
AC 2011-2662: OPPORTUNITIES IN POWER BEAMING FOR MICRO RENEWABLE ENERGY

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Abstract

Developing advanced concepts that go well beyond today's practices, is a useful way for students to learn about innovation across discipline barriers. In this paper, the experience of aerospace engineering students is described as they develop a concept that cuts across aerospace technology, several areas of electrical and civil engineering and socio-economic issues. The subject is how to develop a power transmission and distribution architecture based on wireless beaming complementing and reaching beyond the wired power grid. The processes of defining requirements and selecting parameters in this wide-open area, are set out. The education here is not through course lectures but through cross-disciplinary learning on projects. Student experience over the years is reviewed, starting from initial concept exploration to present refinement. It is argued that millimeter wave beaming is essential, and that viable end-to-end efficiency can be achieved, to succeed in the marketplace. Student participants in this concept development over the years, have been at levels ranging from freshmen to PhD students. Their ways of exploration, knowledge extraction, validation and innovation are discussed in the paper.

Introduction

A primary feature of engineering education related to renewable energy is that the constraints and innovations come from a very broad range of disciplines within and outside science and engineering. This is perhaps true of any discipline as it is forming, which appears to be the case with renewable energy. Accordingly, the imaginative reader is requested to consider that there may be no sections on "the pedagogy" or "the course" or "the student happiness survey proving the greatness of the teacher" in this paper. The paper is about how learners from traditional disciplines deal with grand challenges and opportunities to innovate towards far-off goals, learning what they must learn, wherever that knowledge can be found, and surviving the continuous onslaught of superstitions without losing sight of reality.

The paper is organized as follows. The genesis of the project is traced from a course assignment in an International Policy class. The daunting list of concepts to be mastered if one were to become a true expert in this field, is used to explore alternatives, and define the idea of concept resilience as it applies to students and faculty developing advanced concepts. The evolution of the concept is then traced as students and faculty learned from initial concept exploration, to finding out the needs and constraints that successively refined or expanded the search for solutions. This leads to the argument for millimeter wave beaming, and hence generation and conversion technologies that are at the leading edge of technological endeavor. Shifting gears, we then look at the market opportunities and constraints of retail power beaming and large-scale solar power exchange. The appropriate organization of learning resources is then discussed in the context of the power beaming example.

Why study power beaming

The concept that drives the learning described in this paper is of electric power delivery to customer sites through narrow beams of electromagnetic waves, rather than through the wired power grid. The motivation for revisiting and developing the concept is that this is an essential component in exchanging power through the atmosphere and Space. Such exchanges at the largest scales enable power delivery in and from Space [1,2,3,4]. In the nearer term they also enable solar or wind power plants to be built at remote sites, while reducing the amount of auxiliary generation capacity required to meet the “baseload supplier” criterion [5]. Solar plants could exchange power between the sunlit and night hemispheres of the planet (or of the Moon), greatly reducing the amount of storage needed at each plant. On a medium scale, power delivery to islands and mountainous sites could be accomplished using towers, mountain ridges or lighter-than-air platforms floating in the high atmosphere. At a retail scale, power beaming allows delivery to rural homes and villages, and allows micro power generation systems to become viable. At a very small scale, power beaming provides essential services to people who have no other access to electric power other than portable batteries or fossil-powered generators. Thus, power beaming has massive significance in advancing the prospects for renewable power generation, and for rural electrification.

How does one go about developing such an idea, and how will students learn the basic issues, concepts, theory and skills required to develop the concept? This is the subject of this paper.

Genesis of the project

The idea that power could be delivered over a distance in a narrow beam was shown by Tesla [6], before the wired power grid infrastructure became common all over the world, and utility-scale power plants became the norm. The wired grid in modern industrial nations offers values of transmission efficiency that no beamed power system can match. Our interest in power beaming came from an assignment in an International Security Studies class in 2004, where students were asked to come up with their arguments on how the USA should formulate public policy to deal with the Kyoto Protocol to the United Nations Framework Convention on Climate Change. A possible aerospace engineering approach might be to create a technical mechanism to deal with the uncertainty in the rate of change of global temperature. Thus, we mused that if the Earth were indeed warming, heat should be radiated out to Space, and if it were cooling, heat should be collected and beamed in. A good reason was needed to beam power out, and this led to the idea of a power exchange between day and night hemispheres, thus benefiting the development of solar power plants. This led us in turn to investigate the area of Space Solar Power. This unlimited, steady source of clean energy has remained a dream because the existing architectures for realizing it present utterly insurmountable costs to first power delivery. The idea of a power exchange led to the notion of using a constellation of satellites as a Space Power Grid, providing an evolutionary approach to generate revenue, establish the market infrastructure, and then proceed to capture and bring solar power from Space.

