
**AC 2011-2661: TESTBEDS CONNECTING SPACE TECHNOLOGY TO
TERRESTRIAL RENEWABLE ENERGY**

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Testbeds Connecting Space Technology To Terrestrial Renewable Energy

Abstract

Technologies to exploit resources beyond Earth bear great relevance to the problem of developing cost-effective solutions for terrestrial micro renewable energy systems. This paper summarizes the approach taken in a course-curriculum-laboratory initiative to help learners understand and use the special features of these areas. The issues span numerous disciplines across engineering, science, economics and sociology. Technical innovations from space research are summarized. Learning approaches to convey depth and breadth are presented. The public appetite for micro energy solutions, and the relevant price points are discussed. Hybrid systems integrating extraction of multiple resources, and adaptable for multiple applications, can break through mass market price barriers. Recent work by the Micro Renewable Energy Laboratory to develop learning resources and test beds is summarized. Two courses have been developed. One is a cross-disciplinary elective course open to juniors and seniors across the campus. The other is an engineering graduate course. A set of five technical testbeds is described. Strategies for formative and summative assessment are discussed through student and instructor experience across these efforts.

Introduction

There is a strong commonality of sizing considerations between technologies intended for extraterrestrial *in situ* resource utilization in the Space program, and terrestrial mass-market micro renewable power generation. The former enjoy the best of technical resources but suffer from lack access to a mass market, thus making them too expensive, while the latter suffer from lack of technical sophistication to meet their complex challenges, and hence fail to penetrate the mass market. Yet the mass market potential of the latter offers the way to advance the former, while the technical excellence of the former offers the way to make the latter successful in the mass market. This is the combination of opportunity and challenge motivating the project behind this paper. The thoughtful reader is reminded that innovations in engineering education sometimes have to go beyond classroom teaching, and that archival publications should reference, rather than repeat, material already presented in prior papers. Hence, for such items as detailed course outlines, student comments, etc., references to previous papers are given to published work. The pedagogical aspects are in relating knowledge and learning across disciplines and skills. They require the structure of this paper.

A Micro Renewable Energy Systems Laboratory has been developed at the author's institution over the past 4 years. This aims to prepare undergraduates and graduate students at the interface of Space Resource Exploitation technologies and terrestrial micro renewable energy. The need for such an effort crystallized through the discussions that led to the "Eighth Continent Chamber

of Commerce” project conducted at the Colorado School of Mines under NASA sponsorship¹. That effort sought to identify markets that would lead to the growth of extraterrestrial ISRU capabilities. The link to the terrestrial energy marketplace was studied, and revealed the need for both public education and technology development that would pave the way. A related effort² studied the viability of a micro renewable energy architecture in the context of a developing-world energy market. This concluded that a massively distributed architecture comprised of micro generators would be a good way to accelerate renewable power and secondary economic development in regions where capital and land for large utility plants are scarce. Through this effort it also became clear that the obstacles to developing successful devices were not technical but mainly due to lack of comprehension of the system linkages to societal needs and aspirations, and better thinking about ways to fund mass-production ventures.

A survey of existing college curricula showed that courses related to energy were specialized to particular technologies, such as nuclear, fossil-thermal, or hydroelectric, and were for the most part focused on the large utility plant approach. Conventional thermodynamic and macro-economic analysis could quickly show that this approach is the preferred one, to generate the best long-term Return on Investment (ROI) on invested capital. On the other hand, there was much hands-on knowledge scattered in books and websites on the realities of implementing small energy projects, and renewable energy projects, at the village level. On the third side, there is a little-appreciated but extremely valuable body of knowledge generated by the space agencies of various nations, on how to implement the devices needed to exploit space resources. The question that came up was how to bring a student through this diverse knowledge base, developing the mental attitudes and learning skills to tap into a very current opportunity spread across diverse areas. Clearly, this required some innovation and faith in designing courses.

In turn, the above realization led to the creation of two courses. Both were titled “Micro Renewable Energy Systems”. The first was set at the level of a senior college elective to enable graduate students to receive credit, but was opened to students from all over our predominantly technological campus, who had reached junior level, and sophomores from our own discipline who had completed certain basic courses. The intention was to attract students specializing in economics, public policy and international affairs, in addition to students from the colleges of sciences and architecture. Sad to admit, this grand intention did not succeed in attracting students from outside engineering. The reasons probably had to do with the fear of engineering courses (and perhaps of grading standards) that appears to pervade the happier colleges.

