Realize The Worldwide Dream of Space Solar Power. Guest Lecture, EE6390, Fall 2011. DRAFT for student preparation, probably full of errors.

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Chapter 1

Foreword

The dream of Space Solar Power (SSP) is to bring cheap, limitless, clean, quiet solar electric power to the world, helping us break out of the tightening vortex of fossil costs, the dangers and costs of nuclear power, and the growing shortage of clean water that plentiful energy can solve. However, SSP has remained a dream because it is immensely expensive and difficult. There have been periodic surges of apparent interest in SSP, but these appear to be well-correlated with moves to win funding for other priorities of national space agencies. The difficulties come down to 4 parameters. First, the sheer magnitude of the problem: we would need over 4,000 Gigawatts of space solar power, to really replace much of fossil primary power generation. The second is the specific power, or power generated per unit mass that has to be placed in orbit. Present technology using photovoltaics (PV) reach only about 30 percent of the specific power level that is required before viable systems can be designed. The third is the relation between orbit height, beam frequency and receiver size. The preferred location of GEO (Geostationary Earth Orbit) 36,000 kilometers above the equator, is seen to be impractical because the receivers would have to be on the order of 100 kilometers or more in diameter, regardless of the level of power being beamed. In other words, there is no apparent possibility of an evolutionary or staged approach to SSP using GEO. Lower orbits require dynamic pointing and intermittent beaming, demanding technological improvements over what was possible in the 1960s. By going to the atmospheric propagation window at 220 GHz, we argue that a 2-order of magnitude reduction in receiver size can be achieved; however, losses in moist atmospheres become prohibitive, requiring ways to either burn through or avoid moist air. The last obstacle is launch cost, which at well over 3000 dollars per kilogram to low Earth orbit, remains much higher than the few hundreds of dollars per kilogram that must be reached before the immense scaling up to Gigawatts can be envisaged. Only runway-operated airbreathing, reusable launchers flown with nearly airline-level routine operations can hope to achieve such cost reductions. For these reasons, traditional approaches to Space Solar Power do not appear likely to lead to viable scale-up under any scenario. The combination of the above problems implies that SSP cannot hope to achieve a cost per watt of installed power generation and hence the cost of power, that can even imagine competing with terrestrial alternative uses for the limited money that can be invested in renewable energy. In short, we argue that SSP as we dream of it, will not occur without some strong, globally-endorsed motivation other than the direct one of civilian space-based electric power generation. No market magic, financial wizardry or dog-eat-dog competitive scenario is likely to defeat the obstacles posed by the laws of Physics. Innovative, collaborative or radically new approaches are needed.

We then argue that this is no reason to give up hope. We argue for a more deliberate approach, recognizing that there is no great hurry in view of the above realities. The Space Power Grid (SPG) architecture described in papers from our group since 2006, is an evolutionary approach to realizing the global dream of space solar power. The grid part of the name that we gave to this concept, is clearly intended to convey the fact that power transmission occurs both ways: Earth to Space as well as the traditional Space to Earth route. SPG first concentrates on helping terrestrial power plants become viable, aligning with public policy priorities. It enables a real-time power exchange through Space to help locate new plants at ideal but remote sites, smooth supply fluctuations, reach high-valued markets, and achieve baseload status. With retail cost kept to moderate levels, we model a constellation that grows in 17 years to 100 power relay satellites at 2000 km sun-synchronous and equatorial orbits and 250 terrestrial plants, exchanging beamed power at 220GHz. In another 23 years, power collection satellites replacing the initial constellation will convert sunlight focused from ultralight collectors in high orbits and add it to the beamed power infrastructure, growing SSP to nearly 4 TWe (4,000 GWe) with wholesale and retail delivery. Our calculations using what we consider to be defensible and realistic technical and economic assumptions, shows that the SPG-based SSP system can break even at a healthy return on investment (ROI), modest development funding, and realistic launch costs. The immense launch cost risk in traditional GEO-based SSP architectures is exchanged for the moderate but certainly non-trivial risk in developing efficient millimeter wave technology and dynamic beam pointing within the next decade. We note that the latter has been demonstrated in Space-based or airborne and shipborne laser missile-defense weaponry, and is used routinely in smart antennae employed on cell-phone towers all over the world. The former is finding use at various power levels in systems ranging from so-called crowd non-lethal crowd-control systems, security imaging, personal communication devices and automobile radar, outside a long history of use in military and astronomical imaging applications and particle accelerator facilities.

Starting up a complex system such as SPG certainly poses formidable obstacles, primarily in building global credibility and support. A US-India space-based power exchange demonstration would constitute a rational first step towards a global SPG. We discuss two options to achieve near-24-hour power exchange: 1) 4 to 6 satellites at 5500km near-equatorial orbits, with ground stations in the USA, India, Australia and Egypt. 2) 6 satellites in 5500 km orbits, with ground stations only in the US and India. However, we also argue that a continuous 24-hour power exchange is not essential. Concepts such as our afternoon Sun scenario can provide the power exchange service that enables terrestrial solar power plants to achieve baseload status, even with a small number of satellites in the constellation.

This e-book version is laid out in a bare-bones format, directly imported from a set of slides developed for a guest lecture to a graduate class in Electrical Engineering at Georgia Institute of Technology. Where time permits, some slides have been replaced with narrative text, lists or tables from recent papers presented by our group. This is very much a draft, intended primarily to allow students to have a heads-up with a day to go before the lecture. Our papers starting from 2006 are available separately to follow the steady stream of problems that we have encountered and, I hope, overcome since then. With your help, we can break through the rest, and make Space Solar Power a reality within our lifetimes.

Thanks for your attention and patience.

Narayanan Komerath Atlanta, Georgia September 6, 2011

Chapter 2

Outline

The e-book that follows is laid out roughly in the order of the presentation prepared for the classroom lecture. The sequence of logic is listed below.

1. We All Love SSP
2. Are they serious? Why should it matter if they are not?
3. Pie in the Sky? Interplay of technology, economics and geo-politics
4. Implication of orbit choice
5. Antenna Sizing: Case for Millimeter Waves
6. Specific Power
7. Launch Cost
8. Market Magic Meets Laws of Physics
9. SSP is Hard
10. Ngorongoro Viability Parameter
11. Space Power Grid Concept
12. US-India Demonstration Model
13. Knowledge Needs
14. Discussion and Summary

Chapter 3

We All Love SSP

Welcome to this lecture. I note first of all that I am a diehard believer in Space Solar Power as a solution to many problems facing Humanity. You may find this hard to believe, as I systematically destroy many fanciful notions that you may find in various magazines and news reports about the imminent arrival of SSP, and I cannot blame you for concluding that I am a cynical spy sent out by the Oil or Nuclear Lobby to destroy your optimism. My response is that if you are going to win, you must know the difficulties and be able to negotiate the curves and the steep hills, and still understand that there are good solutions. The first slide below, is from New Scientist Magazine, and presents the idea that 1 square meter of solar photovoltaic array in Space is equivalent to 43 square meters on Earth. There is of course more to consider than that.

The professional society of the aerospace community, like yours is IEEE, is AIAA. They have this advertisement, asking aerospace enthusiasts When They Realized that they were aerospace enthusiasts. You can read many breathless stories of how the Space Shuttle or other glorious achievements inspired my fellow enthusiasts. Sadly my story is nothing of the sort, but happily they have not asked me.

A few years before the Apollo 11 Moon Landing of 1969, the USA and the USSR were in a fierce competition, not just in the Space Program but in propaganda to win the hearts and minds of people all over the world about the altruism of the respective Space Programs. The British series was a spoof on this. You can see the gist of the movie in Figure 4.1. The Duchy of Grand Fenwick had successfully submitted a proposal to get external funding to install indoor plumbing in the Duke's Castle. Funding was only available under the International Space Program, and required them to promise to do research towards, guess what - a Manned Lunar Mission. Grand Fenwick hired a Mad Professor to write the proposal. Bad decision. Instead of using the money to buy gold plumbing, he decided to pursue his AntiGravity Liquid invention, a bowl of which was enough to lift a rocket.

The impressive part of the movie was when the US and USSR discovered that Grand Fenwick was actually going to launch a Moon rocket. Each assumed that the other had sneaked real technology to G.F. to build the rocket. They went into a deadly serious race. Too late. The astronauts from Grand Fenwick were standing around on the lunar surface when the US and Soviet landing capsules (which looked like Gemini and Soyuz capsules) came blasting down to the surface, going full speed (could not afford to slow down in case the others won). Instead of smashing to smithereens, fortunately, both went straight into the dust pools that were then believed to cover the lunar surface (many of us feared that Apollo 11 would suffer the same fate). The astronauts and cosmonauts had to be dragged up to the surface by the Fenwick crew.

The moral of that story was very simple: big and small governments would pursue high-sounding technology programs for their own special ends. It is up to the Mad Professors and their brilliant students to ignore those noises, and scrounge for what resources they can get from these programs

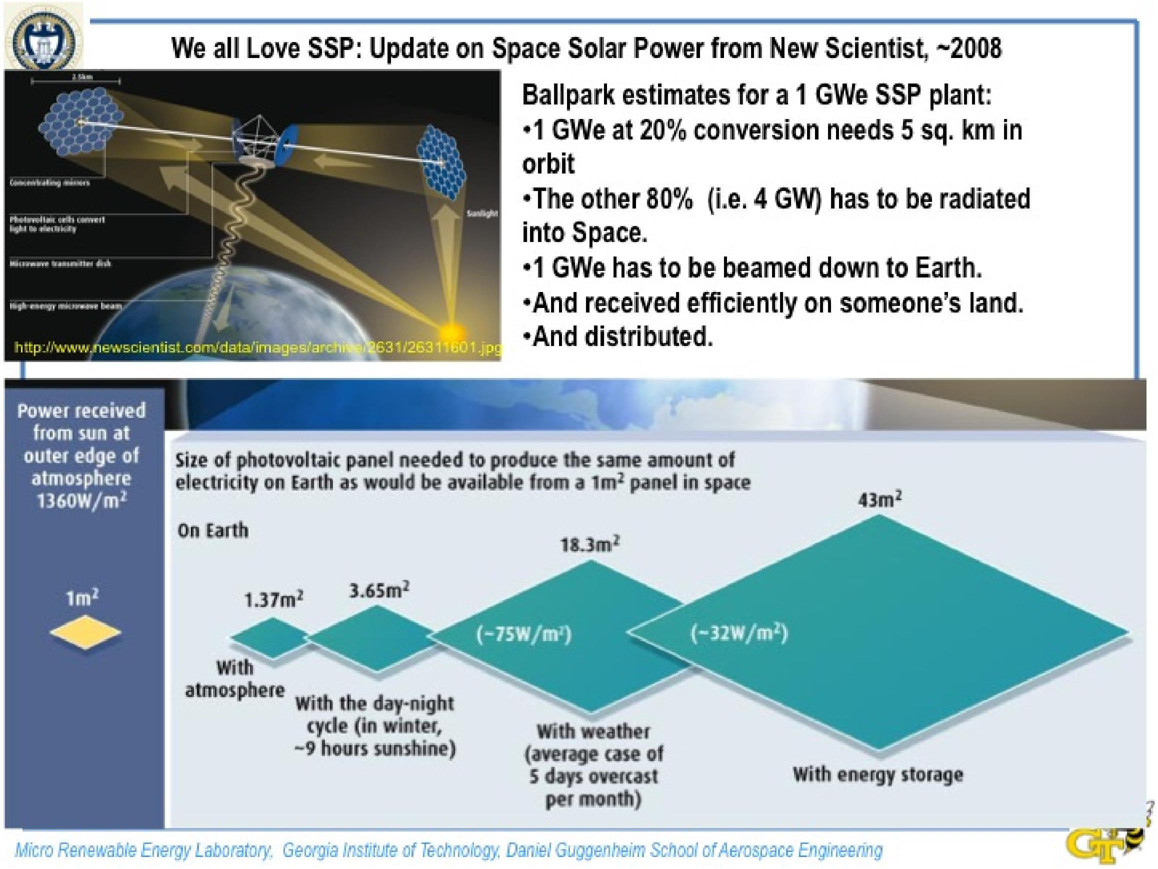

Figure 3.1: We all love SSP

and solve the technical problems. If we succeed, well, the governments might actually get serious and take it from there. If not, we'll just have to go ahead alone regardless.

Chapter 4

Are they serious? Why should it matter if they are not?

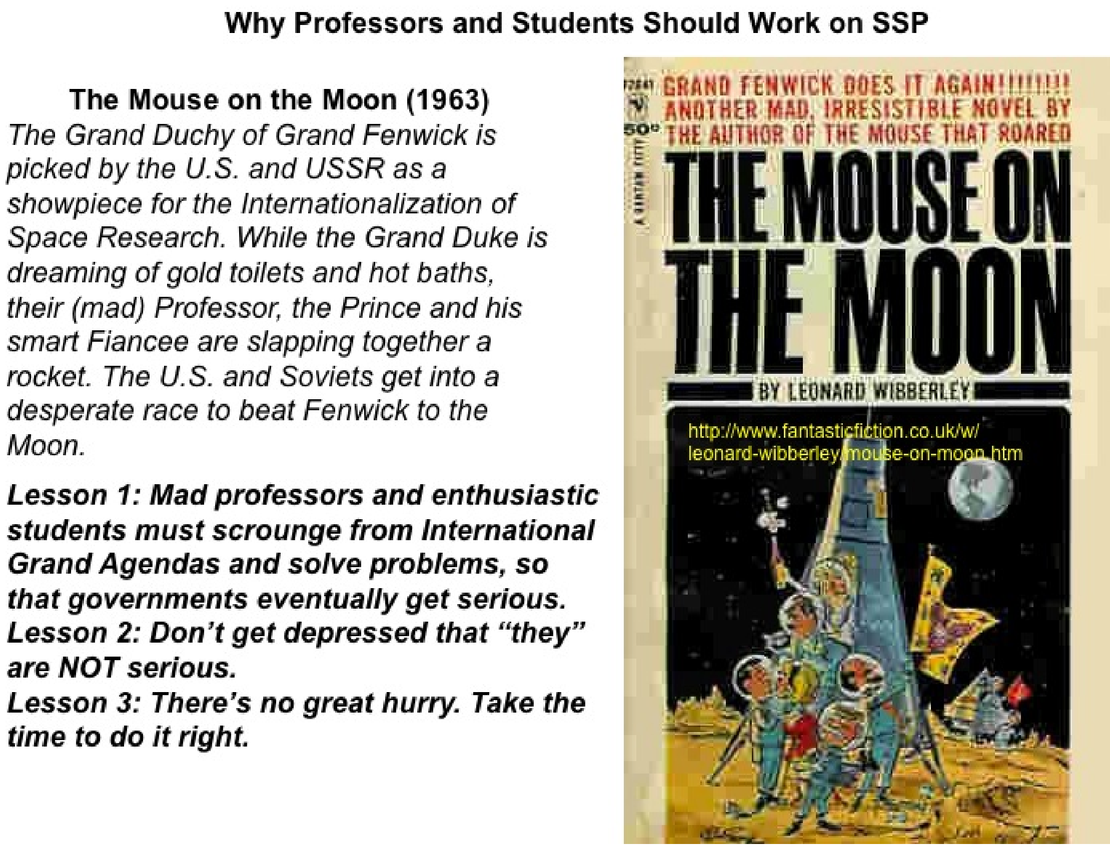

Figure 4.1: We all love SSP

Chapter 5

Pie in the Sky? Interplay of technology, economics and geo-politics

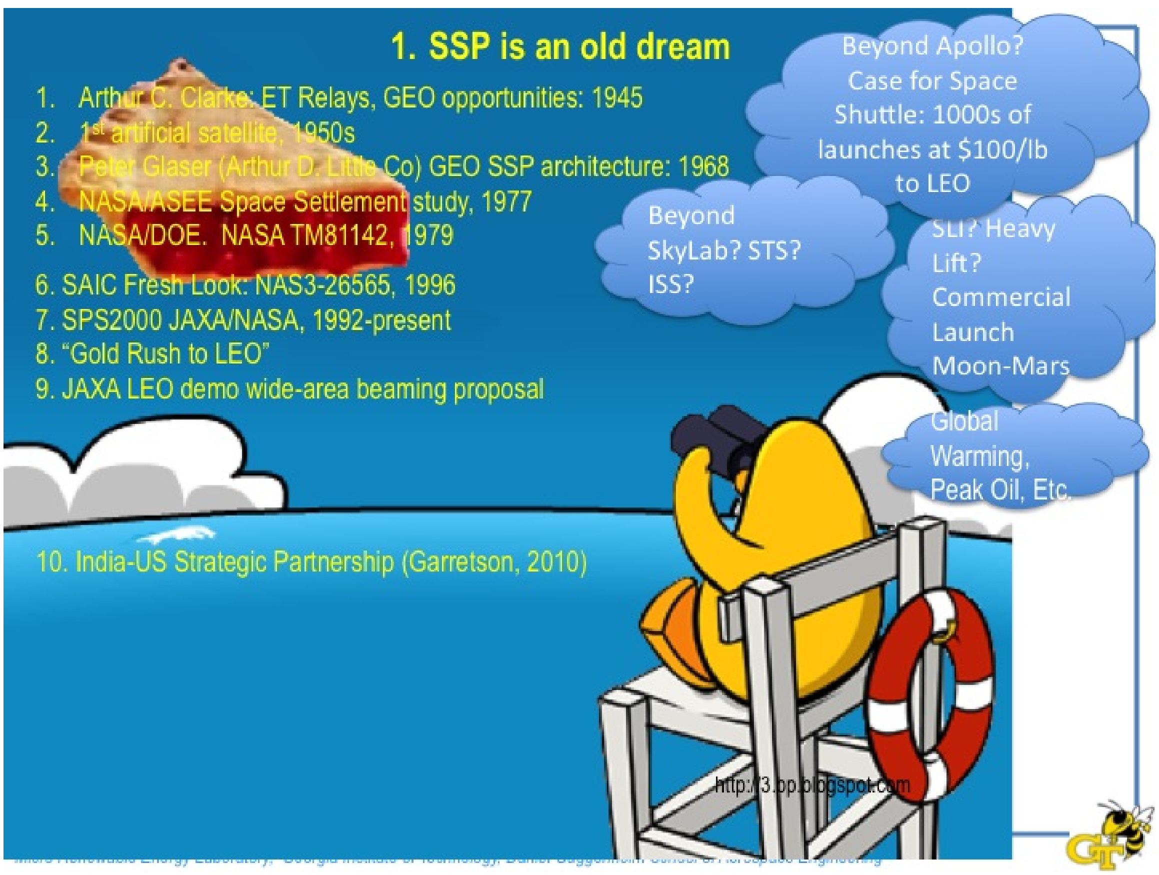

Figure 5.1: SSP is an old dream. It has been revived many times over the decades, usually concurrent with other priorities