Learning issue #1: concept resilience

To understand the issues in power beaming, enough to consider developing viable solutions, the learner must surmount a daunting array of obstacles. Some of the issues and areas are summarized in Table 1. The usual conclusion on seeing this list would be that it would require a cross-disciplinary team of specialists, which is an expensive proposition, to be deferred until a major project is funded. The corollary to this is that no such project can be contemplated until concept development has shown that there is a feasible path in the near term, and only the detailed design remains to be developed, with all required technological solutions well established and available.

Table 1: Issues and discipline areas involved in power beaming

Issue	Disciplines
History of space solar power architectures	Orbital mechanics
Geosynchronous Earth Orbit	Propulsion and mission design
Low earth orbit; sun-synchronous orbits	Space mission cost modeling
Rocket equation	Robotics, telepresence
Launch Cost	Quantum mechanics, chemistry,
Orbital construction	Molecular interaction with electromagnetic radiation
Atmospheric propagation	Diffraction
Antenna sizing and efficiency	Mie and Rayleigh scattering and geometric optics
Phase array antenna	Electromagnetics
Millimeter wave generation	Electrical engineering
Thermal management in space	Ohmic losses
Material properties for antennae	Spillover losses
Waveguides	Wired power grid losses
End to End Efficiency	Thermodynamic cycle efficiency

In a university setting, the informal way to break out of this circle and explore an advanced concept is to send interested students to talk to their instructors in classes in the appropriate disciplines. The drawback to this is that unless the student has the perspective and the “concept resilience” (faith backed by depth of knowledge) to pick the right ideas from what such an instructor would explain, the student usually comes back with the sage advice that “s(he) said it won’t work”. A simple example might be illustrative. It came from sending students to ask the seemingly straightforward question: “What value of efficiency should I use as being possible, for conversion between AC line power and beamed microwave power?” To the unwary aerospace engineer, the answer to this seems to be what one might describe as “antenna efficiency”. However, reality is far more complicated.

It quickly becomes evident that beaming large amounts of power is not a popular subject in modern textbooks. Antenna design issues generally drive quickly towards the application of receiving signals with good signal to noise ratio, optimized on either the broad-band high-sensitivity astronomical radio telescope application, or on the needs of miniaturized devices for personal communication. One example of the difficulty is that most electrical engineers (and this

includes many faculty) “know” that antenna efficiency is around 0.55, but few can give a coherent answer as to why this is so low, and whether the answer would be different if the efficiency of conversion were critical. Obviously a transmission system that loses 45 percent at each end is not an attractive option. Brown [7] reported conversion efficiencies above 80 percent in exploratory work in the 1970s, so a better answer than “0.55” must be possible. This is the “concept resilience” aspect. The professor who embarks on such a project must have a good deal of such resilience, tempered by the constant fear of leading students down a path to ridicule. Obvious learning resources for such an endeavor are textbooks used in electrical engineering, and their teachers. One should take the intellectually correct route of re-deriving the relevant equations from first principles, and independently develop the answer. In practice, this means specializing for a few years in this field before one has enough credibility to believe one’s own derivation and its practical relevance to modern engineering. Thus this derivation step will realistically come not at the beginning, but at a much later stage of the project. The above experience suggests that alternatives must be explored. Thus the primary learning resources become technical papers generated by people interested in power beaming. This in turn faces the obstacle of lack of fundamental knowledge and skills.

Learning issue #2: initial concept exploration

One anecdotal reference point for power beaming comes in fact from a signal transmission example. An undergraduate student searching for an example of high power beaming from an antenna in another context in 2002, found this example at the instructor’s urging, to the effect that “Look, if NASA were engaged in listening for aliens, they must surely have not been able to resist the temptation to broadcast that fact to the aliens”. At the inauguration of the Arecibo astronomical radio telescope in Puerto Rico, NASA used the 1-kilometer diameter “dish” to send a sustained “message” out to the universe for 3 minutes at a very high power level, as part of the Search for Extraterrestrial Intelligence (SETI) program. Presumably this was pointed in the direction of some interesting galaxies. No alien intelligence is expected to receive the signal, nor we to receive their response, for several thousand years. However, since this exercise did not melt the power connections to the antenna, it may be taken as evidence that electric power can be coupled with some reasonable efficiency to a transmitting antenna in the radio frequency regime.

