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Terrestrial Micro Renewable Energy Applications of Space Technology

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Abstract

This paper explores the synergy between technologies intended for extraterrestrial in situ resource utilization and those for terrestrial mass-market micro renewable power generation systems. The case for a micro renewable energy architecture is presented. The obstacles hindering market success are summarized, along with opportunities from recent demonstrations suggesting that the public appetite for sophisticated technology worldwide may be underappreciated by technical researchers. Technical innovations from space research are summarized along with estimates of possible conversion efficiencies. It is argued that the cost-effectiveness of micro power generation must be viewed through the value of the first few watts of available power, rather than the marginal cost per kilowatt-hour of electric power from utility power grids. This leads to the finding that the actual target cost per unit power, and efficiency, are well within reach of space technology products. Hybrid systems integrating power extraction from multiple resources, and adaptable for multiple applications, can break through mass market price barriers. Recent work to develop learning resources and test beds as part of a Micro Renewable Energy Laboratory is summarized.

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1. Introduction

This Forum and others celebrate the innovation coming from the best minds in the world aimed at the difficult challenges of space exploration. A wealth of proven ideas and laboratory demonstrations has steadily advanced human capabilities to explore and develop extraterrestrial resources. The dominant

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funding sources who understand the technical roadmaps for such research are government agencies. The market focus for most of the research conducted on exploiting extraterrestrial resources, especially "*in situ* research utilization" (ISRU), is limited to government space missions. The participants and readers here are surely aware of the challenges faced in continuing these lines of research and development, given the uncertainties, shifting priorities and resource shortages of national space programs all over the world. Government agencies are keenly aware of the benefits of showing commercial spinoffs from space research. The NASA Tech Briefs, for instance describe efforts since the dawn of the Space program to commercialize many of the innovations. These, and similar efforts in other nations, have led to the absorption of space program research results into numerous commercial applications.

Given the one-off nature, and uncompromising scientific excellence characteristic of mission-related innovations, the unit cost of devices developed for space missions is extremely high. In the case of power generators other than the main engines, the mass constraints of earth-launched spacecraft dictate that the power levels of space power systems are very low by terrestrial standards. Accordingly, it appears that power generation technologies developed for the space program are at best suited for "designer" applications on Earth.

At the other extreme of human endeavor is the unglamorous effort to enable large segments of humanity to access basic electric power. Here the emphasis is on keeping the cost low enough to suit people who lack the resources to obtain food, let alone a good education and the technological sophistication to operate space technology applications. The traditional view is that devices designed for such users must use the lowest levels of technology, and lowest cost of development. This paper takes the opposing view that the problem of developing efficient, standalone power generators on a small scale is no less challenging for these mundane terrestrial applications than it is for extraterrestrial applications. Further, bringing the unit price and cost per unit power of such devices down to where they can succeed in the mass market, involves the simultaneous solution of problems in technology, economics, mass education and societal realities. The paper lays out some avenues of thought and solution approaches, exploiting the remarkable similarity in many of the technical problems.

The problem is not lacking in magnitude. Some 1.4 billion people on this planet face daily shortages of energy and other basic resources, their prospects becoming more grim every day as prices of fossil fuel and food rise. While the need to shift towards renewable energy and conservation measures is obvious, strategies for meeting that need are not so obvious. Simple macro-techno-economic calculations would show that going with the largest utility-scale plants, especially nuclear power plants, is the most cost-effective way to independence from fossil resources. This approach is fraught with technical and socio-political delays, conflict, community dislocation, economic shortages and sometimes the extreme risk of war. On the other hand, it is remarkable that so few people today own personal renewable-power generators given that the need is so obvious, and that they would acquire them if it were cost-effective to do so. Total global electric power generation capacity in 2008 was over 1100GWe, which works out to less than 200 watts per human being. A healthy 75kg human can generate over 120 watts mechanical (probably meaning only 40 to 60 watts electrical), in riding a bicycle, for a short period. Though not suggesting that people should all become power plants, this does mean that becoming self-sufficient in power generation using small renewable-power generators is not beyond the realm of possibility on an individual level. Getting small-scale power generation devices to mass-market success has proven to be extremely difficult. The commonly-cited reason is that small generators are not able to match the efficiency or cost per unit power that the large-plant approach has achieved. Perhaps this whole problem needs good re-thinking by technical innovators.