Chapter 6

Implications of orbit choice: GEO, Moliyna, Sun-Synchronous

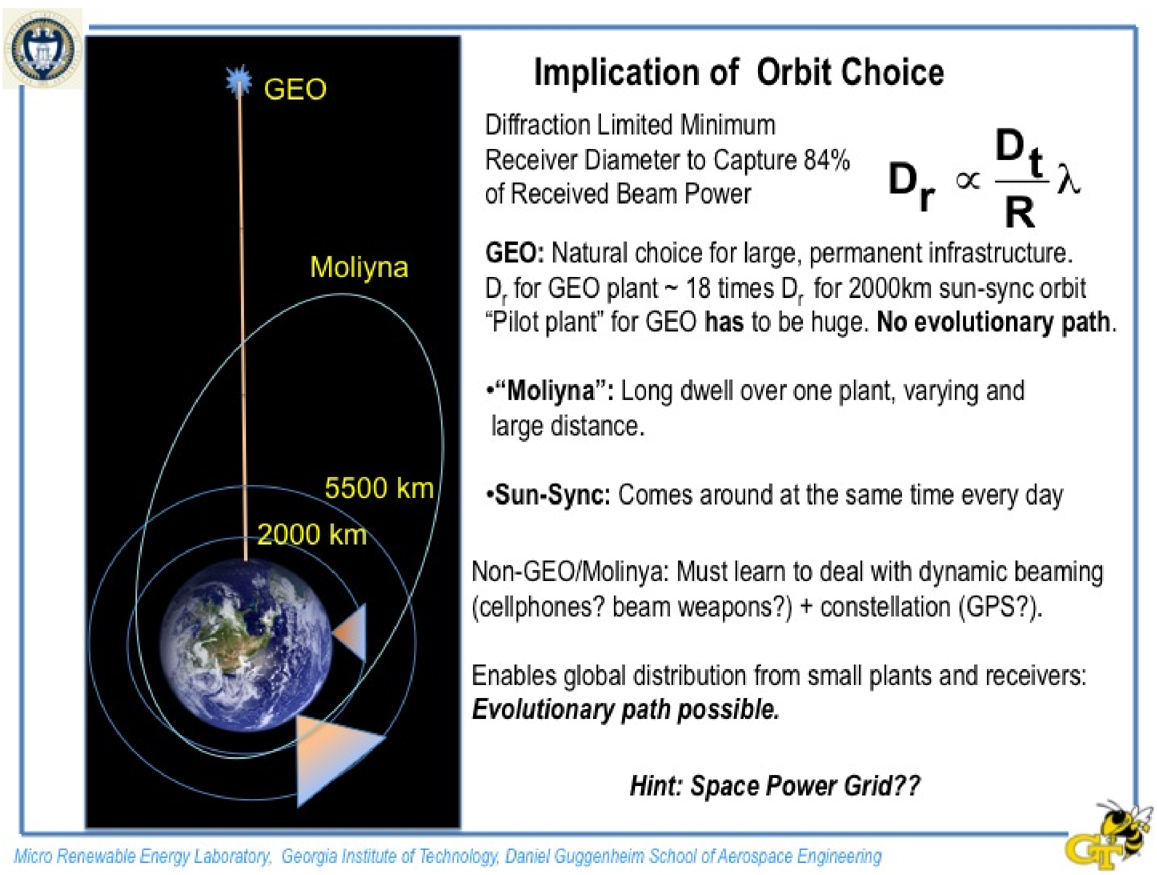

Figure 6.1: Implications of orbit choice

Chapter 7

Antenna Sizing: Case for Millimeter Waves

Figure 7.1 shows the variation of receiver diameter with beaming distance and frequency, for a given (reasonable) transmitter diameter. I have used logarithms to base 10 in order to get all the results on the same page. You can use the equation from Figure refImplications of orbit choice to check the results. This is for 84 percent beam capture. That is because a typical beam cross-section pattern has a central bright spot, surrounded by weaker rings. The central lobe contains roughly 84 percent of the total power in the beam. The next lobe might contain about 14 percent more, but the diameter would have to be roughly 1.5 times that needed for just the central lobe. You can see why designers of receivers for, say, 2.45 or 5.8 GHz beams from GEO would not try to capture that first outer lobe. It would mean increasing a 100 kilometer diameter dish to 150 kilometers.

For lasers, we used a 10 m diameter transmitter rather than a 150 diameter transmitter. There are two reasons. First, the receiver size for a laser will be limited by the intensity of the beam, so it will be considerably larger than the tiny diameter needed to capture the beam. Secondly, it is much harder to build a 150 m diameter mirror for laser wavelengths. Typically, a mirror has to have a surface with imperfections that are much smaller than a quarter of the wavelength. In the case of a millimeter wave, this means making a fairly smooth grid, perhaps made of fine wire. In the case of a laser with a wavelength of 10 microns, it means making a polished mirror, or, realistically, several mirror elements, independently controlled. For these reasons, the laser transmitter is smaller. The receiver is still quite small.

Lasers seem to be very attractive, but there are substantial issues associated with scattering by air, and by atmospheric aerosols, microscopic dust particles and clouds. Most laser SSP concepts describe receivers that are located in the ocean, far from human habitation. Finally, international treaties ban the positioning of high-power lasers in Space.

This leaves us with the hard realization that only millimeter waves can be used for a practical solution to power beaming from Space. Take a look at the atmospheric transmission spectrum in Figure refDry Atmos2800m. As best I can recall, this figure comes from data acquired at the Mauna Kea observatory in Hawaii, a US government laboratory. The observatory is located at roughly 2800 meters above sea level. This figure, which is found in many reports, illustrates another aspect: most of the public-domain data on atmospheric propagation of millimeter waves comes from the astronomical observation community, who are interested in correcting what a telescope sees, for this absorption.

The point of the figure is that the 200-225 GHz window, and the 140 GHz window, are surprisingly good for atmospheric transmission, down from Space to 2800 m altitude. Given how close 140 and

220 are in transmissivity, I would choose 220 GHz, simply because the receivers and transmitters turn out to be smaller.

But how good is 220 (or 140) GHz in other aspects? The news is bad. Both are terrible when there is rain in the air. Only the regime below 10 GHz appears to offer promise for transmission through rain. But this is a false promise, in my opinion. All data that I have seen in this regime from actual experiments, suggests that there is heavy loss due to something. Data collected by Indian Railways, a long-time pioneering user of microwave communications, reports severe signal dropout at 7 GHz through fog-shrouded valleys, and generally near coastlines and rivers. Field demonstrations of power beaming at 2.45 or 5.8 GHz, conducted in support of SSP efforts in Hawaii, have not produced the theoretical capture fraction of the transmitted beam, even over a distance of a few kilometers. Perhaps refraction and other effects play a strong role, beyond the diffraction-limited beam spreading. The moral of this sad story is that one should avoid trying to beam power through moist, dense air.

Recent work by our team has been exploring the use of antennae mounted on hydrogen- or helium-filled aerostats floating at 4000 to 5000 meters. The transmission between Space and this altitude is nearly perfect. Horizontal propagation between aerostats at these altitudes is also very efficient. The transit up and down between the ground and the aerostat could be done using waveguides built into the tethers. This only works if the waveguide is millimeters in cross-section, meaning that it will only work for the 220 GHz window (or, of course, for lasers).

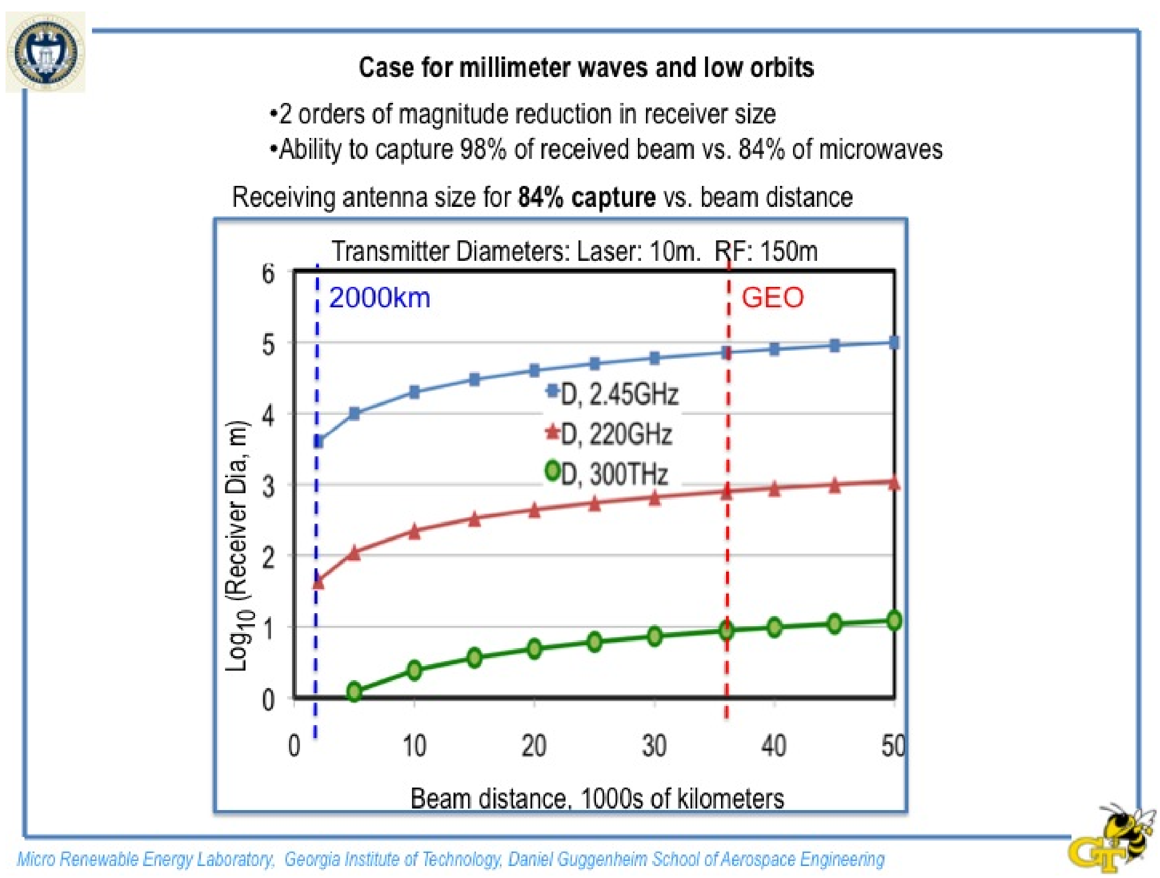

Figure 7.1: Antenna Sizing: Case for Millimeter Waves

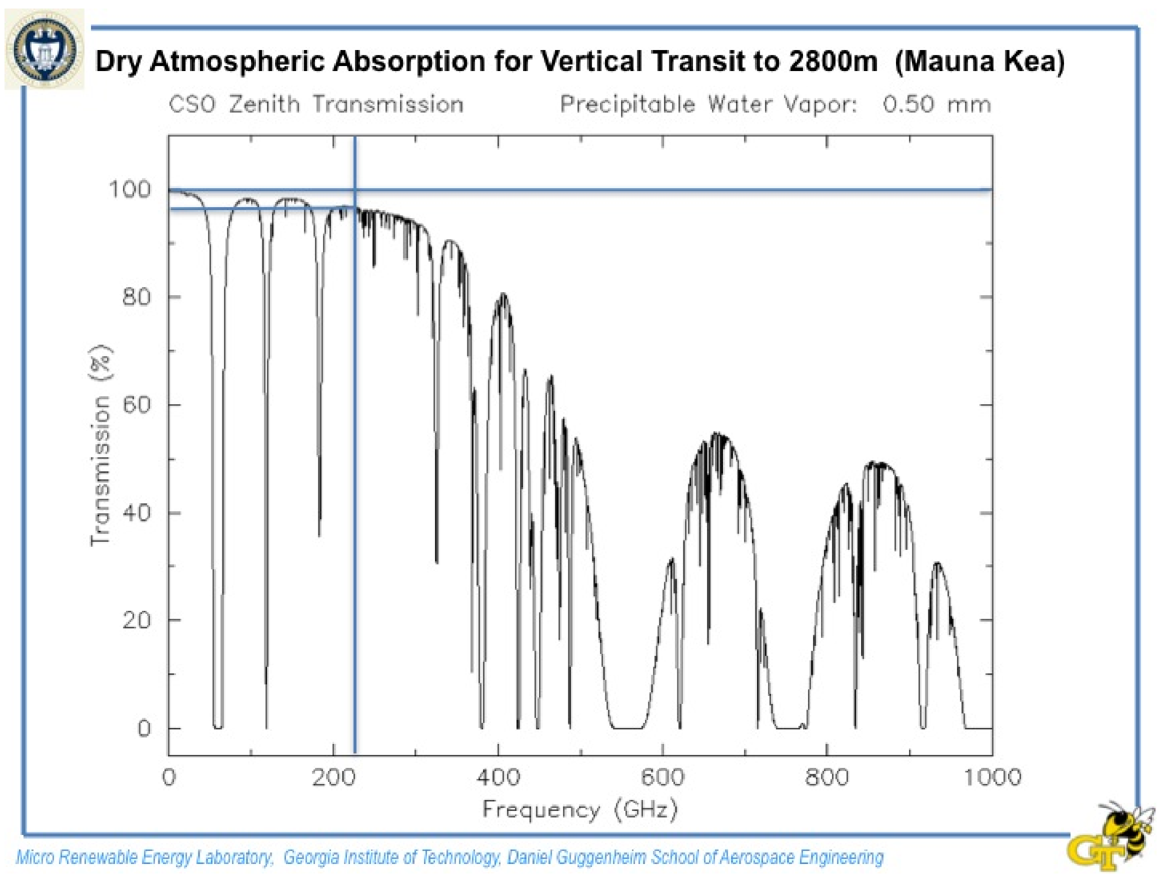

Figure 7.2: Dry Atmospheric Absorption for Vertical Transit to 2800m (Mauna Kea)