The first concept explorations were performed by the PhD candidate doing his assignment for the International Policy course. The experience was a happy one in that we found the idea of power exchange through Space to be worth exploring, but the student’s experience in presenting this concept to the class was by no means a happy one, though it is typical of what concept developers encounter. The class included several other PhD and MS candidates from across the campus, being a course to give technical PhD candidates some exposure to the processes of policy-making in order to equip them to work in the International Security area. Thus there were several self-anointed “experts” who gave their expert opinion that such beaming was impossible. Each was ignorant of those aspects outside, and most aspects inside, their declared “discipline”, and was quite immune to the notion that careful reading of the literature might be a valid way to alleviate that ignorance. The presenter was not prepared to deal with the resulting hailstorm of negativity – another demonstration of the importance of concept resilience. The PhD candidate had the resilience in abundance – he continued to research this topic, which was only peripherally related to his dissertation research.

Learning issue #3: identifying the required and achievable bounds on efficiency

A student team consisting of the same PhD candidate and two undergraduates in 2006 participated in developing a peer-reviewed paper to the Space Science Technology International Forum, where the audience includes people with a substantially broader and deeper understanding of advanced technology [8]. This paper set out the range of efficiencies needed and potentially achievable from a range of technologies, to bring about a Space Power Grid, proceeding eventually to full-scale space solar power capture and delivery. The basic conclusion of this paper was that in the near term (5 to 10 years) the Space Power Grid beam power system could achieve overall efficiencies roughly half that possible using the wired power grid, but that in the longer term, the overall efficiency would exceed that of the present wired grid. The key difference was seen to be in the possibility to bring about direct conversion from broadband solar power to narrowband beamed power through some version of an optical antenna, entirely avoiding the step of converting to direct current. Potentially, this could take the conversion efficiency into the 80 to 90 percent range when used in space with intensified sunlight and given the low sink temperature of Space. It could also greatly reduce the mass per unit power of the conversion and beaming system, which would be a crucial enabler for large earth-launched space systems. Before dismissing such possibilities, the interested reader should review reference [9] which describes conversion of a simulated broadband solar spectrum to beamed infrared laser with over 38 percent efficiency, using a solid state laser. Reference [10] describing initial efforts and defining the technical challenges of direct conversion is also worth considering.

It is worth noting here that Space Solar Power is an ambitious enterprise. To match today's terrestrial electrical power generation systems, the total generation needed is in the range of 4 Terawatts (4E+9 kilowatts) of electric power delivery. Given that 1 square meter of sunlight capture area in space at the orbit of Earth around the Sun captures 1.38 kilowatts of sunlight, which may translate at the most optimistic and futuristic projection, to about 1kilowatt electric delivered, this means a capture area of 4,000 square kilometers.

Learning issue #4: minimum power transaction level for system breakeven

The next step was to explore under what conditions, a constellation of near-earth satellites might be economically viable, the enterprise breaking even (zero net present value) in 17 years (a usual criterion in the space satellite industry) at a rate of Return on Investment that is defensible but as low as possible. This step required a venture into space economics and rudimentary cost estimation, in addition to relating the mass of each satellite to the choices of technical parameters. Reference [11] presented this initial system description. A description of the architecture was constructed using a spreadsheet, relating basic choices wherever possible to the final system Net Present Value.

One of the questions to be answered in system sizing was the amount of power to be beamed per satellite, to make the system viable. Evidently, given the large fixed costs of space launch and satellite management, and that the revenue from beaming depends on the amount of power received, there is a minimum power level that each satellite must handle, for the system to break even. This turned out to be very high, on the order of 100 MW per satellite. Even if the transmission through the satellite were 99 percent perfect, the 1 percent dissipation means 1 MW

of heat dissipated at the satellite. The thermal management system of the satellite is thus a critical consideration. A survey showed that this capacity is 2 to 3 orders of magnitude above the level of present day systems, again demanding quite a bit of “concept resilience”. However, the students found defensible estimates for heat engines suitable for aerospace applications, to handle that much heat and produce useful power from this as well. This exercise required a venture into jet engines, closed cycle heat exchangers and radiative heat transfer [12].

Learning issue #5: argument for millimeter wave beaming

Another product of the spreadsheet exercise was the clear result that space-based power exchange was simply not viable unless the frequency used was into the near-millimeter wave regime (100 to 300 GHz) rather than the 2 to 5 GHz considered for most Space Solar Power architectures. This is because of the beam divergence associated with transmission of electromagnetic waves over large distances. The antenna sizes needed to send and capture the power would be prohibitively large otherwise, and drive the launch cost beyond all reason. The shift to millimeter waves is not a simplification in the near term, because not much is available in the open literature on the scaling of such conversion to high power levels. Therefore it is hard to extrapolate to the efficiencies possible with such frequencies. The concept resilience needed here came from looking at papers published in the 1980s about millimeter wave systems being developed under the Strategic Defense Initiative. Much more recently, the swift advances in millimeter wave technology occurring in the telecommunications field [13], and in applications related to naval radar, provide much more technical information.