Figure 1 shows an ancient windmill. In modern terms, this would be described as a terrestrial ISRU system generating renewable power at the point-of-end-usage. It is located in a community where customers have access to the products and services made possible by the power. Despite its inefficient drag-based (rather than lift-based) aerodynamics, failure to clear the atmospheric boundary layer, large support interference, crude bearings and rather primitive construction techniques, a good system analysis must show this facility to be viable. The proof is historical. Thousands of such systems proliferated in

Europe at the leading edge of the industrial revolution, before fossil fuel transport systems and power grids centralized power generation. Routine operations, maintenance and related trades provided a stream of employment for locals. Today, many parts of the world do not have power generation capability even at this level. Two lessons from the windmill example are the ideas of integrating multiple functions and technologies into one system, and of thinking well beyond the primary power generation thermodynamics at the conceptual design stage.

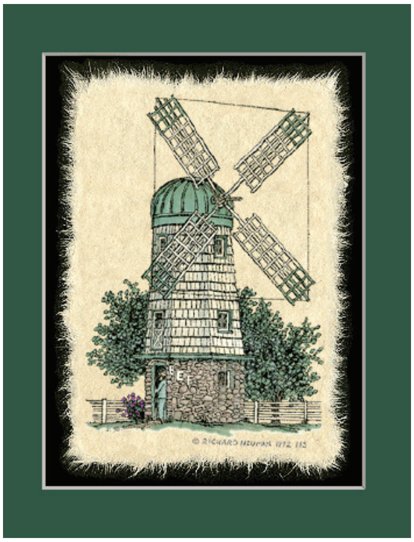

Figure 1. Painting of an ancient European windmill. Published by permission of Mr. Richard Neumann

2. Terrestrial Micro Renewable Energy Systems

The systems of interest in this paper have power ratings from 0 to 3 KW, focusing especially on the 10 watt to 3KW regime. This is the same range as that of interest in most extra-terrestrial ISRU systems, which are designed to perform reliably in hostile environments despite having low mass per unit power. Many concepts and technologies have been demonstrated in the laboratory but not adopted for scale-up to utility or mini-grid levels. These may be ripe for diversion to micro power applications.

The first problem in developing micro renewable power generators is that they are rarely true "standalone" devices. To be effective, they must be set in the context of a system. Hence the descriptor of "micro-renewable energy *systems*" (MRES). "Micro" here denotes devices suitable for a single person, family or shop, usually meaning that the power level is limited to 3 kilowatts, the level needed to sustain a modest family. This is far below the Megawatts that utility corporations or turbine manufacturers might classify under "micro", and far above the micro-watt level imagined by modern electronics engineers. "Renewable" means that the items consumed by conversion do not come from deposits of finite resources, but are either recovered (such as water from hydrogen-oxygen fuel cells) or are essentially infinite (such as salt water and sunlight). "System" intends to convey that one must consider the entire chain of resource capture, conversion, storage, control, delivery, synergy with other technologies and applications, and the human social and economic circumstances that are essential for success.

Ulleberg [1] summarizes the constraints on stand-alone energy systems. Local environmental constraints include minimizing noise, smell, toxic waste, and aesthetic offence. Financial constraints include capital and operational costs, to which one must add the cost of money, opportunity cost and desired rate of return. Social and public constraints include availability of humanpower, technical expertise, roads, utilities including water, telecommunications, organizational priorities, and competition or conflict with other resources and approaches. These constraints vary widely depending on the development level and the freedom of the social and political systems in a given nation. Applications of stand-alone power listed by Ulleberg included power for communication stations, weather monitoring, navigation, especially 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.