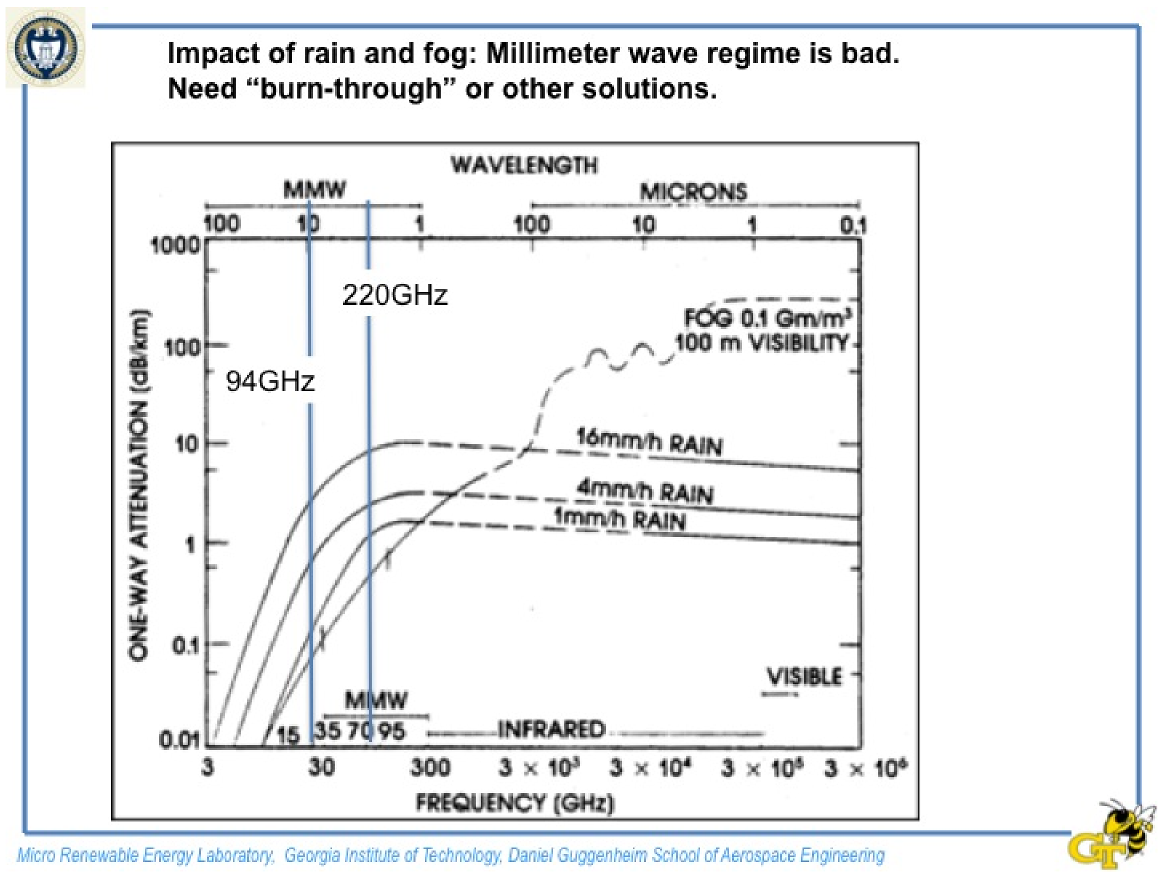

Figure 7.3: Impact of rain and fog

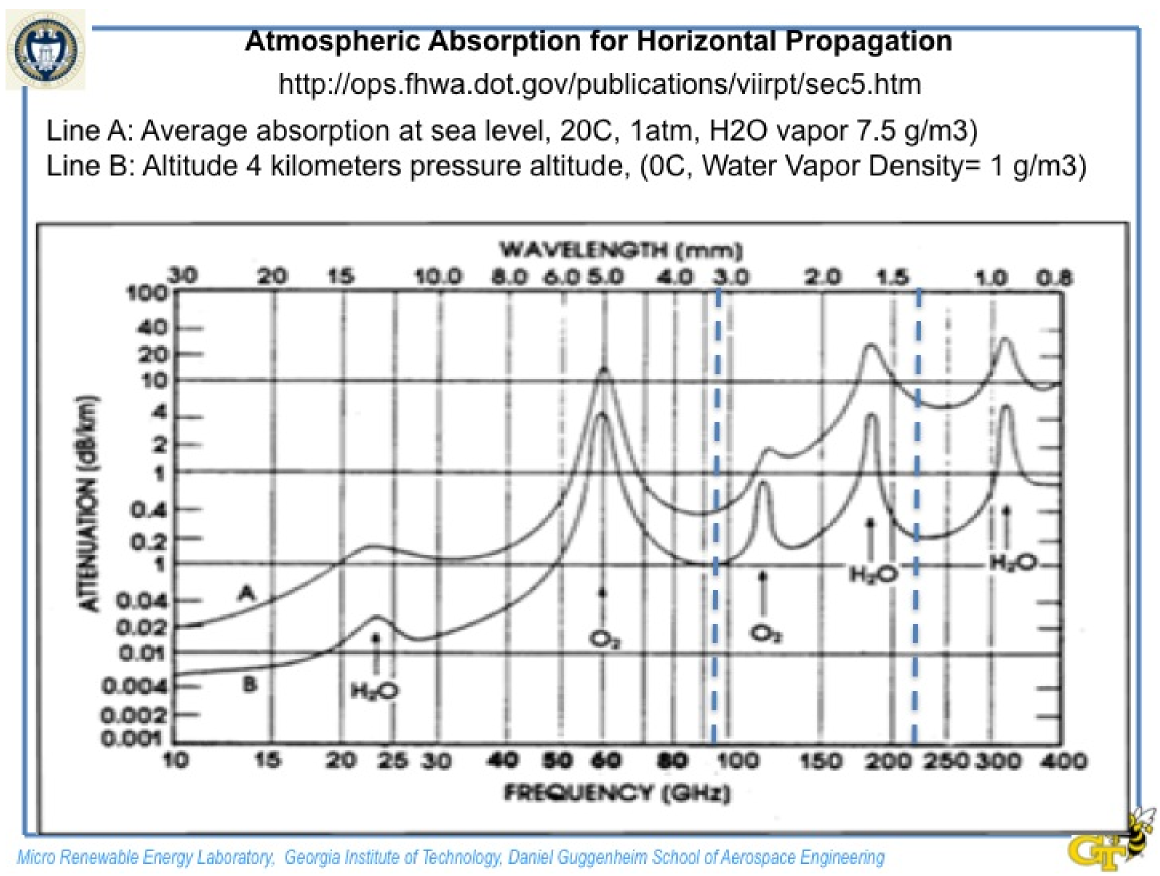

Figure 7.4: Atmospheric Absorption for Horizontal Propagation

Chapter 8

Specific Power

The biggest obstacle to SSP is Specific Power, or the electric power generated, per unit mass that one has to place in orbit. Present SSP architectures achieve somewhere between 0.1 and 0.3 kilowatts per kilogram in orbit. Until we reach 1 kilowatt per kilogram, SSP cannot really be made viable. We can see why from a very simple calculation. At 1 kW per kg, 1 kW requires around 6,000 dollars of launch cost alone to generate 1 kiloWatt. When it reaches the user on the ground, the kiloWatt may become half of that, so the cost of installation is at least 12,000 per kiloWatt, or 12 dollars per Watt. Compare this to the 3 to 5 dollars per Watt cost of installing terrestrial solar power. Would you spend money on SSP given that?

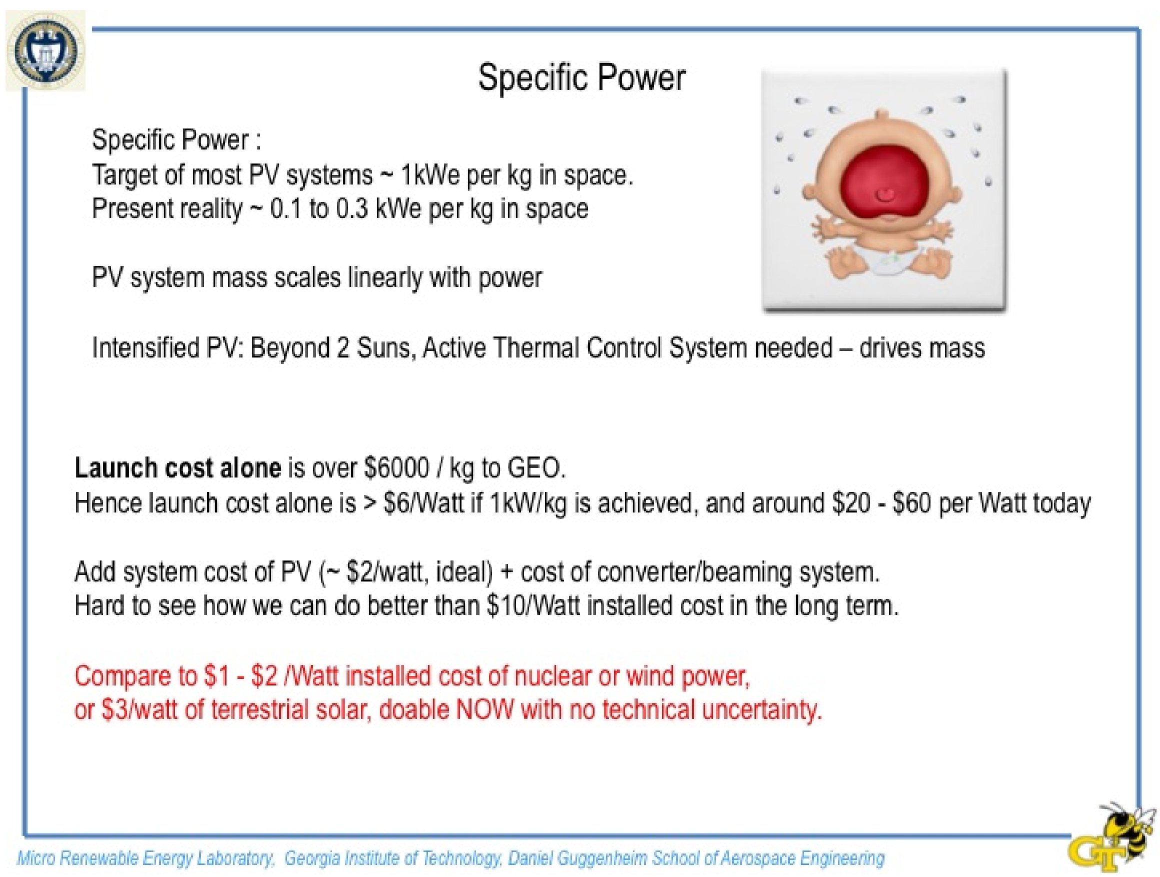

Figure 8.1: Specific Power

To solve this problem, we must devise a means of generating large amounts of electric power with low mass in Space. We are now studying how to do this using Brayton Cycle heat engines, instead of broad-band photovoltaics. The gist is that we believe that we can achieve a specific power of 2.5 kiloWatts per kilogram, or more. More on that later, look for the name InCA, or Intensifed Efficient Conversion Architecture, coming from our research team.

The story on launch cost, as shown in Figure 9.1 is simple. The Mass Ratio of a launch vehicle is given by the Rocket Equation relating the initial (total liftoff) mass M1 to the final (payload) mass M2 through the velocity increment)(delta V) representing the energy needed to reach that orbit, the specific impulse of the propulsion system, and the constant g0 of 9.8 meters per second-squared. The Ariane 5 ECA launcher is a modern, large rocket with 3 stages. The first stage has strap-on boosters, but also a large propellant tank, to feed large hydrogen-oxygen engines that offer the best specific impulse in the chemical propulsion business. To put 16,000 kg in low Earth orbit, the vehicle at liftoff is 777,000 kg, which is quite a large structure to put on the launch pad and boost into the sky. The same vehicle can only put about 10.500 kg into the Geosynchronous Transfer Orbit, and when that load burns its on-board propellant to station itself at GEO, it will probably (depending on the type of propulsion system) be down to about 8000 kg.

You can calculate what it takes to put up the 1 million kilograms required to put a 1 GWe SSP satellite in orbit, when we finally get the Specific Power up to 1 kWe per kg. So far, the entire history of the Ariane series includes some 59 launches, of which 32 have been the ECA version. With one more launch, the total mass put into GEO may reach 480,000 kg, almost enough to get half of the first GW SSP station into GEO. Despite their long experience, Ariane has not got the cost down anywhere near the 400 dollars per kilogram needed to make SSP viable, even at 1 kWe per kg specific mass.

Chapter 9

Launch Cost

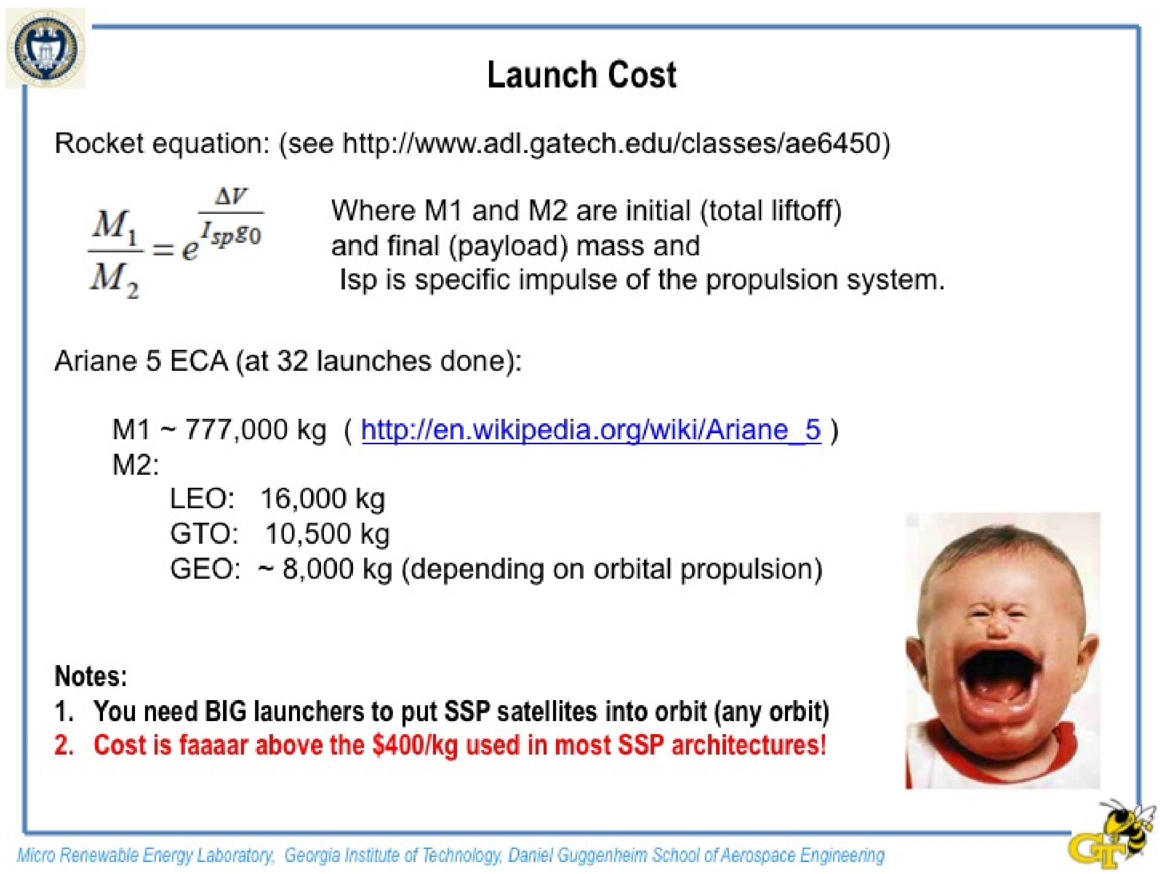

Figure 9.1: Launch cost considerations

Several schools of thought exist on how to slash launch cost. I will let the slide summarize them, because this is a highly controversial subject, with several people holding fierce beliefs on which I have no wish to tread. It appears to me that launch costs are dominated, not by the cost of the fuel (which is substantial) or of the metal and plastic and composites thrown away each time a vehicle is discarded (which is also substantial). The dominant cost is that of paying all the people, and for the testing facilities, to ensure safe operation of a very large, very powerful, very fragile and hence very complex vehicle, which is always being operated for the first time. This is one reason why they used to say that no one could pin down the precise cost of a Space Shuttle Mission. Whether the mission was launched or not, there were continuous heavy costs to maintain the operations as Kennedy and Johnson Space Centers and other places devoted to conducting Shuttle operations safely.

What this means to me is that launch and operations costs cannot be brought really down, until we are able to go to repetitive, routine missions conducted from runways, using self-powered, maneuverable vehicles that would serve numerous missions. This means a Reusable Launch Vehicle, that is built and operates like an airplane, rather than like a skyscraper building. Runway operation probably means an aerodynamic vehicle, that uses an airbreathing engine, to pull in the oxygen from the atmosphere, rather than having to carrying it from the ground. We will leave that exciting field for another day, another discussion. Reusable Launch Vehicles (RLVs) that use Air Liquefaction to capture and store oxygen on the way up into Space, are topics of great enthusiasm among several experts, but they also tend to trigger concerns related to International Traffic in Arms Regulations (ITAR).

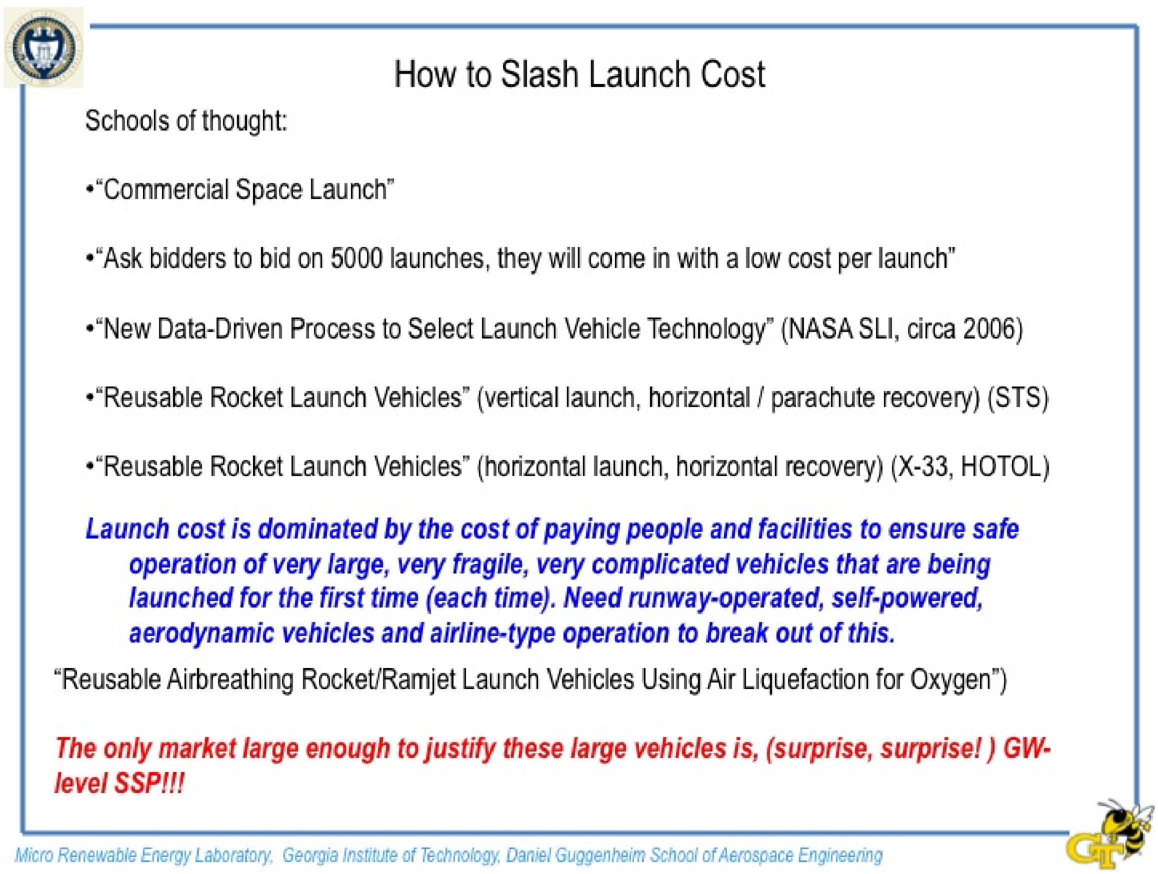

Figure 9.2: Schools of thought on how to slash launch cost

Chapter 10

Market Magic Meets Laws of Physics

Figure 10.1 is, I hope, self-explanatory.