After one trial of this course, an advanced version at the graduate level was created, with added sections dealing with space ISRU concepts that would be too difficult to present to undergraduate juniors. Both courses were co-taught (same classroom hours) and highly cross-disciplinary, but structured to enable students to conduct an individual assessment of market realities, then join up in teams of two to conduct a more in-depth technical project. At the end each student was to develop a brief business plan based on their project, which would be submitted in confidence. The detailed course structure, course outline, and teaching experience with the undergraduate course, detailed comments from students at all levels, as well as the implications of the course for opening international collaborations, have been discussed in two papers presented at the ASEE Annual Conference in previous years^{3,4}. The policy aspects of micro-renewable energy systems are discussed in Reference 5.

Requirements for terrestrial micro energy systems

Stand-alone (off-grid) energy systems are generally located in close proximity to communities. They face local environmental constraints⁶ on noise, smell, toxic waste, and aesthetic offence. Capital, operational cash flow, cost of money, opportunity cost and ROI are financial constraints. Social and public constraints include availability of humanpower, technical expertise, roads, utilities including water, telecommunications, and competition or conflict with other resources and approaches. Stand-alone power serves communication stations, weather monitoring, navigation, lighthouses, light industry such as fisheries, facilities for tourists, water pumping for agriculture, schools, hospitals, and emergency use such as in rescue operations, field hospitals, refugee camps. To this list one may add home use during power outages anywhere. Reference 7 shows that very small amounts of power and energy suffice for several critical applications. This realization in turn leads to the design of micro renewable energy systems. We define the requirement as between 0 and 3 kilowatts of rated power, providing enough storage to deliver up to 24 kWh per day.

Space and terrestrial micro energy

Small power generation systems, especially those powered by renewable resources, encounter some common issues:

1. Low thermodynamic efficiency of heat engines with small temperature gradients
2. Large surface area per unit mass, resulting in high friction and heat transfer losses.
3. Highly fluctuating power
4. High fixed costs of power control and transmission subsystems per unit power transacted.
5. Generally high mass per unit power.
6. Need for energy storage

The famous NASA/JPL Mars Rovers are solar-powered, self-propelled devices that communicate with Earth, operate cameras, navigate using robotics, scoop up samples, and conduct chemical analyses. Other technologies are less famous but also important. Table 1 lists several space technologies, and their terrestrial applications.

Table 1: Space technologies and their relevance to terrestrial renewable power testbeds

Space Technology	Terrestrial Testbed Incorporation
High intensity solar cell	3KW Hybrid solar PV/thermal generator
Optical waveguides to convey solar power directly use point	Reduce PV cell area needed on home systems. Add to solar water heater.
High temperatures electrolysis.	Combine with PV arrays.
Photocatalytic water purifiers to convert organic impurities in water to CO ₂ .	Integrating into solar water heaters. Ion/UV water purifiers ⁷
Solid oxide fuel cells chemically convert hydrocarbon fuels to extract hydrogen.	5kWh/day home fuel cells combine furnace, water heater, electric generator
Thermoelectric (TE) spacecraft power. Nanostructured TE generators ⁸ .	Portable TE refrigerators powered by vehicle batteries.
High temperature thermo PV extraction. Theoretical 85% narrowband conversion.	Tungsten photonic crystals ⁹ extract power from household cooking flames.

Converting sunlight to microwaves using PV	Crop drying in unseasonal rain.
Solar Rankine Cycle: spacecraft thermal management systems	Rooftop solar thermal using supercritical CO ₂ at 70 atm ¹⁰ .
Spacecraft Stirling cycle engines on exploration missions, with temperature differentials as small as 6 Celsius. Various fuels and heat sources.	Thermo acoustic cooker-refrigerator ¹¹ uses exhaust heat to drive acoustic resonance moving heat from ambient air.
Atmospheric water generation	Solar condenser extracts drinking water.
Solar vapor-condenser refrigerators	Battery-free operation in arid regions
Algae and terraforming	Oil yield 2 greater than other crops ^{12,13}
LED Plant Growth	Suitable for specialized cash crops
NASA Fe-Cr REDOX system.	Alternative to lead acid battery storage.
Micro or “Pico hydel” - Efficiency estimated to reach 55% on average. Needs high dynamic head.	Direct mechanical energy from wind turbines to drive micro pumps

Efficiency comparisons

One major revelation for students about small power systems is that even the space technology versions achieve only low values of overall efficiency. Table 2 lists some practical values.