Since 1998, the electric power grid has reached hundreds of millions of more people, but a good portion of this is because of urban population growth. More than one billion people around the world still must depend on stand-alone systems for any access to electric power. On the other hand, it is useful to note that society existed long before electric power became available, and there are still many functions that may be more efficiently performed using direct conversion from renewable resources at the point of use to mechanical and thermal power. The needs for standalone power vary greatly depending on the economic standard of living, need for transportation and climate. Cold regions have substantial needs for winter heat, whereas hot and humid regions can benefit greatly from air conditioning. Ulleberg's classification of needs ranges from "small" meaning 10 to 100 Watt ratings for homes, cabins, and instrumentation in developing areas, to "medium" meaning 0.1 to 10 KW, and "large" above 10KW.

In the long term, a hydrogen economy may develop, where hydrogen is the preferred fuel at both the utility and stand-alone system levels. Veziroglu and Barbir [2] and Selvam [3], cited by Ulleberg, showed that hydrogen would win based on considerations of motivity, versatility, utilization efficiency, environmental compatibility, safety and economy. Ulleberg's analysis leads to the conclusion that a solar-hydrogen energy technology would be the best choice. The present paper departs from this conclusion in noting that a path to an eventual solar hydrogen economy can be built at present by adopting a wide range of concepts and developing the technical confidence and mass market demand for standalone power systems.

3. Requirements Definition

The interest in this paper is in MRES. Accordingly, the power level of interest is from 0 to 3 KW. This is based on the estimated needs of a single person or small family, or a small retail shop in a village. Table 1 allows a definition of basic and advanced requirements, computed separately for cold-region and tropical users. Clearly, even 300 watts would satisfy basic needs for electric power in many cases, and as little as 100 watts would enable basic lighting, air movement, a television set, a portable computer and wireless connectivity if used sparingly. A combination of a 3KW system and a 1KW system would satisfy heat and power needs of a middle-class family living in the standards of comfort to which urban dwellers in wealthy nations are accustomed. This determines the focus on devices ranging from 100 watts to 3KW, with possible storage for up to 10KWh electric and 15KWh of heat per day.

4. What Is The Value Of Electric Power?

Renewable energy systems are usually unable to match the marginal cost per kilowatt-hour of electric power that is offered by fossil-burning or nuclear plants connected to an efficient grid. MRES technologies are much worse off because of their small scale, *e.g.,*Table 1. Estimates of the Levelized Cost of utility-scale electric power are given by the US Energy Information Administration [4] in Year 2008 dollars per kilowatt-hour of systems entering service in 2016. This predicts coal-based systems offering \$0.10, nuclear at \$0.12, solar photovoltaic (PV) at \$0.49 and solar thermal at \$0.26 per KWh.

This section argues that the traditional ways of measuring the value of a power system, in terms of its installed cost per watt, and in its cost per KWh of delivered electric power, are both inadequate to determine the value of the first few watts of access to electric power. Two important criteria are proposed. The first is the extremely high value of the first few watts, for an emergency SOS signal, a rescue beacon, in monitoring life-saving radio instructions, in emergency lighting, medical services, keeping medicines refrigerated, and operating critical medical equipment in hospitals. At the next level comes lighting that allows students to remain competitive with the outside world in learning. A third is providing charging power for communication devices. A fourth is providing power for communication devices such as radios, and now TV sets. This is hard to quantify, as the value of the life-saving first watt-seconds is infinite.

Table 1. User Requirements for Micro Renewable Energy Systems.

Use	Cold-Region KW rating	Cold-region KWh per day	Warm-region KW rating	Warm-region KWh per day
Lighting[1]	0.020	0.200	0.020	0.120
Fan[2]	0.034	0.407	0.034	0.407
Communications[3]	0.004	0.012	0.004	0.012
Computers[4]	0.113	0.452	0.113	0.452
TV[5]	0.100	0.400	0.100	0.400
Wireless Router[6]	0.007	0.007	0.056	0.056
Refrigerator[7]	0.400	6.800	0.400	9.600
Total Electric	0.678	8.278	0.727	11.048
Cooking[8]	1.000	2.000	1.000	2.000
Water Heating[9]	1.000	2.000	1.000	1.000
Air Heat or A/C[10]	1.350	10.801	1.900	4.275
Total Heat Energy	3.350	14.801	2.713	4.603
Total Energy	4.028	23.079	3.440	15.651