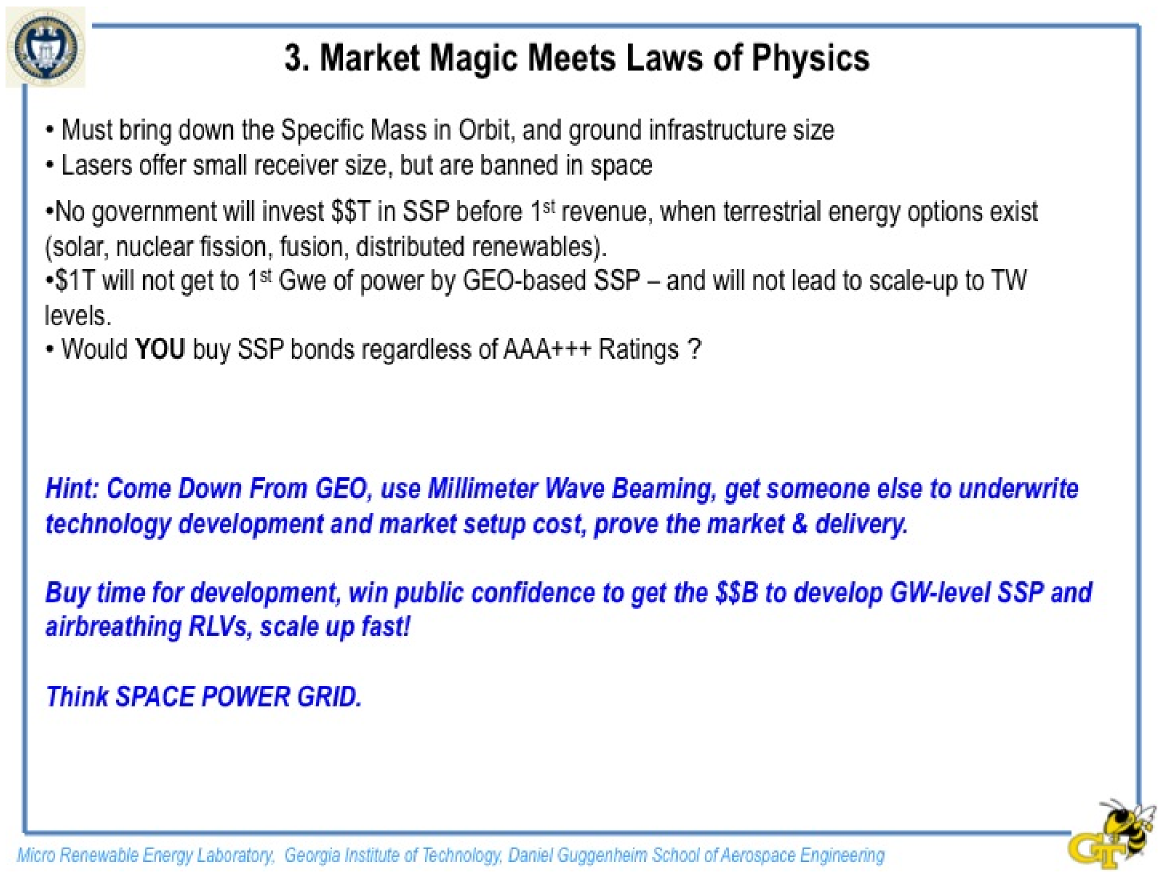

Figure 10.1: Market Magic Meets Laws of Physics

Chapter 11

SSP is Hard

The Ngorongoro is a high altitude volcanic crater in Africa. it is home to a unique ecosystem and is a famous animal sanctuary. With good reason: the animals cannot get out over the high and steep crater rim. They can roam around the beautiful crater bowl. There may be several potential escape routes apparent to the animals, but each route is steep and very difficult, with several obstacles that can be seen, and probably several that cannot be seen until one gets to the crater rim.

This is analogous to the situation in which the national space agencies of the world find themselves, with regard to SSP. Some would focus on the launch cost reduction route. Others may focus on other ideas. I say that millimeter wave beaming offers the best route (and, hey, look, the best route is that!) But let us not kid ourselves: all the routes are tough.

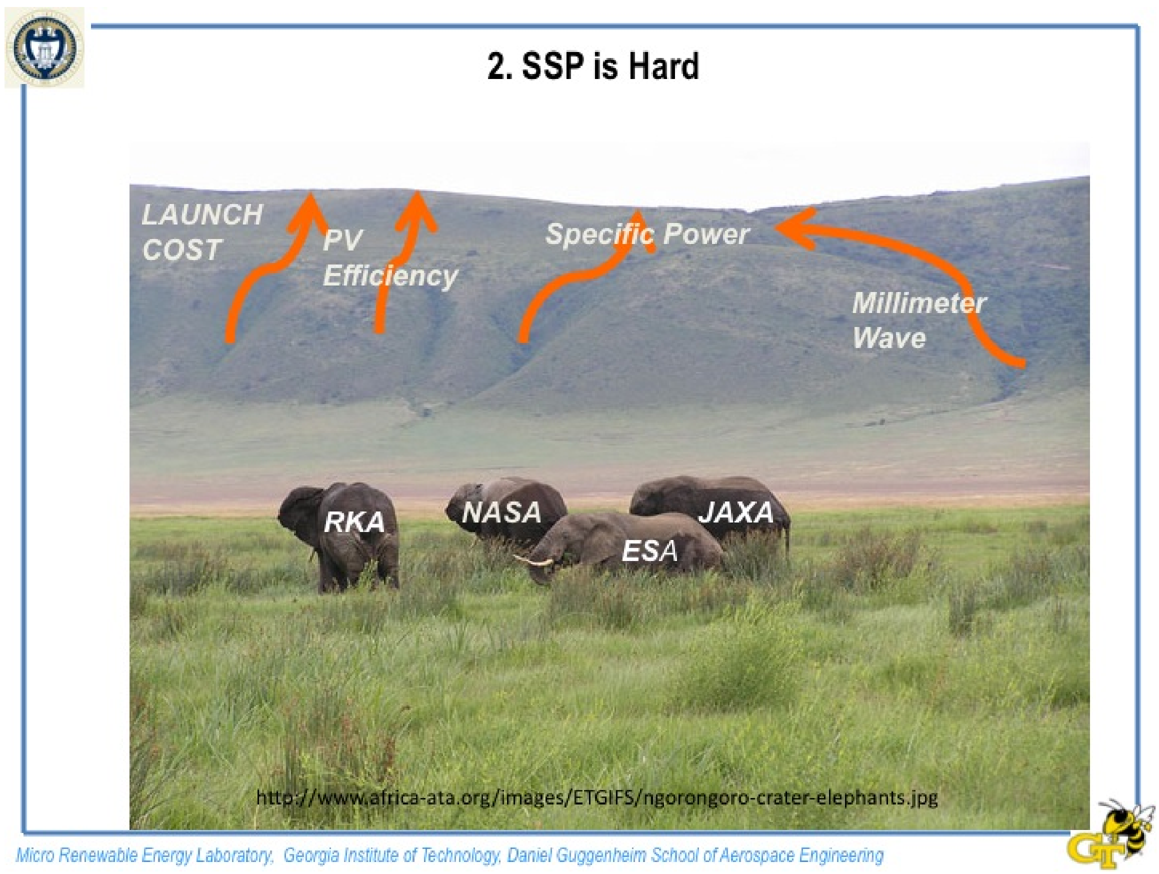

Figure 11.1: SSP is Hard

Chapter 12

Ngorongoro Viability Parameter

The preceding discussion leads to the definition of an empirical "viability parameter". From many hours spent juggling the parameters using a Fortran computer program, and looking at what it takes to make full-scale SSP break even with 4,000 GWe of capacity installed by Year 50 from project start, we submit that this parameter must reach a value of approximately 1 if viable SSP is to be achieved. The 25000 factor is purely empirical to force k to become 1 at the appropriate values of the other factors. The table in Figure 12.1 shows where we are with present-day systems and technologies, with respect to where we need to be to take k to 1.

There is of course another school of possible thought on when SSP will become viable - that would be when the cost of all competing power generation sources rises so much that they surpass the astronomical cost of SSP. Indeed, a realist could point out that the cost of nuclear fuel has shot up much faster than the cost of petroleum. Coal may become very costly at some point. Oil-fired power generation will become impossibly expensive long before that. Other resources such as wind power are far too small to compete seriously. Terrestrial solar may also go up. This hope is shown schematically in Figure 12.2.

But proponents of that other great hope of humanity, terrestrial nuclear fusion power, would argue that the cost of that approach will come down rapidly at some point in the future. So even that bright idea for making SSP viable by doing nothing, may not work out.

These arguments then, add up to the blunt assessment presented in Figure refBlunt Assessment. It may be summarized in the old saying: If you keep doing things today the way you did them yesterday, why do you expect better results tomorrow? To be sure, there have been many advances in photovoltaics technology and microwave technology. However, they do not lead to the breakthrough by 3 orders of magnitude that is necessary to even begin to make SSP viable. We need some other rationale to build towards SSP, and develop an evolutionary approach where we do not have to ask anyone to sink in the hundreds of billions of dollars that must be invested to scale up to SSP, until we have everything in place to minimize the technical and market risks.

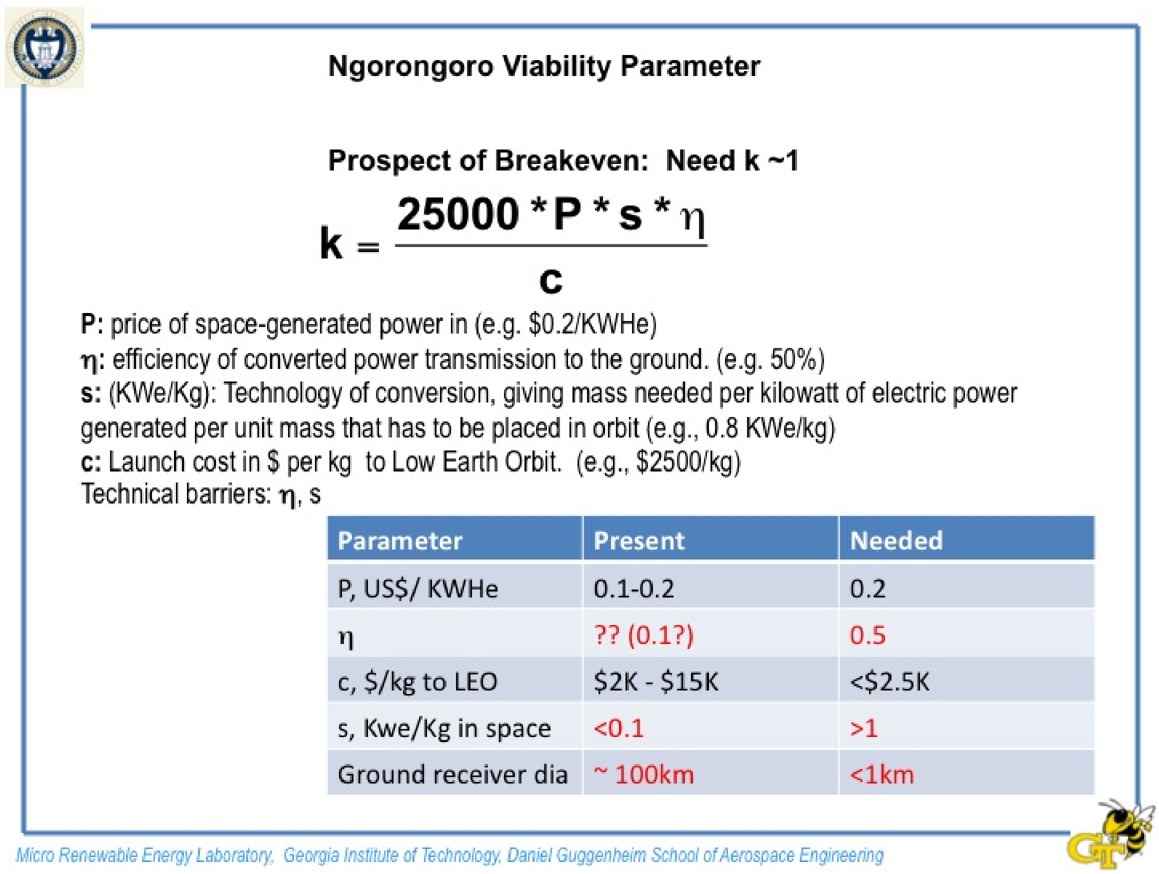

Figure 12.1: Parameter values needed to break even with full-scale Space Solar Power

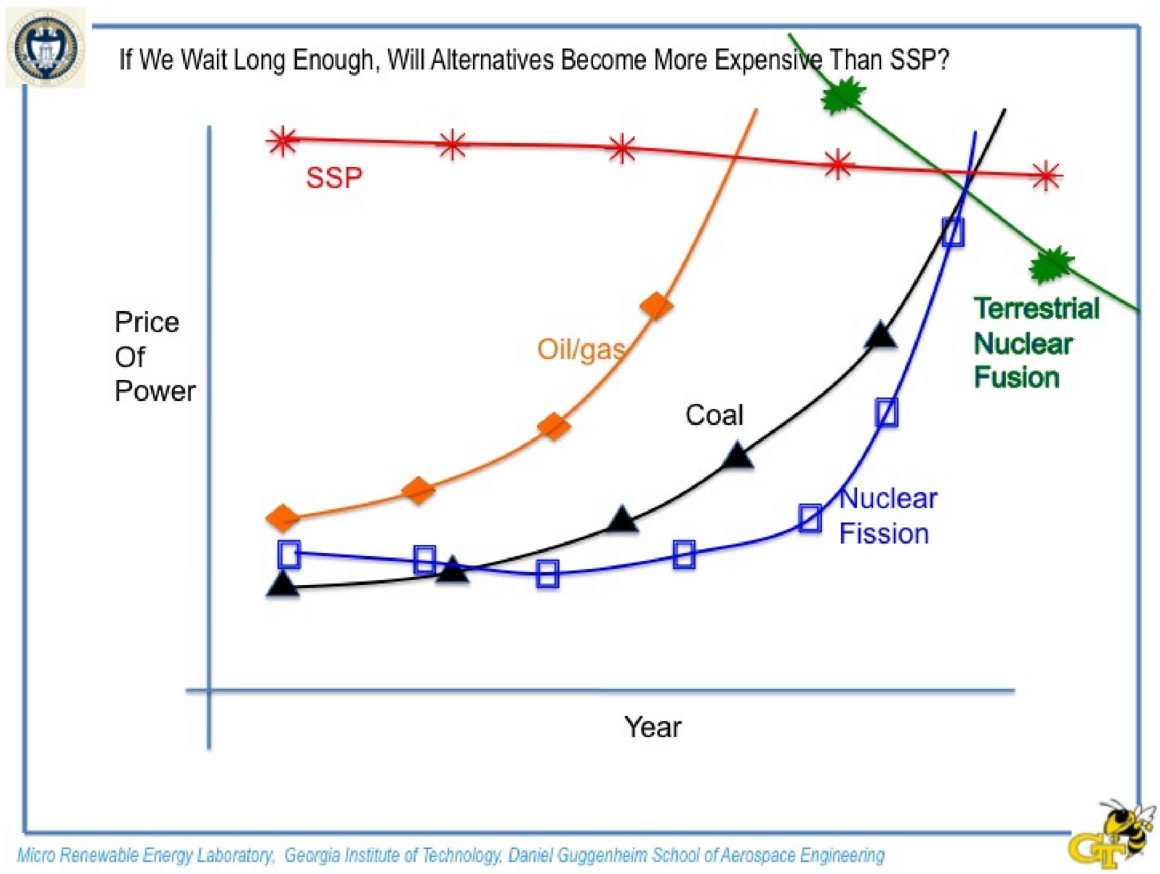

Figure 12.2: Speculating on the long-term price of power

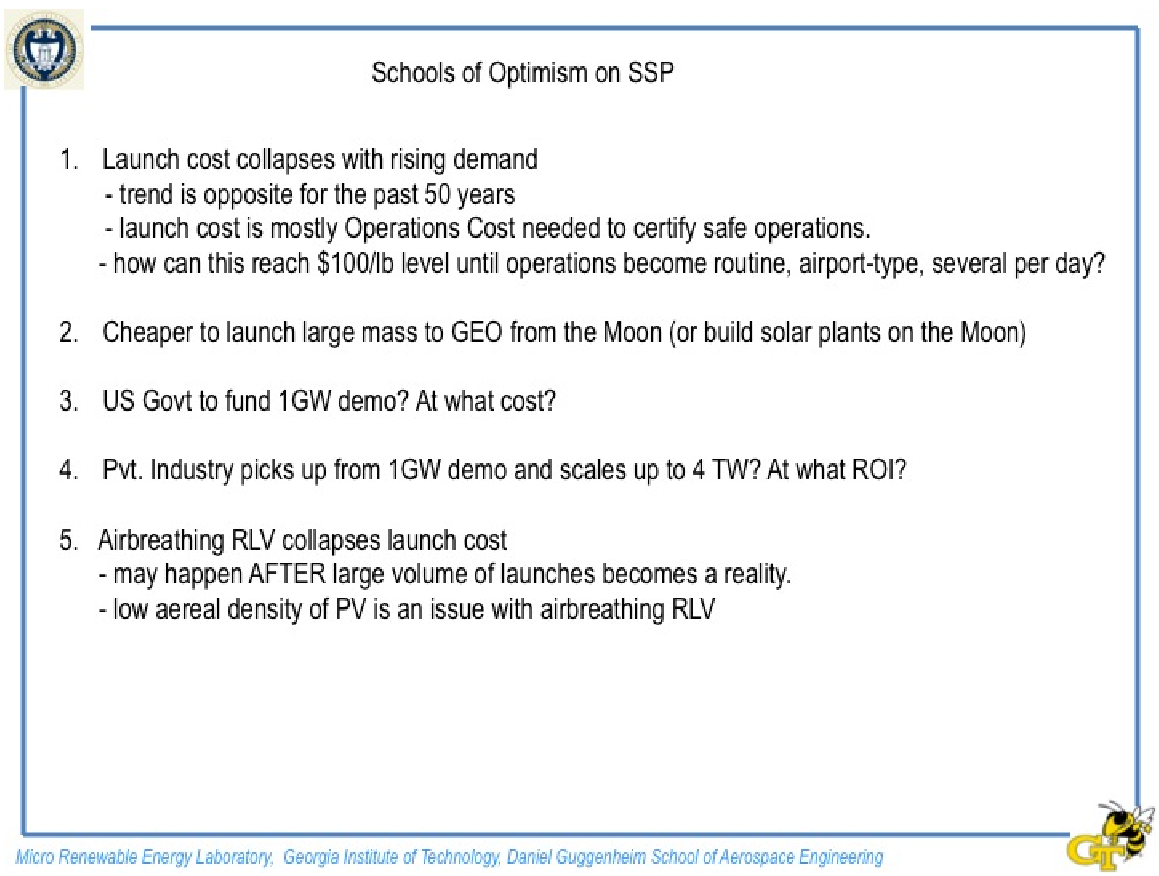

Figure 12.3: Schools of Optimism on SSP

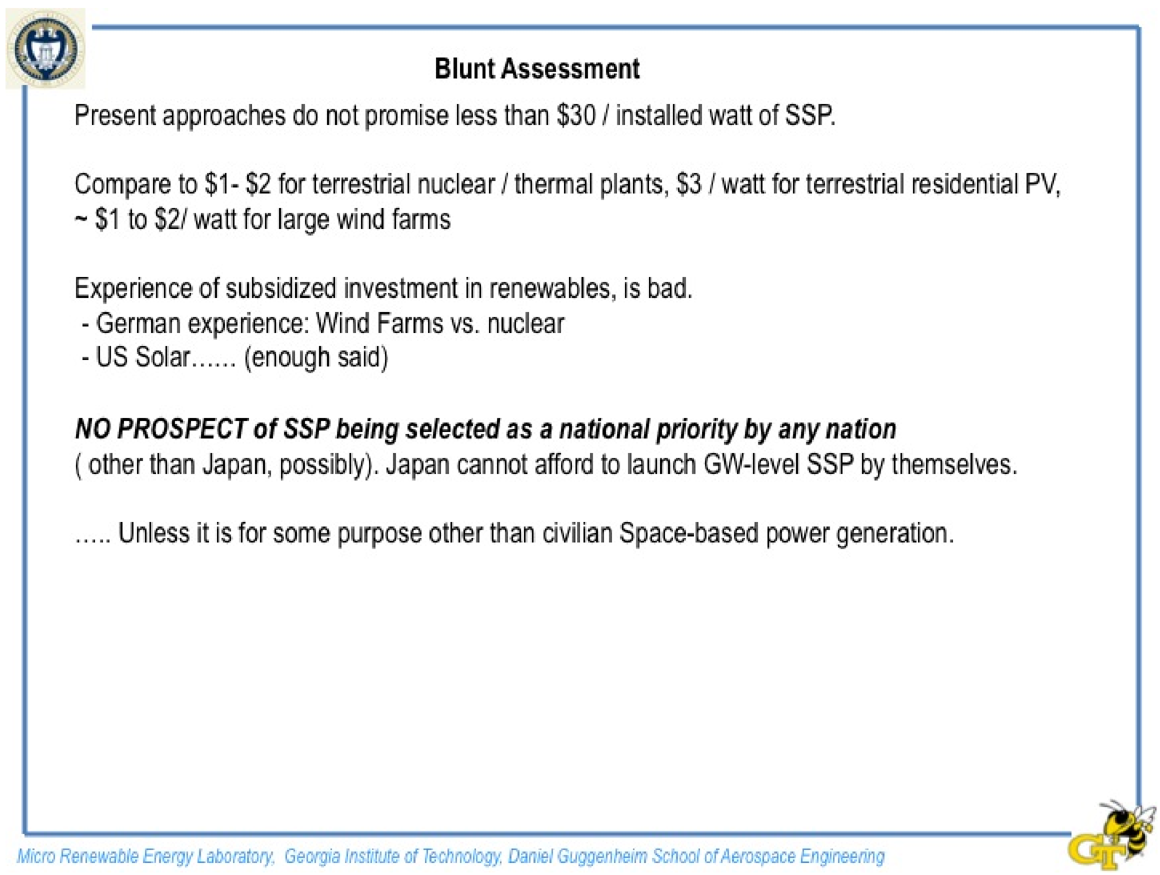

Figure 12.4: Prospects for SSP making a significant impact on global electric power supply using traditional approaches