Table 2: Typical efficiencies of technologies used at small scale

Technology	Typical efficiency	Comments
Thermoelectric	4%	200C, mechanical simplicity.
Rankine engine ¹⁴	<10%	
Hub-mounted bicycle dynamo ¹⁵	66%, at 6W, 12V	Compact, simple, expensive
Automobile alternators	90% w/electromagnets	Hybrid car industry
Portable diesel genset	15% with HC fuel	Heavy, maintenance.
Micro wind turbines	<10%	Wide power fluctuation
Solar Stirling engine	<20% even in Space	Low rpm applications
Pico water turbines	>55%	High rpm

Learning Approach

The two courses helped develop a knowledge base rapidly with the lecture notes as well as the student reports on conditions in various parts of the world. Several testbeds have been developed to bring concepts from space research into micro-renewable energy systems. These are being developed by graduate and undergraduate students.

Vertical axis wind turbine

The vertical axis micro wind turbine development started in 2006 with a small device built from bicycle parts and Styrofoam blades (Figure 1). A 1m x 1m version has been built and wind tunnel tested with various blade-building and support technologies³. The testbed is aimed to focus efforts in developing cost-effective components such as blades, supports, bearings, transmission and power conversion. Simulation efforts are underway as well and constitute a major part of the learning effort. A 2m x 2m version is being designed to survive Pacific Coast

winter winds and generate up to 1 KWe. An initial prototype based on the 1m version was tested in the large return section of the John Harper wind tunnel at Georgia Institute of Technology. The set up is shown in Figure 2. This experiment yielded data on the behavior of highly flexible blades, but was otherwise a failure in power generation. An improved model with much more rigid blades is being built, with the blade construction effort pictured in Figure 3. The ultimate aim is to integrate such machines with other renewable generators, sharing the same footprint and power control systems. In 2006-07, progress was rapid, with one Master's degree candidate



Figure 1: Bicycle Wind Turbine Test Article

working on it at full speed (he was later recruited by a wind energy company). Undergraduates supporting this effort then took over the project, but it has moved much slower since then, given their heavy course load. The emphasis until now has been on keeping component costs low until the efficiency has been maximized. For instance, all rotating components are from bicycle parts, and blade construction for the smaller turbine is from easily available materials such as PVC pipes, plywood and roof flashing, enabling people anywhere on the planet to take ownership .



Figure 2: 2m Wind turbine with flexible blades in wind tunnel testing

One major issue is that vertical axis wind turbines operate best when the tip speed is 3 to 5 times the wind speed, but getting to that range requires an electric motor and control system to drive the machine to its operating speed, and relatively high rotational speeds which cannot be reached under wind power alone. Present efforts are developing a simulation package integrating blade element and stream tube interaction methods, to attempt to quantify the various performance detraction mechanisms.

Micro solar

The solar thermal generator testbed is sized for a footprint compatible with roof terraces in the developing world. It uses a reflective trough of aluminum sheeting formed by a simple wooden truss, covered with 99% reflective Mylar to focus

sunlight onto copper tubes that form the heating element of a gaseous heat engine. System analyses came to the conclusion in Spring 2010

that for the operating temperature range and safety constraints of the device, an open-return air-based heat engine was the most cost-efficient. Initial tests were conducted in Fall 2010 on the roof of the School of Aerospace Engineering. These “shakedown” tests alleviated safety