[1] LEDs equivalent to 200watts of incandescent lamps
[2] Lasko vertical fan, 120vAC, 0.4A
[3] Cellphone charger, Samsung 2004 model
[4] Sony VAIO 17 inch-display laptop charger, 2010 model
[5] LCD/LED Flat panel TV average, 2010.
[6] 2010 Average
[7] 18 cu. ft. US average, 2010
[8] Electric cooktops, 2010
[9] Electric showerhead heater takes 2.75KW, 2.5GPM flow
[10] Cold regions use AC 3 months, warm regions 6 months, but have natural ventilation. Only cold regions use heat.

The second criterion is the cost of alternative means of generating the first few watt-hours of power. At low power levels, the obvious alternative is to have a supply of dry cells. Figure 2 captures the cost per unit power of Alkaline batteries, taken from the lowest advertised internet prices found in the USA on November 12, 2010. These prices include a nominal domestic shipping charge and are well below what a retail customer in a remote place might have to pay. At the lowest level, devices may use AAA sized batteries, followed by AA, C and D batteries for larger devices. The cost is 3 to 4 orders higher than the marginal cost of electric power for a customer in a grid-connected urban area in the USA. Even when one goes as high as 1KWh (lead-acid rechargeable batteries), the cost does not fall much below this level. Cast in this light, renewable power devices are extremely valuable, and need not try to compete on cost per KWh with the non-existent grid. Figure 2 allows designers to set reasonable price targets for MRES innovations.

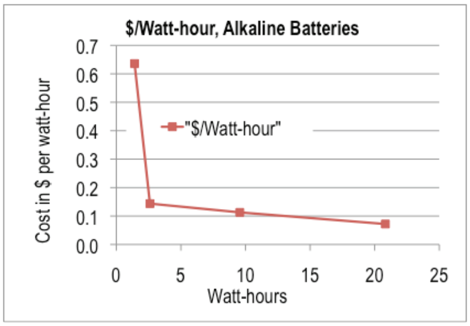

Figure 2: Cost of the first few watt-hours of electric energy using disposable batteries.

5. Do Poor People Need Laptop Computers and Flat-Panel Televisions?

One point that strikes students coming to western universities from “less-developed” nations is that the technical community appears to confuse currency conversion factors with intelligence conversion factors. While many devices that are considered to be cheap in industrialized nations, are beyond the reach of people in much of the world outside, people there are no less aware of these devices, and have no lack of appetite for technology. As economic activity and wealth started increasing in developing nations, devices such as cell phones have permeated the mass market at astonishing speed. So have television and the idea of satellite reception. People in “less developed” areas are in fact substantially more likely to accept highly technical solutions long before they are accompanied by the kindergarten-level User Manuals and Customer Service that are considered essential in advanced nations. Similarly, the notion that users might have to go outside and adjust the orientation of a solar trough once a week to account for the changing season, or re-orient an antenna, is perfectly acceptable to such people. The power grid being as unreliable as the landline telephone network that they recently discarded in favor of “mobiles” (cell phones), people are also used to voltage regulators on every device, as well as power inverters and truck batteries as their backup electrical storage. These experiences, frustrations and resources make them ready for renewable power generators with their fluctuating power output. This should answer readers wondering why the needs for undeveloped areas include laptop computers and wireless internet routers. The authors’ assessment shows that people in underdeveloped areas are nevertheless eager to adopt modern technical conveniences, and very often these are seen and used for innovative small business concepts. Advanced mass-market devices such as LED lighting, cell phones, internet connectivity, and other appliances of the future are assumed to be at least as energy-efficient as today’s versions. Thus the move towards micro renewable energy systems is by no means a move towards accepting a lower standard of living, nor a declaration that rural populations should be satisfied with second-class conveniences.

The requirements above have been assessed based on strictly residential needs. In rural areas and everywhere in developing countries, small businesses are integrated with homes, or have needs similar to those of homes. For instance, instead of a refrigerator or computer it may be an electric sewing machine that is enabled. Instead of an air conditioner it may be a small mill or machine tool. Instead of a fan it may be a juice maker. Even the small computer and internet connection may be the core of many small businesses.