Chapter 13

Space Power Grid Concept

Let us start with that one ray of hope: that SSP may develop because of the need for other priorities of humanity. The terrestrial renewable power industry, as lovable as it is to the public, is not doing well in the marketplace. Stocks of biofuel companies have not done well in recent times. Nuclear power is not exactly popular, though it offers the best hope for nations that can go that route, in the short term. Wind energy cannot increase very much and is extremely unsteady and spiky in nature, since power is proportional to the cube of wind speed. Terrestrial solar power is the greatest hope for a large addition of renewable power, but even there, some large failures continue to appear in the headlines.

One huge problem is that none of these technologies are able to compete head-on with the cost efficiency of coal and nuclear power. Sure, there will come a time when the costs of coal and nuclear will rise exponentially, but that may be far too late to start building up renewable power. Governments have been trying to prop up renewables using subsidies and using taxes on fossil sources, but there is not enough money to go around, nor room for more taxation.

Here is where we can help. Let us look in Figure 13.1 at a few definitions from your industry, the electric power utility. If we could exchange power in real time between plants on different sides of the world, we could help these plants achieve baseload status and command prices as high as what their established competitors can command. This is a good reason for them to pay somewhat higher prices for the beamed power, which is good thing because we will doubtless lose quite a bit of power in the beaming process. Think 50 percent loss overall - that means that we have to charge twice as much as we would if we had perfect transmission. But this is not so bad as it sounds, because we can deliver this power to remote locations. There are already some customers who pay incredibly high prices for electric power. An example close to home is the US military, which, by some accounts, pays over $3 per kWh for power (as opposed to the $0.10 that we pay in metro Atlanta for wall-plug power) at forward bases in remote locations. Worse, the alternative is to run diesel generators, with the diesel having to be transported in tanker trucks through, say, hostile terrain past ambushes. Many lives have been lost delivering such power.

This leads us to the first idea behind the Space Power Grid: think of Space as a place for a Power Grid where power is exchanged, rather than as a place to produce and sell power. This is a hard come-down for those of us used to thinking of ourselves as world-saving builders of new generation capacity, but this step down to the level of being a service provider to other generators, makes all the difference in the world to the ultimate viability of SSP.

This is not all altruism. The point is that the terrestrial renewable power industry needs help. It is worth good money to them, to pay for the power that we can convey from one place to another. This means that there is revenue to be generated, and people willing to share the risks of this new technological and market experiment. If it succeeds, we will have a distribution grid, ground facilities

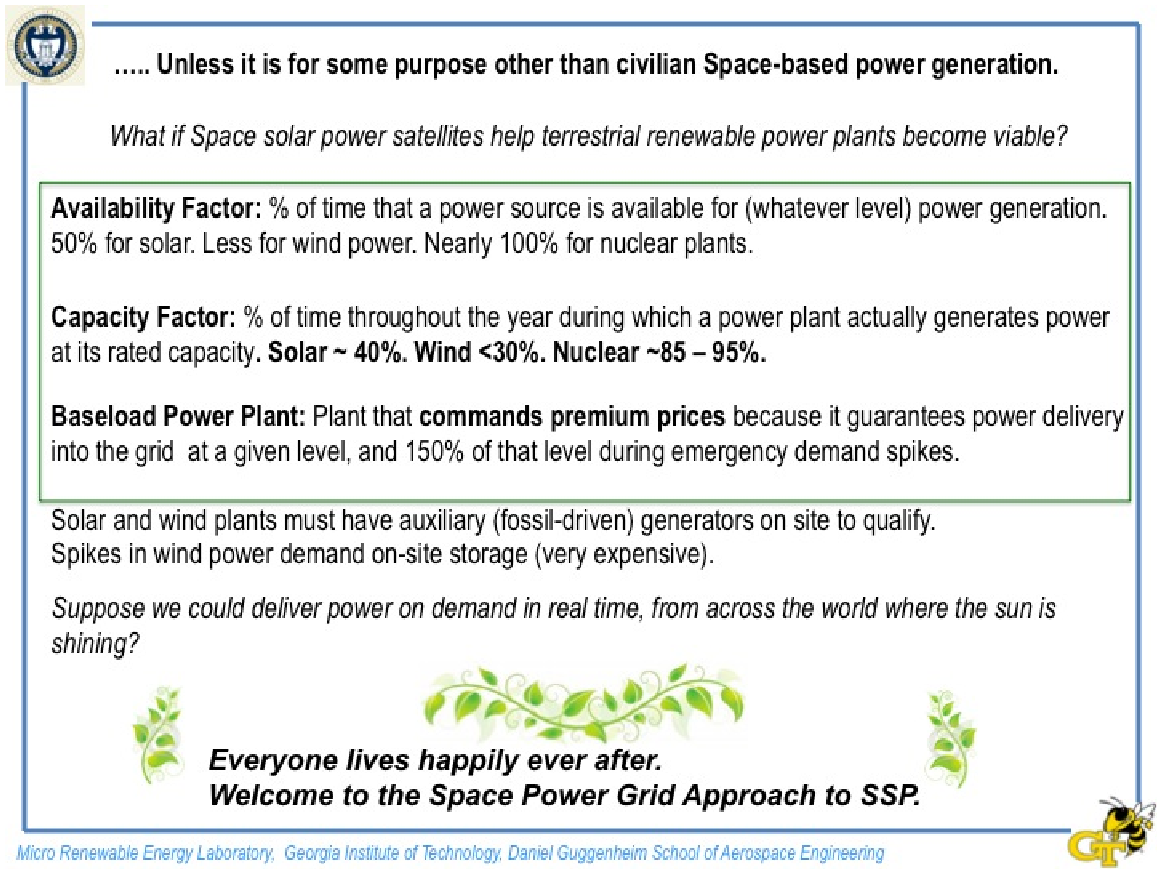

Figure 13.1: Opportunity to help: Needs of the terrestrial renewable power industry

and an established market, all developed with other people's money, all generating revenue, waiting to receive the power generated by SSP. In principle, since SSP is generated in Space, it needs only one pass through the atmosphere, so that it enjoys better efficiency than the terrestrial power that we deliver in the first phase. So we will have a slight cost advantage when SSP kicks in.

13.1 Assumptions and Parameter Choices

In Table 13.1 the present assumptions and parameter choices of the Space Power Grid architecture calculation are listed, going from choice of frequency and altitude, to the Net Present Value calculation to ensure breakeven by Year 17 for Phase 1 and Year 50 for 4 Terawatts of installed SSP. Some parameters change between Phase 1 and Phase 2-3. Most important of these is the launch cost to LEO. In Phase 1 it is around $2500 per kg, but in Phase 2 and 3 we assume that it comes down to $1300 per kg or lower because of the seriousness factor. In other words, with Phase 1 working and seen to be making money, we can believe that investors in Reusable Launch Vehicles and other such technologies will start bidding on mass launch operations over several decades, and accordingly, projecting low per unit costs.

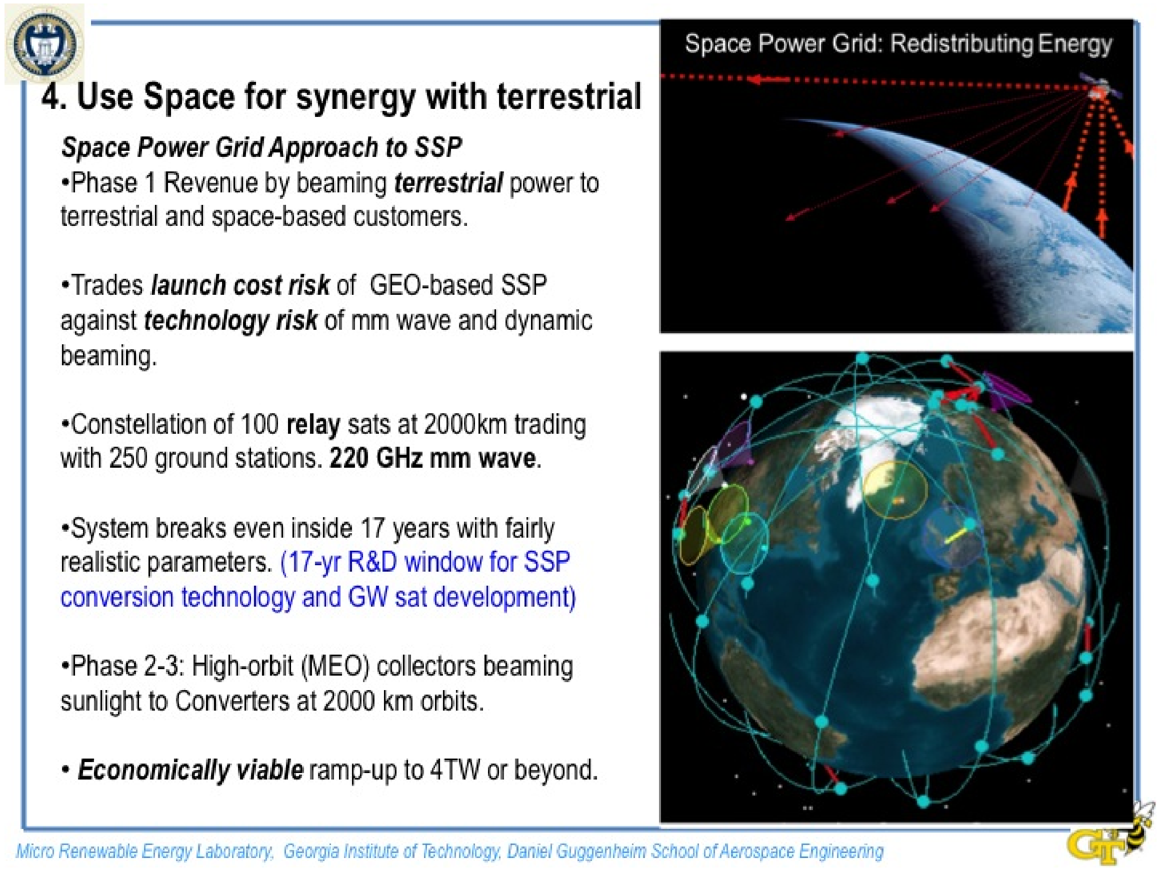

Figure 13.2: Use Space for synergy with terrestrial

13.2 Bases of Parameter Values

1. B1: The 220GHz window offers up to 90% transmission through a dry atmosphere, compared to 95% below 10GHz, and 92% at 140GHz. Above 10GHz, wet weamerther operation is poor at low power levels. Continuous megawatt-level beaming through a raincloud remains to be explored.

2. B2: Solar power can be converted to DC using high-intensity PV arrays at over 42% efficiency [39], and from DC to microwave beamed power with roughly 80% efficiency [40]. We assume 40% efficiency with 220GHz conversion. Direct conversion using optical antennae, perhaps made of nanofibers [41] may offer efficiencies well above 40%. Theoretically, 80% conversion is possible, but nothing close has been demonstrated to our knowledge.

3. B3: 80% conversion from line frequency to beamed microwaves has been demonstrated. We project that conversion to 220GHz can reach at least this efficiency.

4. B4: A reciprocal conversion efficiency of 80% is deemed possible for the same reason.

5. B5: Atmospheric propagation data at 220GHz [42].

6. B6 and B7: Approximate estimates.

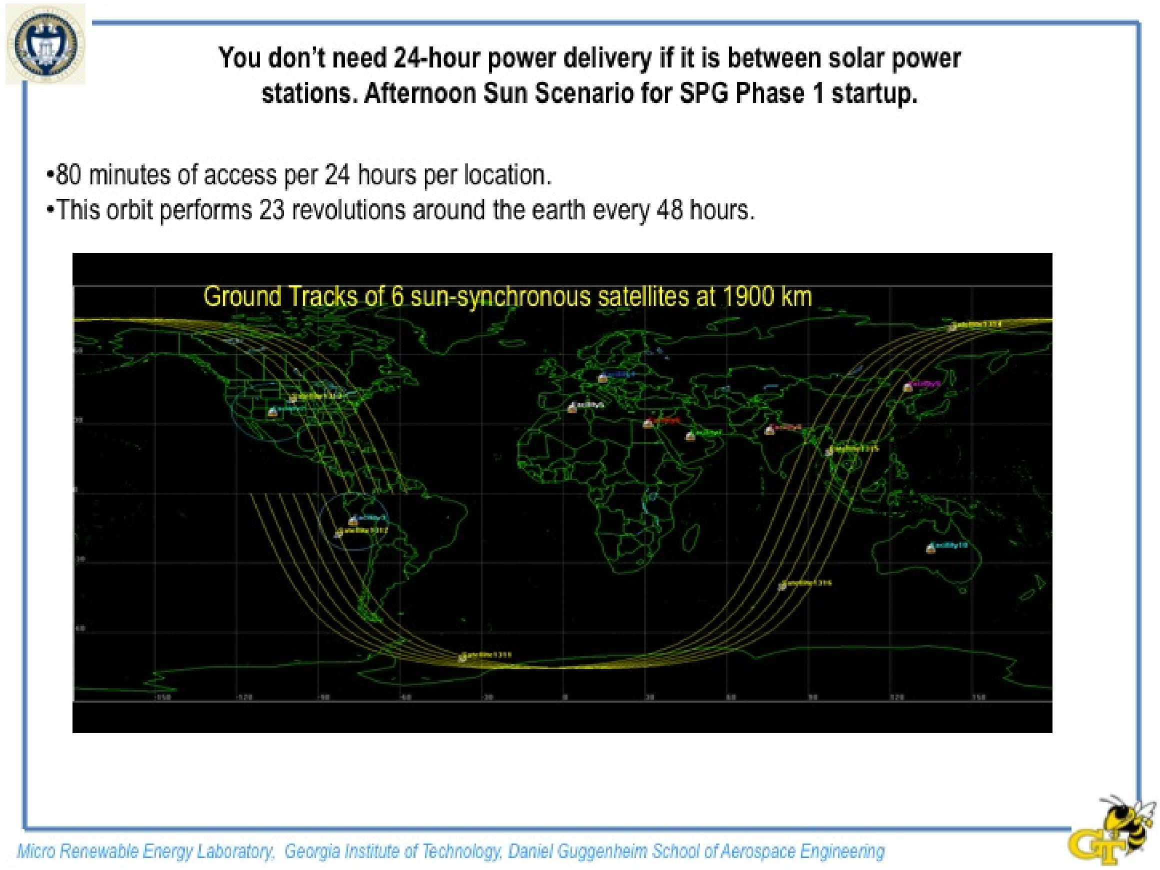

Figure 13.3: Afternoon Sun Scenario to optimize scheduling of sun-synchronous satellites

7. B8: Aereal density of 3 to 7 grams per square meter are cited for solar sail craft. Naval Research Laboratory estimate, 2008, of the areal mass of large solar sails [43] including their support structures is much smaller than the value that we have assumed.

8. B9: A 5% allowance for other systems is conservative compared to [16], but we have not detailed the subsystems.

9. B10: Reflector may be similar to B8, but some thermal control is needed in view of the intensified sunlight, and lower Phase 2 orbits demand stronger structures.

10. B11: Converter mass per unit power is a critical limiting technology. We assume this value of 0.5 Kg/MWe at large power levels with 300-sun intensified sunlight. It is feasible with direct conversion or mechanical-electric conversion.

11. B12: The Phase 1 SPG satellite is conceptualized as transmitting and receiving antennae connected through waveguides, with minimal internal dissipation. This drives thermal management system mass. For a narrow-band tuned antenna and waveguides, 1% loss may be conservative.

12. B13: With 220GHz, the antennae is sized for 99% capture.

13. B14: Ground antenna efficiency is taken as 0.9 based on claims of people in the microwave beaming community.

14. B15: The effective diameter of the receiving antenna on the Phase 1 spacecraft is taken to be 50m.

15. B16: Orbit height of 1900+ miles enables a sun-synchronous orbit where each satellite stays in view for a few minutes each time.

16. B17: Each ground station is assumed to have a clear view of the sky down to 45 degrees from the zenith. This is conservative, but atmospheric propagation loss data are available for 45-degree transmission [42].

17. B18: A design distance of 2400km is chosen for intersatellite beaming, to size the space antennae. When used for longer distance beaming, this implies either a loss at the receiver or a need for larger receivers.