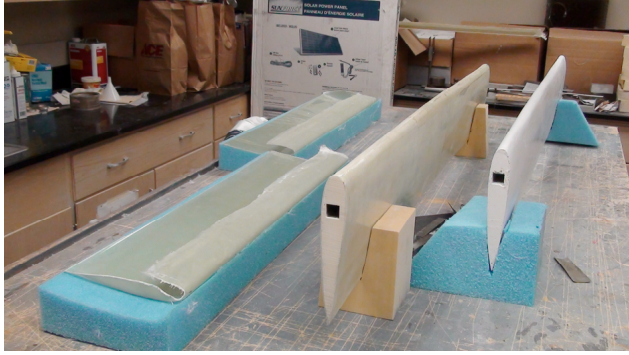


Figure 3: Blade construction for 2m x 2m wind turbine

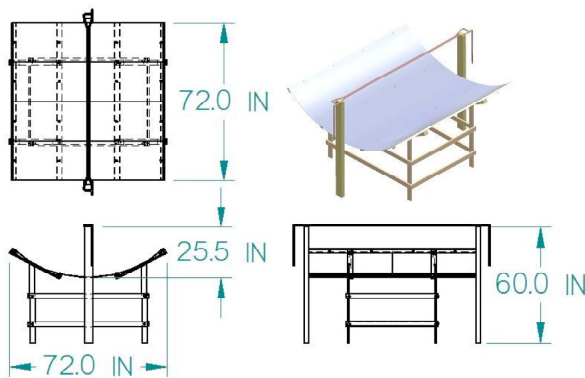


Figure 4: Micro solar thermal testbed

drive fresh air through the fire, improving combustion efficiency to reduce fuel needs and pollutants, and exhaust pollutants out of the kitchen, and (b) steady LED lighting, enough for a child to read and do homework, without having to leave the kitchen and escape supervision. A strict design criterion here is that the device must be an add-on that can be tailored to the shape of the “stove” used by the family, rather than expecting them to buy a complete stove. Attempts elsewhere to provide readymade new stoves have been less than successful because the recipients felt that food cooked on the shiny new devices lacked the “flavor” that came from their old “stoves.”

Beamed power

Not all testbeds need be hardware. In the case of beamed power, the testbed development consists of developing concept analysis models using computer programs and published data, to reduce uncertainty and explore different system tradeoffs. In the longer term, the current plan is to integrate a millimeter wave antenna with a photovoltaic panel.

concerns, but showed the need for a large-angle inclination system for the northern latitude of our location and the late Fall time of year. Performance was steadily improved through several tests, with the system broken down and reassembled each time. The temperature rise values obtained were quite small, but there were several good reasons for this. A major redesign is planned for early Spring based on the data and usage observations, for the next iteration when outside temperatures are expected to be much higher and sun’s path closer to the zenith. The utility of this testbed will come when it is integrated with other machines, such as photovoltaic converters, micro wind turbine and possibly an algae biodiesel tank sharing the same footprint. The micro solar system footprint can be seen from the prototype shown in Figure 4.

Thermoelectric

A third testbed is the “EduKitchen” project, which envisages a device that improves the efficiency of a slum-dwelling kitchen woodstove, generating enough electrical power to (a) a feedback-controlled fan to



Figure 5: Symbiotic Algae-Mushroom Testbed

Symbiotic algae-mushroom testbed

Algae growth is integrated with mushroom cultivation in this testbed. Mushrooms can grow very well beneath the algae tank, since they do not need much sunlight. They generate copious amounts of CO₂, which is pumped up into the algae tank. Modifications were learned to keep the mushrooms from taking over the setup and competing for the water. A small Symbiotic Algae-Mushroom model set up was tested under artificial lighting and tested in Spring 2010. Unfortunately, progress on this project has not occurred since the student researcher graduated, as we await access to the sunlit lab space promised by the School Administration.

Discussion

Organizing Long-Term Progress With a Student Team

Student progress on these five testbeds is interesting to consider. In each case, progress has been slow, but the cumulative effort going into all 5 is substantial. Each semester, several students walk on to our team seeking project experience through Special Problems credit. They are organized into a matrix of projects and teams. Typically, each student is assigned to 3 teams, and each team has roughly 3 to 5 students. In addition, graduate students are expected to be familiar with the issues of all the testbeds and provide some oversight and considerable assistance. As mentioned before, the rate of progress on any given project is much higher when there is a graduate research assistant focusing attention on it as a primary graduate school project. In the absence of that situation, it appears to be a better strategy to be working on several testbeds at the same time. Undergraduates often continue to work on a project in a fragmented manner, procrastinating any learning effort and hence staying unaware of the basics of the project until the instructor realizes the situation.

A series of techniques were tried out over the years to organize such multi-team cross-disciplinary projects within the constraints of a hectic academic semester. The present (and presumably most refined) scheme is as follows:

1. At the end of the first week of classes, when the registration for the semester closes and hence the student list is nearly final, the professor sets up a matrix of projects and people, assigning weightage in distribution of effort of each student over 2 to 3 projects.