6. Integrating Multiple Applications

Once the notion is accepted that people all over the world can be very innovative, regardless of wealth, thinking must expand to imagine many different applications for small-scale power. Water purification, sterilizing stored water using ultraviolet illumination, pumping collected rainwater through household plumbing, timer-based irrigation, electronic security systems, weather monitoring, greenhouses, methane fuel-cell powered lawnmowers, accelerated indoor vegetable cultivation using artificial LED lighting, are all interesting applications. Each cannot justify a special single-purpose system. However, with software and reconfigurable machine technology developed for long-duration space missions, one could imagine multipurpose machines that could be adapted. Such machines may then be able to command mass-market success through production economies of scale. One special feature of such systems is that they may be able to use several technologies that have been shown feasible at the laboratory scale, but have been individually rejected for scale-up to utility or mini-grid levels.

7. Basic Technical Challenges

The basic technical challenges in developing MRES are:

1. Heat engines with small temperature gradients

2. Small rotational speed
3. Highly fluctuating power
4. Energy storage

Where energy is extracted for conversion in MRES, the intensity may be low either because of the small amount collected or because of the high rate of heat loss. Hence the temperatures reached are also low compared to those in propulsion systems, industrial gas turbines or nuclear plants. Thus, fundamental thermodynamic efficiency is low. Designing with such low efficiency is defensible because it enables operation with energy that would otherwise be wasted, or because it enables a large drop in cost with household materials used instead of aerospace materials, or because the device can be built and maintained without specialized facilities.

Conversion of mechanical to electric power usually involves a rotating machine that takes electrical conductors across magnetic field gradients. A high rate of change is maintained by compacting the field gradients within a small diameter, and spinning the device at a high frequency. The frequency is typically tuned to the desired alternating current frequency of 50 or 60 cycles per second, or its sub harmonics (1500 to 3600 revolutions per minute). Many micro devices however, must start generating at low rotational speed, for instance a wind turbine at low wind speed, or a solar generator as the sun emerges from behind clouds. High speeds mean high gear ratios, complicated transmissions and a need for maintenance. Devices with large diameter are in fact more suitable here, but imply numerous wire windings, permanent magnets, or other innovations. For example, wind turbines built around bicycle components would be quite capable of handling the required power levels ranging from tens to hundreds of watts, operating at 300 rpm or less. Wind turbines are especially difficult to build with high efficiency and small diameter. Horizontal axis machines of less than 2m diameter are advertised with electrical power levels of a kilowatt or more, but these operate at speeds that pose dangers in residential areas. Vertical axis machines of less than 1.2m diameter are considered to be impractical [5], however, if such machines could be developed to produce useful power, they would be portable enough to permit many uses that are now not viable.

Both wind and solar power generation systems suffer from extreme fluctuation in the level of power generated. In the case of solar systems, the inevitable day-night cycle and clouds cause fluctuation from zero to a predictable maximum. Solar photovoltaic systems generate some power even on cloudy days, whereas heat engines running off solar concentrators become inoperable unless there is direct sunshine, and have great difficulty operating on days with intermittent clouds. In the case of wind power, the fluctuation goes from zero to some variable maximum. Since the power generated varies as the cube of the wind speed, machines designed to survive the absolute highest possible wind levels have difficulty operating at the low speeds that prevail most of the time. A large proportion of the total energy extracted over a given period comes from very short intervals of high winds. This poses a strong challenge in extracting useful power from wind machines at viable cost.

Storage of the extracted energy poses difficult problems. At the single-family home level, automobile or truck batteries are still the most viable option. These are heavy and dangerous, and the mass per unit energy storage is high. Storing enough energy for a day's use (24KWh) requires a large mass, volume and expense. Alternatives to lead-acid batteries suitable for mass production and long-term rural use are needed.

8. Extraterrestrial ISRU Technologies

The most famous ISRU devices are probably the Mars Rovers, which are solar-powered, self-propelled devices that communicate with Earth, operate cameras, navigate using robotics, scoop up samples, and conduct chemical analyses. However, several other technologies are also important.