18. B19: Because revenue comes from transacted power, there is a lower limit on the power transacted per satellite, for economic viability. This limit may be down near 10MW. The 60MW level is chosen because the intensities of beams at the ground and at the spacecraft are still kept moderate.

19. B20: Collector diameter is set to 300m arbitrarily.

20. B21: Cooling system mass: The assumed level is roughly half of that on an existing spacecraft [44].

21. B22: Launch cost to LEO was varied to the maximum where breakeven is achieved by Year 50 for the given system power level.

22. B23: Transfer from LEO to final orbits, and orbit corrections, are assumed to use Krypton thrusters [16] and the required delta-v is doubled from the Hohman transfer level to account for the continuous low-thrust mode.

23. B24: $5M per year/satellite from NASA-Air Force Cost Model, for 36 sats. Cost decreases as constellation grows.

24. B25: An allowance of 1000Kg provides for miscellaneous sensors and systems on each Phase 1 craft.

25. B26: $1B development cost assumed, for the technology and procedures to exchange beamed power with satellites. The number of ground stations is assumed to be twice the number of Phase1 and Phase 2 satellites. As Phase 3 starts, the older Phase 1 stations have to be upgraded to receive the 1GWe level of beaming from the Phase 2 and Phase 3 satellites.

26. B27: In addition, a $25M cost is assigned to each ground facility to install equipment to interact with SPG.

27. B28: Typical US utility power production cost $0.04 per KWH.

28. B29: Assume that Phase 1 SPG power will be sold at 18 cents per KWH. Customers at solar plants will find this reasonable because it saves the immense costs of installing auxiliary generation equipment.

29. B30 and 31: The SPG part of the ground facilities are attuned to the parameters of the satellites.

30. B32: 6% discount rate on financing needed for the SPG, given low interest rates prevailing today.

31. B33 and 34: In Phase 1, governments will hold expected Return on Investment to 6%. In Phase 2, nations have the choice of getting larger ROI by deploying satellites slower, or investing heavily and ramping up the SSP rapidly. B35 and 36: A loan percentage of 30% [15].

32. B37: Phase 3 sales price of power to break even by Year 50 at the given ramp-up rate.

SPG BASELINE ASSUMPTIONS COMPARED TO JPL "HALO" GEO ARCHITECTURE

	HALO	SPGPh1	SPGPh2&3
Debt ratio	30%	30%	N/A
Debt interest	8%	6%	N/A
ROI on equity	15%	15%	15%
Satellite lead time, years	2	2	2
Satellite life, years	20	17	30
Loan repayment, years	20	Revenue used directly	N/A

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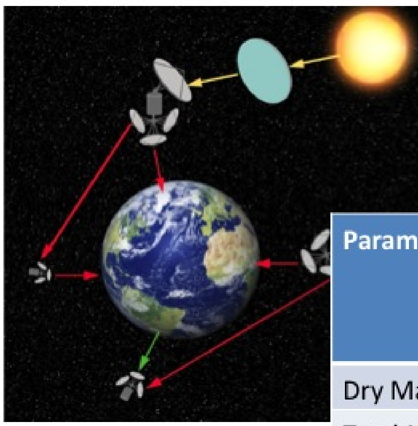
Figure 13.4: SPG assumptions compared to the JPL HALO architecture for GEO-based SSP

Space Power Grid Architecture



Parameter	Phase 1 Relay sat	1GWe Converter /Relay "Girasol"	Reflector, per Gwe "Mirasol"
Dry Mass, kg	2680		
Total Mass, kg	3526	856,000	53,000
Array dia, m	50	150	
Orbit height, km	2000 (5500)	2000	>10,000
Packed length,dia, m	4.6, 2.2 m		??
Launcher class	Delta II	On-orbit assembly	Heavy lift

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Figure 13.5: Space Power Grid Architecture Satellite Parameters

Table 13.1: Space Power Grid Baseline Parameter Choices.

Parameter	Value	Basis	
Beam Frequency (GHz)	220	B1	
Conversion efficiency solar to beam	0.4	B2	
Conversion AC to mmwave	0.8	B3	
Conversion mmwave to ground AC	0.8	B4	
Efficiency of atmospheric pass	0.9	B5	
Transmitting Space Antenna Mass Per Unit Area kg/m^2	0.05	B6	
Receiving Space Antenna Mass Per Unit Area kg/m^2	0.05	B7	
Ultralight Reflector Satellite Mass per unit area kg/m^2	0.01	B8	
Miscellaneous mass added to satellite	5%	B9	
Collector kg/m^2 of converter sat	0.05	B10	
Converter kg/MWe at 300 Suns	500	B11	
Efficiency of reception at Satellite	0.99	B12	
Efficiency of capture at ground	0.99	B13	
Efficiency of ground antenna	0.9	B14	
Diameter of Phase 1 sat receiver, m	50	B15	
Orbit height of Phase 1 satellites, km	2000	B16	
Half-angle of azimuth visibility, deg.	45.	B17	
Distance between satellites (km)	2400.	B18	
Power transmitted (design, MW)	60.	B19	
Phase 2 collector diameter, m	300.	B20	
Cooling system kg/MW of heat	400.	B21	
Launch cost to LEO, $ per kg	1300	B22	
Specific Impulse for orbit transfer, sec.	5300.	B23	
Operations cost per sat $M	5.	B24	
Satellite other systems mass:	1000kg	1000.	B25
Ground facilities development $M	1000.	B26	
$M cost per ground facility cost	25.	B27	
$ per kwh to produce power, ground,	0.04	B28	
Sales price, $ per KWh, Phase 1	0.18	B29	
Number of stations participating	250.	B30	
MW average per plant	60.	B31	
Assumed Discount Rate, percent	6%	B32	
Desired Return on Investment, Ph1 %	6%	B33	
Desired Return on Investment, Ph2 %	20.	B34	
Loan percentage, Phase 1	30%	B35	
Loan percentage, Phases 2 and 3	30%	B36	
Sales price, $ per KWh, Phase 3 SSP	0.20	B37	

Chapter 14

SPG Model Results

The results in Figure refSPG Model Results show that the baseline Phase 1 SPG power exchange model breaks even in 17 years at the given rate of Return on Investment. Early revenue generation, and the gradual production ramp-up ensure that the Net Present Value (NPV) never goes very far into the negative range. Figure refSPG Model Results also shows the sharp negative gradient of NPV at the beginning typical of a space venture, but alleviating as revenue generation starts in Year 6. Beyond 17 years, NPV goes sharply negative again as the huge development and production spending for the massive Phase 2 and Phase 3 satellites commences, 6 years before launch.

In this phase, we assume that the investment comes from numerous entities around the world, all willing to take on an investment that will not break even for 25 years. Each Phase 2- Phase 3 satellite combination is a 1GWe power plant, and each will take several years to break even on its investment. Thus the insistence on breaking even by Year 50 is rather artificial and done only for the purposes of this paper. The time to break even will depend on the power price commanded, and the IRR specified. The total investment needed is several trillions of dollars, but the power generation reaches 3400 GW by Year 50. By varying (i.e., slowing) the production and launch rate of Phase 3 and accompanying Phase 2 craft, it should be possible to fill in the huge NPV dip to a substantial extent, since the system is shown to break even eventually on revenue.

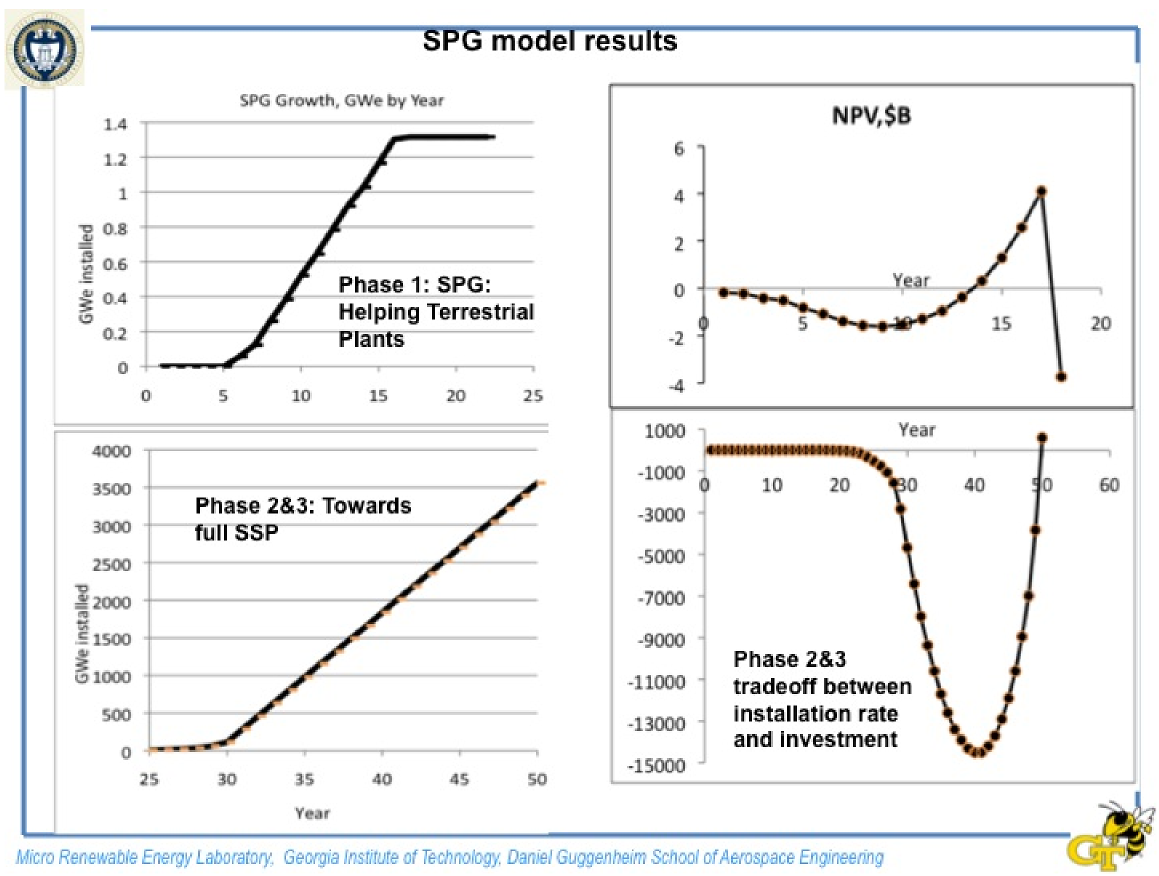
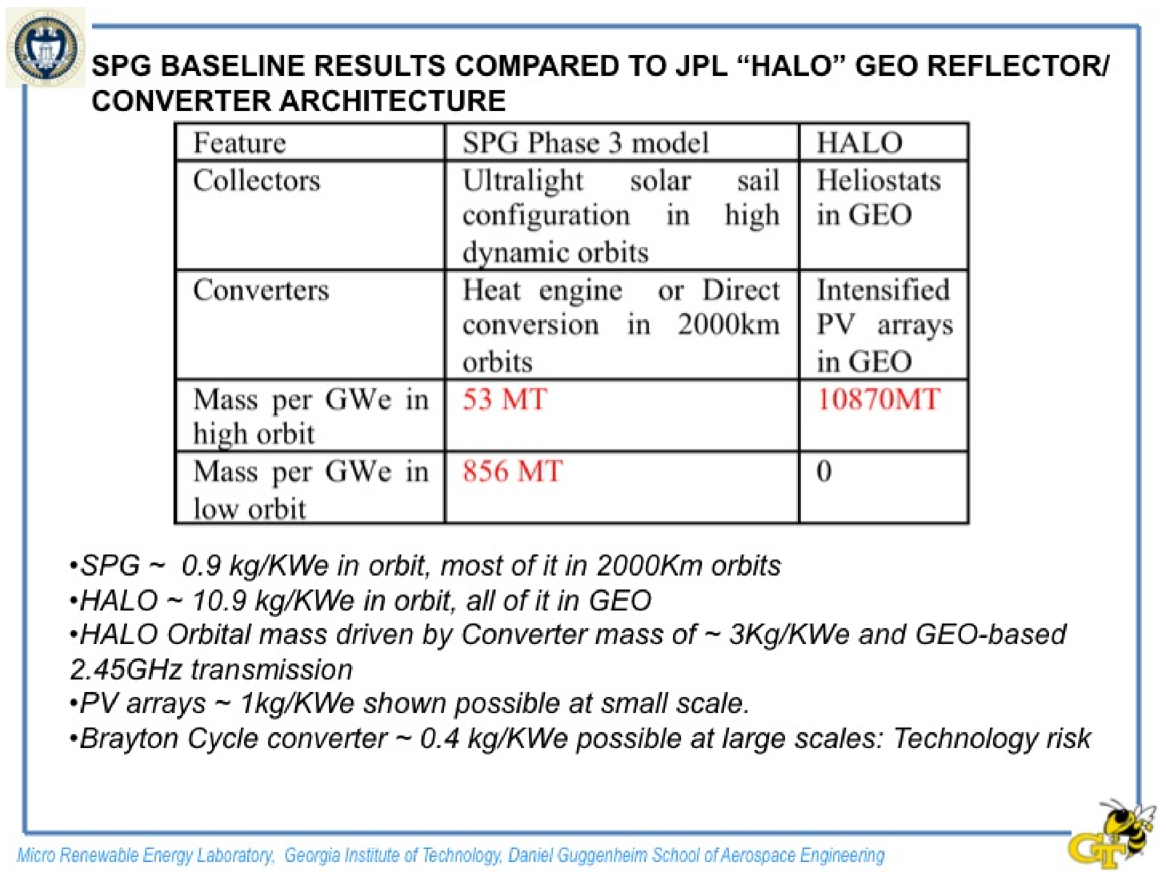


Figure 14.1: SPG Model Results



SPG BASELINE RESULTS COMPARED TO JPL "HALO" GEO REFLECTOR/ CONVERTER ARCHITECTURE

Feature	SPG Phase 3 model	HALO
Collectors	Ultralight solar sail configuration in high dynamic orbits	Heliostats in GEO
Converters	Heat engine or Direct conversion in 2000km orbits	Intensified PV arrays in GEO
Mass per GWe in high orbit	53 MT	10870MT
Mass per GWe in low orbit	856 MT	0

- *SPG ~ 0.9 kg/KWe in orbit, most of it in 2000Km orbits*
- *HALO ~ 10.9 kg/KWe in orbit, all of it in GEO*
- *HALO Orbital mass driven by Converter mass of ~ 3Kg/KWe and GEO-based 2.45GHz transmission*
- *PV arrays ~ 1kg/KWe shown possible at small scale.*
- *Brayton Cycle converter ~ 0.4 kg/KWe possible at large scales: Technology risk*

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Figure 14.2: SPG results compared to HALO architecture results