However, with beaming at 220 GHz, where there is a reasonable clear atmospheric propagation window, the spreadsheet calculation showed that a system with roughly 100 satellites and 200 ground stations would provide global coverage and break even inside 17 years with minimal taxpayer grants except at the initial 6-year Research and Development stage from project approval to first satellite launch. The choice of orbits also provides interesting tradeoffs and options. Here, an undergraduate student taking the Space System Design course generated orbit calculations using an educational version of professional software. The animations generated from this program helped visualize how the beams would be established as each satellite came within a 45-degree azimuthal cone over each ground station, and how the beams would then be sent across and down to receivers.

Learning issue #6: finding sources and strengthening cost estimation

The cost estimation leading up to this stage used thumb rule benchmarks, mainly extrapolated and interpolated from those of the Global Positioning System replacement satellites, and from launch cost data of commercial launchers were appropriate. In the next iteration, the costs were refined using the NASA/USAF NASSCOM cost models from the internet (the names of these models came from students taking System Design courses in other problem areas). These are conservative estimates that relate system costs to system dry mass, complexity and production line quantity. So again, the students involved in the project had to learn about cost estimation strategies, and to think about opportunities for refinement of these estimates.

Learning issue #7: orbits and propagation loss refinement

A further refinement of the orbital system was performed by a student team in 2008. Different combinations of sun-synchronous orbits were explored, relating the orbit height and period to the time of visibility (and hence of power grid usage) of each satellite at given ground stations, for various latitudes. This led to the “afternoon sun scenario” where orbits were timed to provide continuous coverage over selected ground stations for a few hours in the mid-afternoon, when these stations were likely to have excess solar power to sell, and late night, when they were most likely to require replenishment of their storage. This student team also explored the issue of atmospheric absorption in the millimeter wave regime [14], showing that the fears about frequent outages due to weather are overstated and such problems can be circumvented.

Learning issue #8: course development and iterative refinement of knowledge

Starting in 2006, preparations were made to set up courses and a laboratory dealing with the issues and testbed development of micro renewable energy systems. In a second iteration of this course, a graduate component was set up, where students would venture into advanced concepts. Papers on retail power beaming were developed by the graduate students in this course. The first paper studied policy issues related to retail power beaming, while a second dealt with architecture options and costs. The third paper in this series has shown that the optimal architecture will probably be one where stratospheric buoyant platforms will serve to capture and distribute power coming from terrestrial plants either directly or via space satellites. This option reduces the receiving antenna size needed at the ground to dimensions suitable for portable or single-family systems.

Learning issue #8: retail power beaming

With the above refinements, the Space Power Grid portion of the system was reasonably well established. The next step was to look at the retail end of the architecture, and this was done in the above-mentioned course. It attracted the attention of students with competence in electrical engineering and control theory, to take up as a course project, and this led in turn to publications. Retail power beaming is viable, despite the obviously lower efficiency compared to wired-grid power supply, in a number of situations. The most obvious is to reach communities that are not served by the wired power grid, or who depend on locally-generated power. Islands and mountainous regions are obvious candidates, as are hundreds of thousands of villages in the developing world. On a much smaller scale, beamed power systems can reach first responders after natural disasters, with portable receivers deployed. In the longer term, photovoltaic panels could be integrated with millimeter wave receivers, and enable micro renewable power generators to become viable, reducing the cost of storage.

The argument that the cost of beamed power cannot compete with that of grid-supplied utility power, is easily defeated. Where the grid does not reach, the cost of the first few watts and watt-hours of power to small users, is 2 to 3 orders of magnitude above the advertised marginal cost of grid-supplied power, since these users are forced to depend on batteries or fossil-powered generators for which fuel must be delivered from elsewhere at high cost.

Learning issue #9: formalizing resources for knowledge establishment and transfer

The final aspect of this paper is to consider how to formalize the knowledge captured in such concept development, and present it in the form of resources to permit future development of this or other concepts. The EXTROVERT cross-disciplinary learning resource shown in Figure X is in its third year of development, and includes a component directed towards developing advanced concepts. The power beaming concept description is being refined as one of the examples there. The structure is as follows. A Concept Essay (CE) on power beaming brings together the various issues and opportunities in a succinct presentation, aimed at a 5000-word size with minimal use of derivations. It is linked to other CEs, on each of the various concepts. In turn, these CEs present succinct introductions so that the user can apply sizing calculations and relate them to basic, college-level notes and e-books. The best CEs are by no means limited to those that we develop. On the contrary, they are most likely to be found in resources provided by experts in the specific fields.