High intensity solar cells - Sater [6] described a high intensity solar cell that could capture up to 25 times the AM0 (outside the Earth's atmosphere) solar intensity. According to Takamoto [7], Fraunhofer

ISE has demonstrated 41.8% conversion efficiency at 454 suns using a InGaP(~1.7eV)/InGaAs(~1.2eV)/Ge lattice mismatch cell. Efficiency of 48% at 1000 suns is projected. The DOE High Performance Concentrator PV Project [8] projected over 33% system efficiency in conversion of sunlight to electric power at utility scale using multijunction solar cells. This anticipates using 41% efficient solar cells, and projects an installed cost of $1 per watt of photovoltaic power. This may be taken as a benchmark to develop Figures of Merit for smaller-scale solar conversion systems. Concentrators suitable for placing on home terraces can deliver intensities corresponding to 300 suns or more, and thus achieve high temperatures. Of the incident power, 33% could be converted to direct current. Of the 67% convected away by a cooling fluid, some 20% (13.4% of the total) could be converted to mechanical work by a heat engine. The remaining 43% still has sufficient temperature differential to generate voltages using the thermoelectric effect, perhaps converting 4%, leaving the rest as water warm enough for household use. If the expensive high-intensity cells and thermoelectric converters were added as an update kit to a basic solar thermal converter, these could take advantage of mass market production efficiencies, bringing their costs down. Obviously, reaching such high cumulative efficiencies will require intense research and system integration efforts, at the level of space mission development. This level of effort can be justified by considering that the global impact of a solar thermal/ PV combined heat-and-power system that offers over 45% efficiency, and cost-effective for families to acquire, is likely to be very significant.

Optical concentrators and waveguides - Optical waveguides for solar power [9] can convey concentrated solar power directly to where it is used. Stretched Lens Arrays have been developed to increase the concentration of solar power onto photovoltaic cells, reducing cell costs and increasing conversion efficiency. These are being considered for lunar or Space solar power satellite applications, but might be equally applicable to residential photovoltaic panels, addressing a projected shortage of manufacturing capacity for such panels.

Direct photochemical splitting of water - Solar concentrators can produce enough energy intensity and temperature to enable direct photochemical splitting with very little expenditure of electric power. Where essential, these concentrators could be combined with photovoltaic arrays to produce the desired electric current, taking advantage of the high conversion efficiency of electrolysis at elevated temperatures. Photo catalytic conversion of water to hydrogen and oxygen is being extended from the ultraviolet regime where it was first shown to the visible spectrum [10, 11].

Solar Water Purifiers - Photocatalytic water purifiers developed by NASA and others [12], Sobczyński and Dobosz [13] use ultraviolet radiation from sunlight to convert organic impurities in water to carbon dioxide. Integrating this technology into that of solar water heaters or the convection systems for solar concentrators has obvious benefits for rural and urban users. For larger standing water supplies such as water tanks, ion water purifiers operating on solar energy provide an alternative. The worldwide impact of low-power ultraviolet water purification systems in controlling cholera and other health risks [14] and providing safe drinking water to communities, has been amply demonstrated.

Extraction of hydrogen from gas mixtures - Home fuel cells operate as combinations of a furnace, water heater and electric power generator, and are sized to generate up to 5 kilowatt hours per day. They can also be used as backup generators. They chemically convert hydrocarbon fuels. Solid oxide fuel cells manufactured by the Bloom Energy Company have been reported to be operating in several major corporations.

Thermoelectric Generation - Hyder [15] describes thermoelectric conversion applications for spacecraft power. Portable refrigerators operating on the thermoelectric effect are already available for use with vehicles, powered by vehicle batteries. Amatya and Ram [16] describe a thermoelectric generator for micro power applications, using an inexpensive solar concentrator. They claim that a 5.5% conversion efficiency can be achieved using novel thermoelectric materials. Koukharenko *et al.* [17] describe progress towards nanostructured thermoelectric generators.