Chapter 15

US-India Demonstration Model

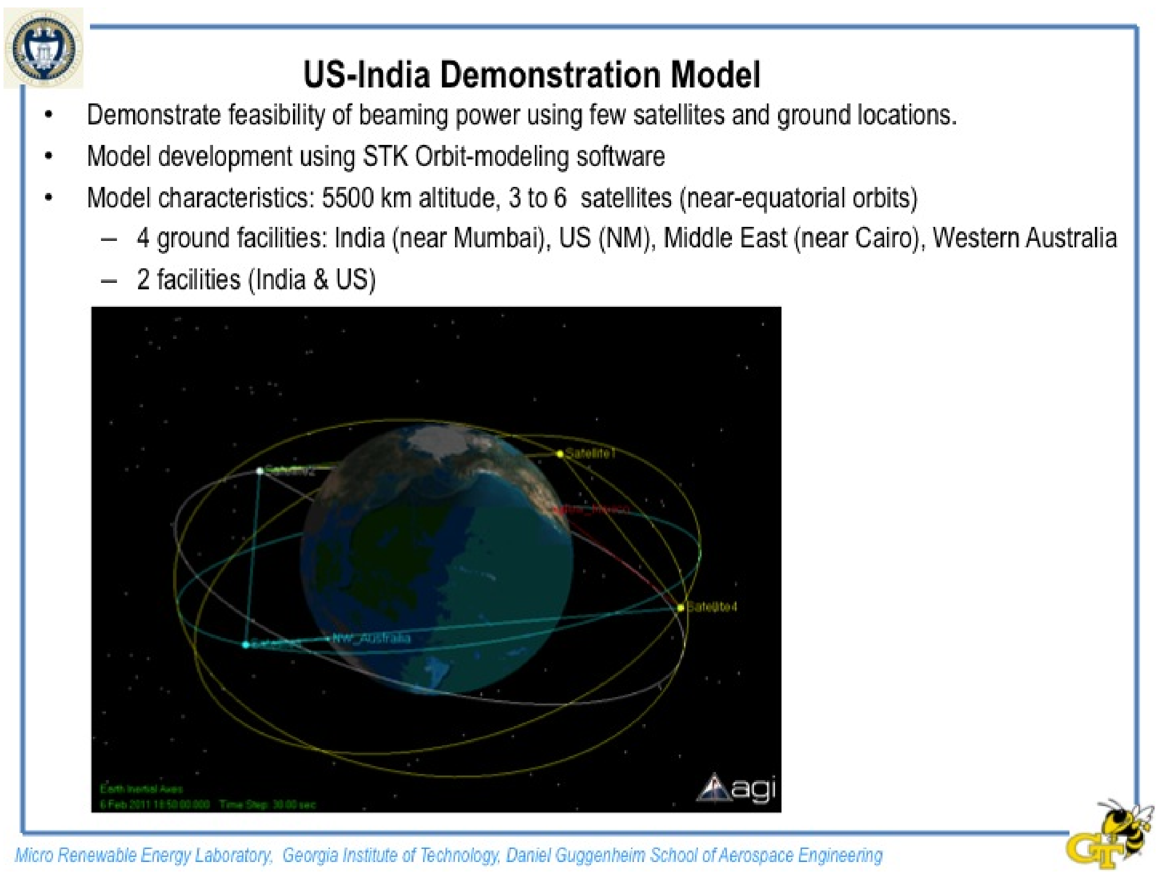

Figure 15.1: US-India Demonstration Model: Way to Start SPG Phase 1

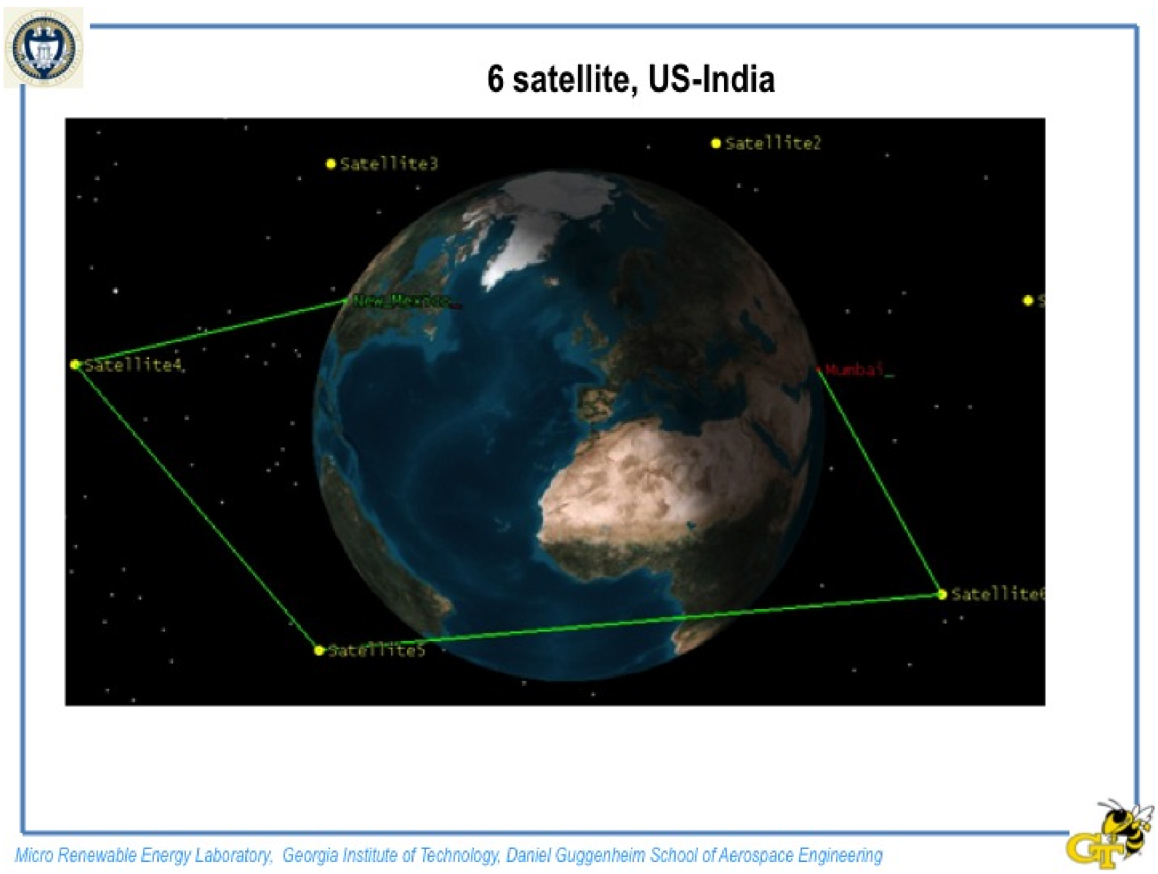

Figure 15.2: 6-satellite, US-India

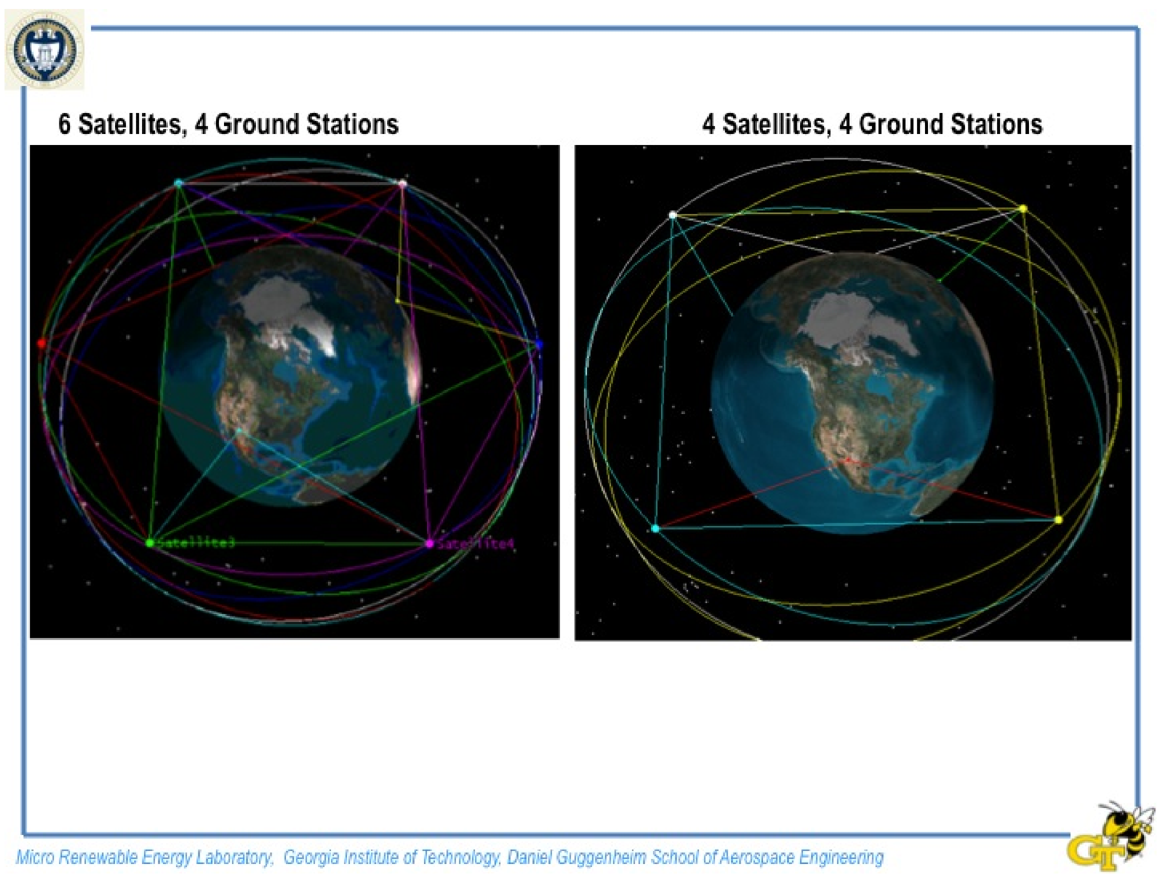

Figure 15.3: Effect of Including More Countries

Chapter 16

Knowledge Needs

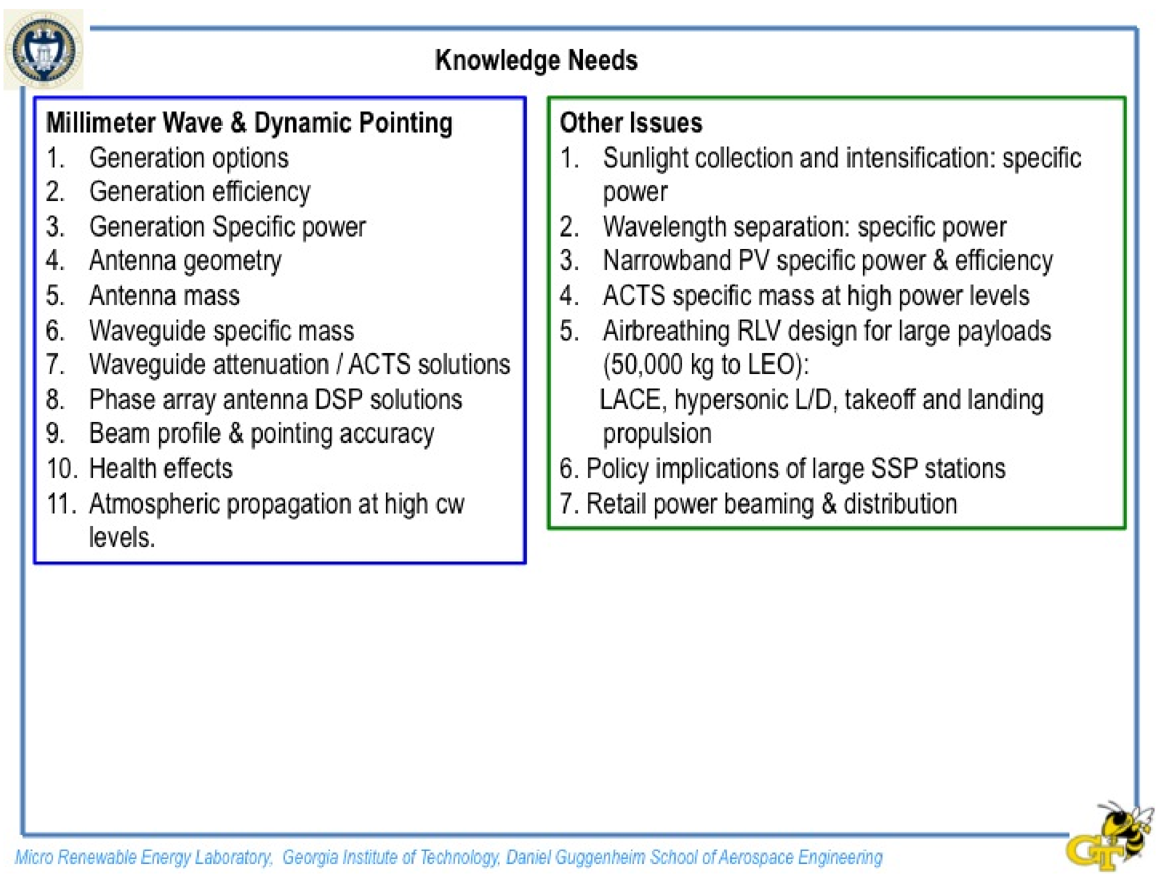

Figure 16.1: Knowledge Needs

Chapter 17

Discussion and Summary

17.1 Why go to the complexity of a Space Power Grid?

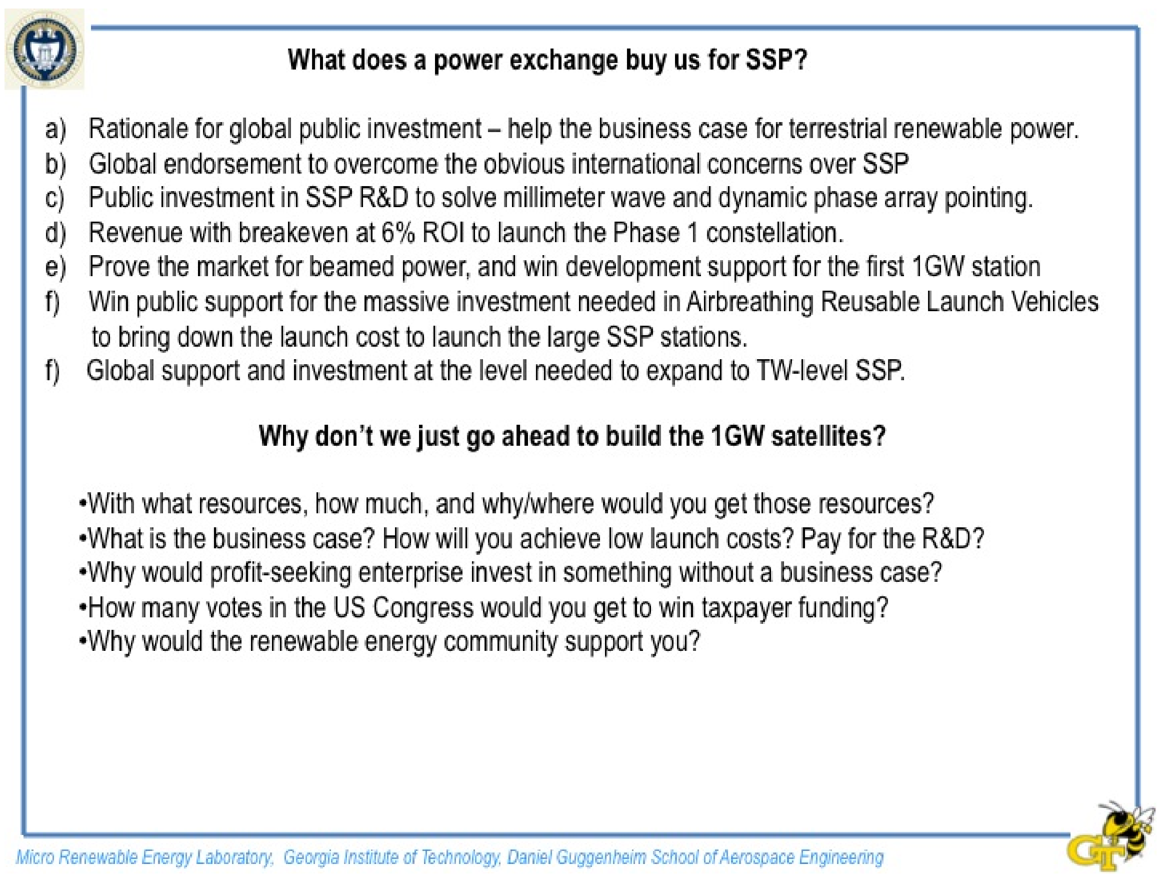

Figure 17.1: What does a power exchange buy us for SSP?

17.2 Why wait so long before launching full-scale SSP?

Note that there are many practical constraints that will delay the first launch of a 1GW satellite. For instance, the launch cost has to come down, which will not happen until airbreathing RLVs look

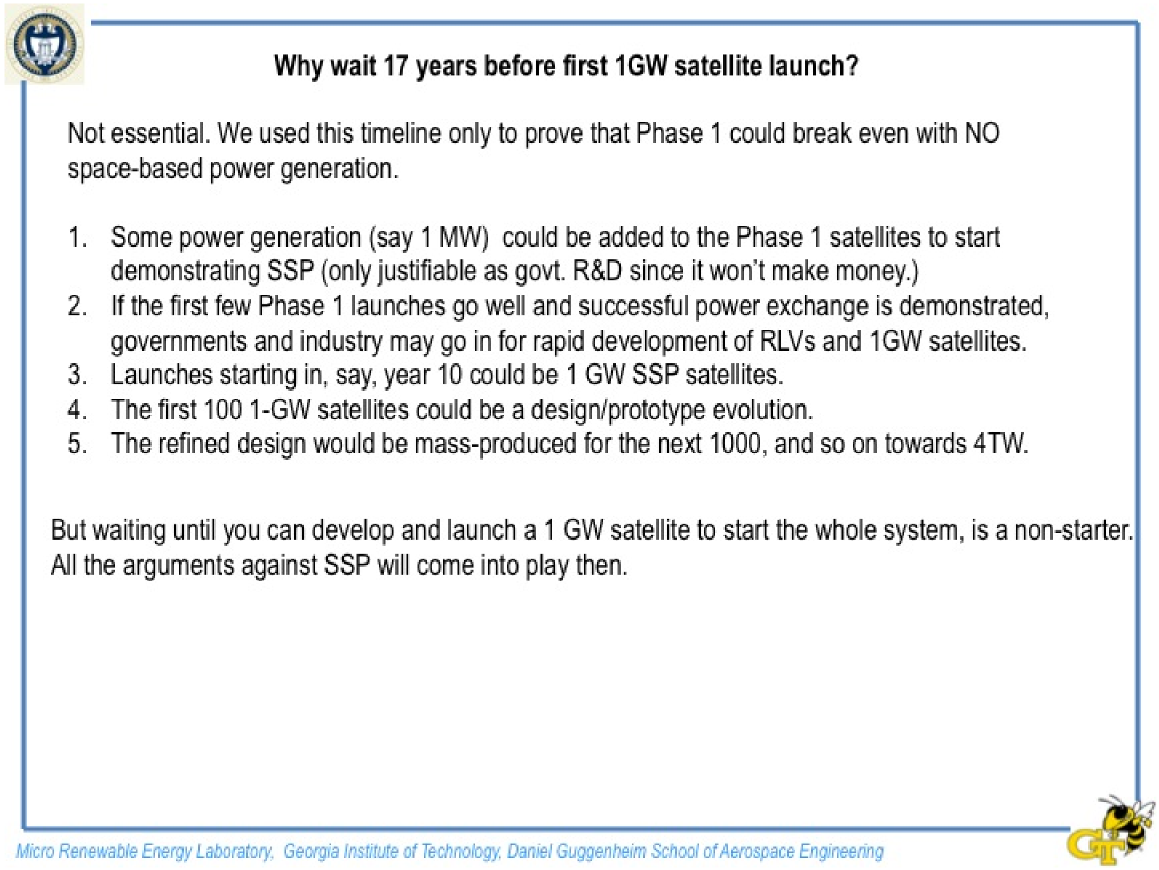

Figure 17.2: Why wait 17 years before first 1GW satellite launch?

pretty certain to work routinely for such large payloads. The experience of Space Shuttle launch cost will certainly be still very much on the mind of anyone who wants to promise that. The revenue stream from Phase 1 will almost certainly be an essential component of the confidence-building towards moving ahead with Phase 2.

17.3 Phase 2 and Phase 3 answers

Why have a separate Phase 2 and Phase 3? The answer is somewhat complex, and tradeoffs should be done on different ways of doing this. Our reasoning is that the collector (Phase 3) should be in high orbit, where the sun is visible all the time, not shadowed by Earth. On the other hand the converter/beamer should be in as low an orbit as possible, for two reasons. First, that is where the vast majority of the mass in orbit will be stationed, so this helps minimize launch cost. Also, minimizing the beaming distance minimizes the antena size and hence the mass. So why not call the combination Phase 2? Because we may not launch the high-orbit craft until we get the first converter/beamers working partly, that is, with only the sunlight that their own receivers can collect. This will only be a small fraction of what they will receive when the concentrators in high orbit are working, but we can prove the point about conversion with only the Phase 2 craft. In addition, the technology of pointing from the high orbit Phase 3 collectors to the low-orbit Phase 2 receivers, is a challenge that must be overcome.