Returning to the problem of antenna technology cited as an example at the beginning of this paper, we point to an excellent CE from the website of the ATI corporation [¹⁵]. At the other extreme of detail, the e-book [¹⁶] provides in-depth, first-principles treatment and plenty of worked examples. These are complementary resources, and one suggested means of learning with these is to go back and forth between these to continuously refine one's understanding. Certainly, in between these, and linking off the myriad concepts in each, are many other excellent resources.

The role of the EXTROVERT site is only to present the seed of the learning. This realization came in the early 2000s as we were considering how to develop such a resource, where each learner would start in their comfort zone and then be provided with guided access to resources in other disciplines. Search engine technology, and users' adaptation to their capabilities, zoomed far ahead of any such guided access networks. What has remained elusive is at the two extremes: in-depth content at one extreme, and excellent, succinct perspectives from experienced experts. The e-book and the CE mentioned above exemplify such resources.

Summary: opportunities in power beaming

As seen above, developing the concept of power beaming opens opportunities in numerous fields, quite apart from the diverse applications of power beaming. This is a central feature of advanced concept development exercises: often the most important near-term products are the various technological opportunities that open up along the way. A few are listed here for the particular example of interest.

As seen from the discussion above, students at all levels and from several technical backgrounds have opportunities to participate, and have participated. The initial team included an Aerospace PhD candidate and another AE graduate student with an Electrical Engineering undergraduate background. The other team members were an AE senior and an AE junior, the latter going on to win one of the few student fellowships to be awarded by the NASA Institute of Advanced Concepts. Subsequent teams have included students taking the Micro Renewable Energy

graduate course, as well as undergraduates taking research Special Problems for credit. The present team includes a freshman, who has contributed in several aspects, as well as a senior.

Table 2: Opportunities in Power Beaming

Technology opportunity	Learning opportunities
Direct solar power conversion to narrow band	Optics, signal processing, nonlinear media, electromagnetic, nanotechnology
High-intensity antenna	Materials, electromagnetics.
Power storage for beamed systems	Fuel cell and battery technologies
Power beaming demonstration experiments	Coupler designs
Waveguides for 100GHz to 300GHz regime	Electromagnetics, materials, optics
Atmospheric propagation of millimeter waves	Chemistry, quantum mechanics, thermodynamics, hydrostatics, Mie scattering
Health effects of millimeter waves	Radiation medicine, protection, cell science
Business models for retail beamed power	Rural economics in various societies
Integration of PV modules with power antenna	Semiconductors, and antenna design
Adaptive beam pointing to satellites	Orbital mechanics, adaptive controls
Stratospheric antenna and relay platforms	Aerostat, antenna and waveguide integration
Thermal management for spacecraft and stratospheric platforms	Convective and radiative heat transfer, heat engines.
Furlable antennae for portable use	Materials, electromagnetics

Students involved in concept development use several ways of learning. One obvious source of cross-disciplinary knowledge is to talk to friends in other schools. This was formalized with excellent results in Fall 2010, when the students prepared a poster presentation for an undergraduate research exhibition. Beyond this, students discuss particular concepts with professors in other classes, and with graduate students. All students of course use the internet, starting perhaps with cross-disciplinary sites such as Wikipedia, but they also venture to the “hardware” library for the tougher concepts. The process of training each other to use professional codes appears to be quite established, with team efforts quickly producing good results. The use of derivations to arrive at scaling relationships and explore other implications, is as yet lagging seriously. This is one area where the EXTROVERT resources will push students to adopt serious technical analysis skills.

Conclusions

In this paper, the example of power beaming is used to convey the process by which student teams guided by a faculty member go about exploring advanced concepts in multi-year endeavors. Power beaming is important to consider, because it enables breakthroughs in renewable power architectures, both on earth and in Space. The use of a constellation of space satellites as a dynamic power exchange grid, reduces the need for local storage and improves the business case of terrestrial solar and other renewable power plants. Beamed power can reach islands, remote communities, and hundreds of millions of people in less developed nations, giving them access to many essential services and to global connectivity.

As an example of concept development, the study of power beaming opens up opportunities at the leading edge of several research areas. Concept development helps the student realize how these advances fit in with each other, and allow progress towards larger goals. Concept development successfully involves students at all levels and from various disciplines. Typical learning methods of students include discussions with other students and faculty, as well as internet search techniques, and reading textbooks. A structure built around concise Concept Essays, web-based tools, and e-books, allows learners from outside the specific field learn what they want through a process of iteration.

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