2. Students with prior experience in the team are assigned to be “team coordinators” with the caveat that the prestige of such a position comes at the price of being the accountable person when things do not move in an organized manner.
3. A team Orientation Guide is given to each student, with instructions to read through and absorb the safety and security rules and common sense practices carefully.
4. All students have to take the Institute’s Right To Know (RTK) on-line course.
5. One or more weekly meeting periods are established so that each student can find one of these periods to attend a team meeting in the professors’ office or in the lab. Generally the preferred time is Monday at 8, or 7:45 for those pleading 8AM classes. These meetings are intended to be short, with each student expected to provide a succinct status report.
6. A set of 16 assignments is set up on the Institute’s course management website. Each assignment is to upload at least one Project Document describing the up-to-date status of that project, between Friday and 8AM Monday. The Project Document is expected to be complete in format and planned sections starting with the first week, but to have its content edited, expanded and updated throughout the semester so that at any point it provides an almost up-to-date description, including the project’s history, equipment details, detailed setup procedures, experiment history, all data and analyses, and most important of all, a sheet on the front delineating next steps and responsibilities of team members. While each Project Document is under the coordination of one person, all team members are expected to upload a copy of the latest version. This of course demands communication between team members, which is part of the intention.
7. At the end of the semester, each student is also asked to provide a summary of individual contributions to all projects, separate from these team documents. This is to demand introspection and assimilation of lessons learned. After the many frustrations of experimental research and dealing with a professor who keeps asking for improvements, this is also intended to induce students to realize that they did learn and accomplish a lot over the intense 16-week period of a semester.
8. Student teams are generally allowed to set their own schedules, with the caveat that the professor will intervene if he finds project meetings and work periods being scheduled for Friday afternoons or weekends, and force a shift to an early morning schedule.
9. When experiments are underway, near-real-time reporting to the professor via phone and email is expected, and the experimenters invariably experience pressure to plan tests well, follow procedures, ensure safety and security, and analyze data swiftly to determine the results and the next steps.
10. At the end of the semester, a clean-up/disposal report is expected to be attached to each project document.

While this procedure looks straightforward, in reality it takes several weeks each semester before students get used to the idea of reporting regularly and showing up prepared at meetings.

Learning methods

Faced with the extremely multidisciplinary nature of these projects, the way students adjust to the learning demands is fascinating. To the extent possible, the professor provides resources uploaded to the institutional course management website, and now into the cross-disciplinary learning website being developed by our team¹⁶. Beyond this, the Project Documents are

expected to be a primary knowledge retention and transfer mechanism. It is unrealistic to expect that students will read and understand everything in good time. Thus Formative Assessment strategies are needed. The weekly meetings are fully intended to provide both encouragement and some intense motivation to learn the essentials. Students go to the graduate students for help, but this is not necessarily a panacea, again due to the cross-disciplinary, advanced project development environment. Thus, to a great extent, individual mentoring is the most effective knowledge development mechanism, with the professor learning along with the student much of the time, but imparting useful experience and leaps across disciplines where possible. Peer-to-peer learning is also a very important aspect of knowledge transfer, with students seeking out friends specializing in other schools. It is a fairly common sight to see teams working intensely together, learning from a visiting friend from another school.

Conclusions

1. There is a fertile area of research and development at the interface between space technology and the terrestrial micro renewable energy systems market.
2. This is a highly cross-disciplinary area, demanding a steep learning curve from student and faculty researchers alike.
3. A set of two courses has been developed to educate students in this area and to develop a knowledge base. One course emphasizes breadth across technical, social and public policy issues that go to the heart of the micro renewable energy marketplace, while the other is a graduate course focused on the technical challenges and drawing on space technology.
4. The realities of micro renewable energy systems show that end-to-end efficiencies are small, even with the extreme technical sophistication of space systems. Thus innovation must focus on inexpensive, sustainable alternatives that retain the technical advantages of the space systems and come close in figure of merit.
5. A set of 5 testbeds is being developed, to provide basic power conversion functions and then enable adding on refined technology modules to provide greater functionality for the same footprint.
6. Organizing student team efforts to carry on these testbed developments poses interesting tradeoffs between timelines and breadth of effort.
7. The evolved method of organizing undergraduate student team activity is summarized.

Acknowledgments

The author acknowledges the support from NASA under the EXTROVERT cross disciplinary innovation initiative. Mr. Tony Springer is the Technical Monitor.

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