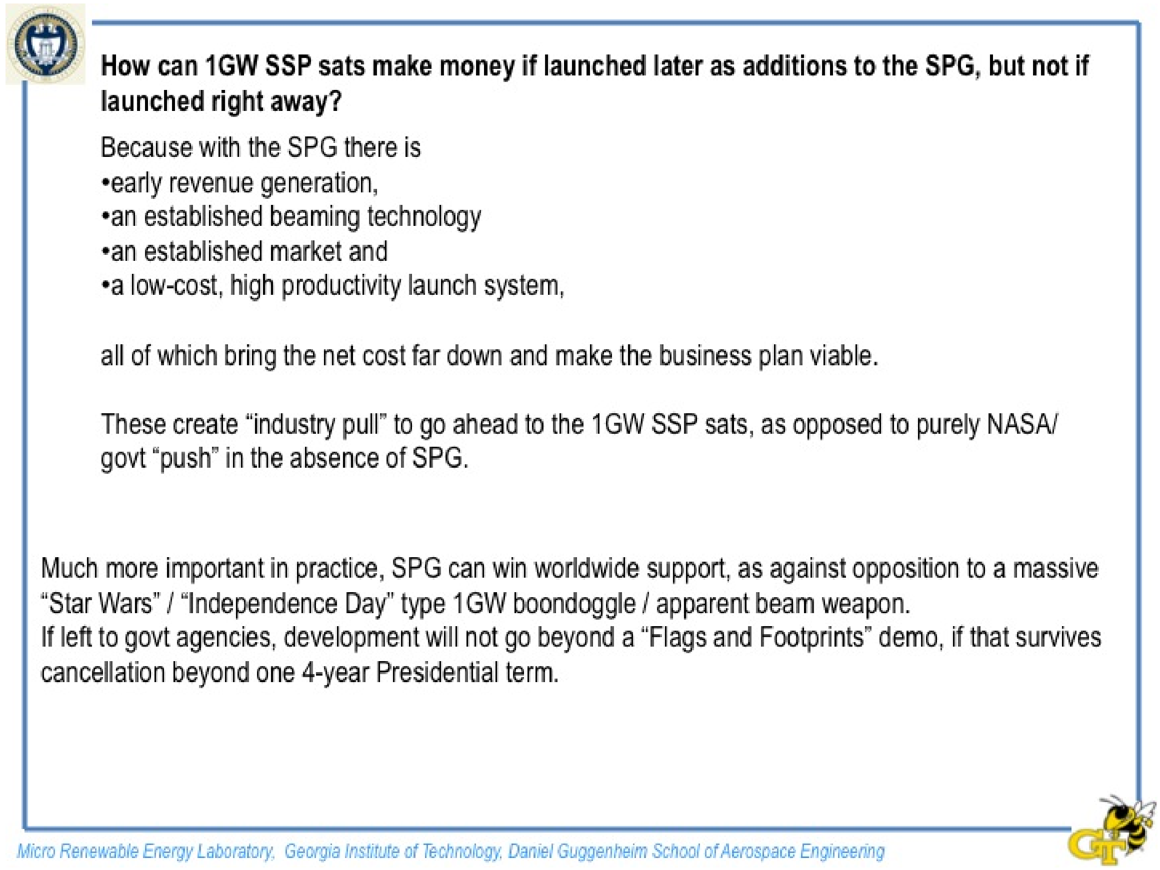

Figure 17.3: SPG effect on viability

17.4 Issues and Superstitions

A few points can be mentioned without taking up much space in this paper, to address the primary superstitions that we have encountered in hearing the SPG system discussed among SSP experts.

1. Millimeter wave generation has been revolutionized by the automobile radar and Homeland Security market demands. While the frequency ranges used for short-range purposes is below 100GHz, components already use 220GHz generation. Mass production is possible, but specific power and efficiency values are not yet where we need them. We believe that there are several interesting alternatives here.

2. Rain above a threshold level kills millimeter wave power beaming. In fact it also kills low-GHz beaming as seen from the loss of satellite TV signals during American thunderstorms and Indian monsoons. However, there are wide swaths of the USA, for instance, where the probability of precipitation above this level is down to less than 5 or 10 hours a year; and this is true of most of the ideal locations for terrestrial renewable power plants (dry, high altitude, remote from population centers). With dynamic beaming, transient patches of rain can be avoided by selecting stations outside the rain area and using the terrestrial grid. This will however not work with GEO-based systems because the stations are so large and so few.

3. The atmospheric absorption data for millimeter waves comes from astronomical observation or radar imaging interests, where low signal level does not affect the air or its moisture content.

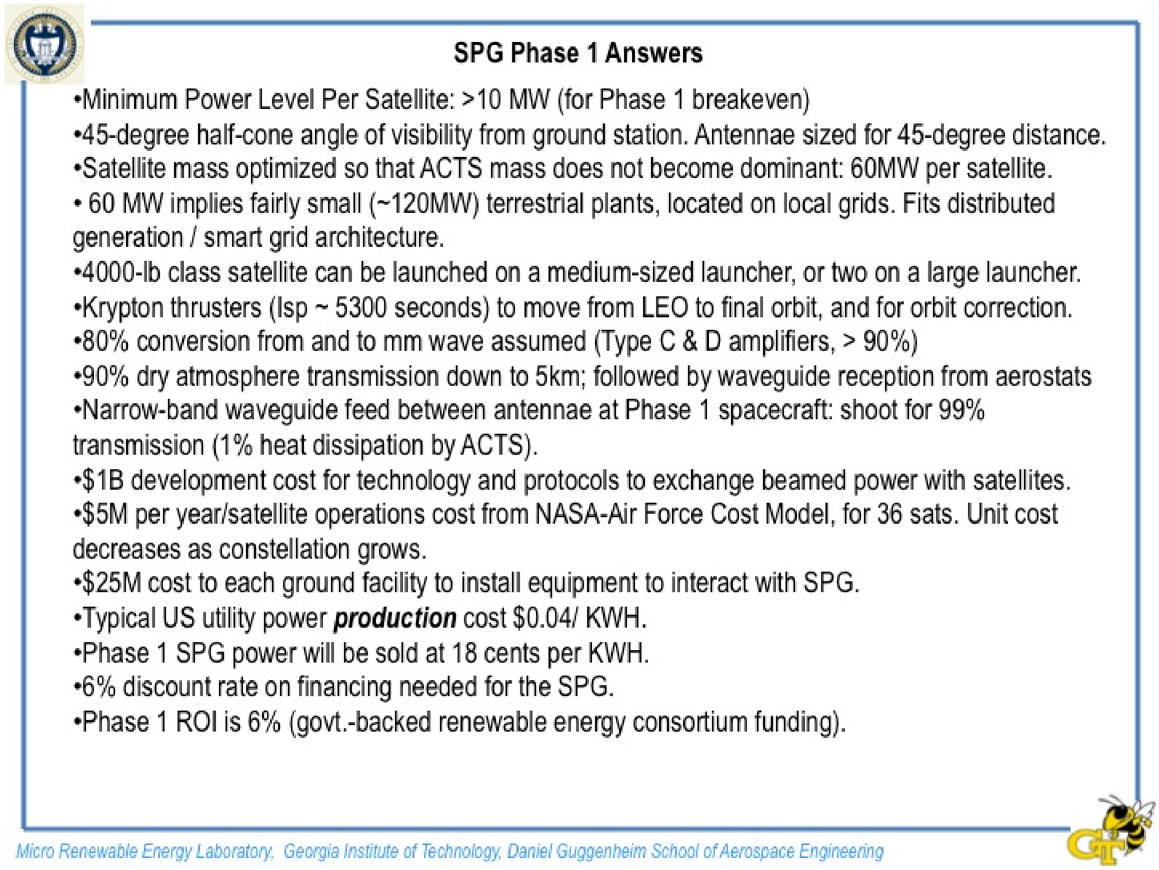

Figure 17.4: SPG Phase 1 answers

When the interest is in continuous wattage (cw) beaming for several minutes, burning through or saturating specific energy levels of water vapor and oxygen of the atmosphere and creating a low-loss path is a much more interesting option. Winds are an advantage in this scenario because they allow the burn-through beam to be placed outside the main beam.

4. Phase-array antennae allow swift and accurate pointing of beams without physical movement of the hardware. The technology exists (whether published or not) since computation speeds reached desired levels in the 1980s for the aircraft-based Boost Phase Intercept problem of strategic missile defense. The problem of beaming to and from ground stations and satellites in well-defined orbits, is trivial compared to the BPI problem, but there may be substantial power requirements or losses in phase array pointing when applied to power beaming. For this reason the ground antenna for 220GHz may even use cam-driven mechanisms with servo motors for small corrections, since they are so much smaller than the versions imagined for the microwave/GEO options, and the motion is so predictable.

5. The SPG architecture is completely compatible with a move to lasers instead of millimeter waves. Policy changes are needed to allow lasers, and atmospheric propagation of infrared lasers remains to be addressed.

6. The Phase 1 SPG satellites are relays. They do not convert from or to millimeter waves, and as such do not impose a large loss in the system.

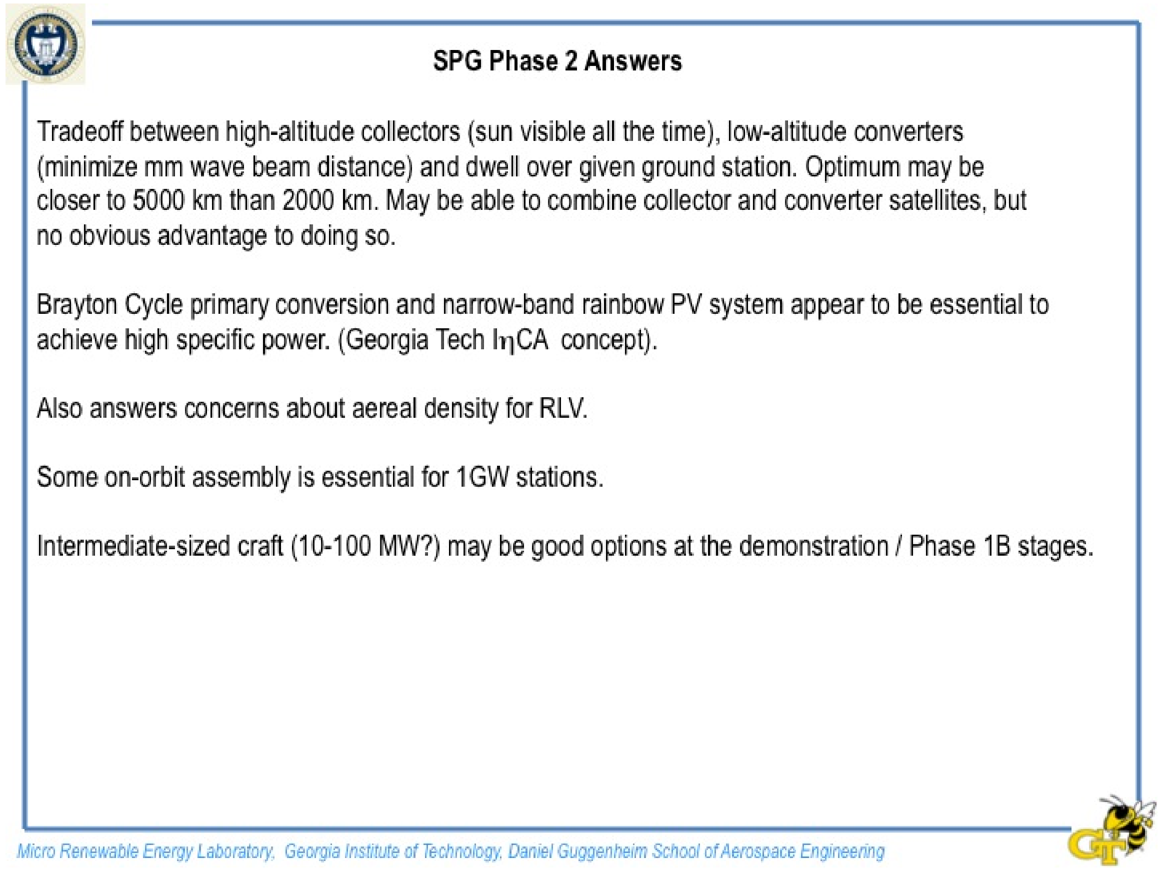

Figure 17.5: SPG Phase 2-3 Answers

7. Transient and intermittent beaming (irrelevant beyond the startup stage of SPG) are not fundamental obstacles to utility-scale electric power transmission in the 21st century, though they were considered killers in the electric grids of the 1960s. Wind power plants routinely face the reality that wind power is proportional to the cube of wind speed, so that a doubling from 6 to 12 mph implies an 8-fold increase in power. The vast majority of wind power in most locations actually comes from transient windows of strong wind. Similarly, hybrid automobile technology assumes the ability to deal with sharp variations in power demand.

8. There are numerous choices for the SPG orbits. As pointed out in [?], the Molniya Orbits used by the USSR to achieve long visible times above high latitudes, may offer some options, but at the cost of a varying and perhaps large beaming distance. Ref. [?] considers a Molniya-type orbit for a space solar power satellite that provides long dwell time over certain Indian stations. We proposed to start SPG with a combination of near-equatorial and sun-synchronous orbits. Continuous beaming for 24 hours is not essential. The afternoon sun scenario shown in Figure 4 [?] uses just a few satellites following closely-spaced tracks in tandem, allowing solar plants to sell their peak output to others that are in the deepest part of their supply wells on the other side of the Earth. The number of satellites needed to achieve continuous beaming is much lower at the high latitudes (where GEO is too low on the horizon), so that SPG is an ideal system to reach those who have the fewest other alternatives to fossil-based power.

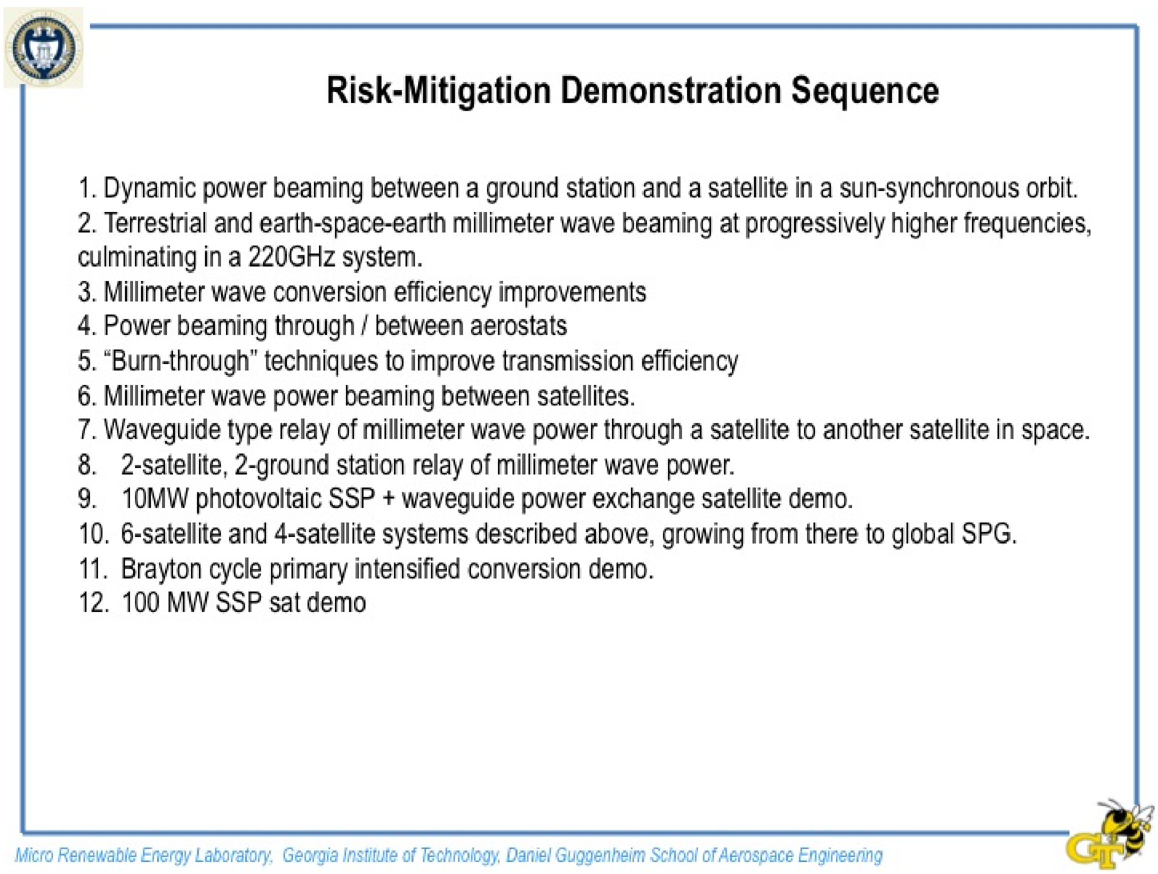

Figure 17.6: Risk-Mitigation Demonstration Sequence

Chapter 18

Conclusions

1. Renewed interest in SSP must be viewed with healthy skepticism, but careful analysis of opportunities.
2. The scale of the SSP system needed to reach 4TWe of space-based power generation poses immense difficulties requiring new approaches.
3. To make SSP viable, improvements are needed in specific power, beaming efficiency, and launch cost.
4. Millimeter wave beaming and orbits at 2000 km in a Space Power Grid architecture, can provide 2 or more orders-of-magnitude improvement in viability.
5. A US-India power exchange provides a unique opportunity to start the Space Power Grid towards full SSP.
6. With 4 or more nations participating, it is possible to set up nearly continuous power exchange with 4 to 6 satellites in 5500 km orbits.
7. Concepts such as the afternoon sun scenario can greatly reduce the minimum number of satellites needed to provide the required service to terrestrial solar power plants
8. With only the US and India participating, a constellation of 6 satellites suffices to demonstrate a continuous power exchange.
9. Primary gas turbine power generation may close the specific power viability gap, when used with SPG.

Chapter 19

Summary

1. A viable price target may be well above the 10 cents per KWhe, uninterrupted electric power that we take for granted.
2. A real-time power exchange through a Space Power Grid (SPG) will help terrestrial power plants become viable at ideal but remote sites, smooth supply fluctuations, and reach high-valued markets.
3. With infrastructure and market established, 2nd-gen SPG will add and expand SSP beyond 4TW
4. SPG architecture is viable at a healthy ROI, modest development funding, and realistic launch costs.
5. The launch cost risk in GEO-based SSP architectures is exchanged for the research and development risk of efficient millimeter wave technology in the next decade.
6. A US-India space-based power exchange demonstration is a first step towards SPG and SSP.
7. 2 options for near-24-hour power exchange are (a)4 near-equatorial satellites at 5500km, with ground stations in USA, India, Australia and Egypt. and (b)6 satellites in 5500 km orbits, with ground stations only in the US and India.
8. A risk reduction roadmap and sequence of demonstrations is laid out