Where high temperatures are present, a thermo photovoltaic extraction technique was described by Wedlock [18]. Here a suitable material, usually a ceramic, absorbs the heat and radiates in a fairly narrow band to which photovoltaic cells are tuned, enabling a relatively high efficiency. Wavelengths outside those that the tuned cell can convert, are reflected back using a filter, so that the emitted illumination matches the absorption characteristics of the converter. Theoretical conversion efficiency is cited as 85%, but it should be noted that this is primarily an advantage in minimizing heating of the converter. An architecture based on cost-efficient production of tungsten photonic crystals is described by Fan, Peumang and Braun [19] where a separate filter is not required. This technology could be used to extract power from household cooking flames where temperatures are high enough to cause strong radiant emission.

Microwave Crop Drying - Crop drying using microwaves instead of direct sunlight is an interesting use of micro renewable energy, eliminating some of the uncertainty that farmers face. Converting sunlight to microwaves could be accomplished using a PV system. Such a system has been demonstrated under NASA technology transfer. In case of unseasonal rainy weather, alternative power sources could be used to generate the microwaves, thus protecting the crop.

Solar Rankine Cycle - Japanese researchers have developed a solar thermal system suitable for rooftops, using supercritical carbon dioxide at peak pressure of 70 atmospheres as the working fluid, blackened double-walled glass tubes as the heat absorbers, and a Rankine cycle heat engine. With operating temperatures lower than 250 Celsius, Zhang, Yamaguch and Uneng [20] report cycle efficiency of 8%, but with the advantage of using the waste heat in the working fluid to provide heat in the building. At small scales, Bammert, Heihal and Mobarak [21] point out that turbine design becomes a difficult issue because the nozzle constriction required to obtain a high pressure ratio through the turbine becomes extremely small, especially when using water as a working fluid. Exotic working fluids such as toluene have been tried, but the basic issue is that the designer is driven towards high rotational speeds and multistaging. These result in high system cost per unit power. This leads to the conclusion that for small scales, open cycle systems may be best, albeit with very low cycle efficiency. In turn, this requires use of air or water as the working fluid to reduce cost.

Stirling Engines - Stirling cycle engines are used on spacecraft to generate high levels of power on exploration missions. They have been shown to work with temperature differentials as small as 6 degrees Celsius, and are optimized for spacecraft power applications. They are also able to operate on a variety of fuels and heat sources. NASA Glenn researchers have developed radioisotope Stirling generators. The use of radioisotopes makes these unsuitable for mass-market application, but the Stirling system itself could be adapted to several low temperature gradient applications. The demonstrated efficiency of Stirling engines is not high except in Space applications where the heat sink temperature is the cold of Space, and even there, the cited values are on the order of 20% [22].

An interesting application of the Stirling cycle is to thermoacoustic heat engines used in transporting heat, or in refrigeration. Here acoustic resonators are used to create standing wave patterns, and the phase difference between temperature fluctuations and acoustic pressure fluctuations provides a Stirling cycle route to conversion. Symko and Rodriguez [23] describes a device that generates electricity from temperature differences as low as 100 Celsius, going through an acoustic resonator cavity and a piezo electric converter. He cites efficiencies that are “a substantial fraction of the Carnot efficiency.” Lee [24] describes a combined cooker-refrigerator where the exhaust heat from the cooker drives resonant acoustic waves in a tube, that transfer heat from ambient air at the refrigeration end.

Atmospheric water generation - Using solar-powered condensers, the moisture present in air can be extracted and used for drinking purposes. Multi-stage dry chemical systems have also been commercialized all over the world.

Vapor-Condenser and Absorption Cycle Refrigerators - Solar vapor-condenser refrigerators use direct PV-driven compressors and a water-based phase change solution. This enables battery-free operation in arid to semi-arid regions with at least 5 hours of sunlight per day.

Algae and terraforming - Certain types of algae grow extremely fast given the proper sunlight, warmth, water, and carbon dioxide-rich air, and as such they are usually grown near industrial plants to use the CO2 sequestered from the exhaust. Rhodes [25] reports a doubling in volume in 2 to 7 days.

These algae can produce an oil yield 2 orders of magnitude greater than other oil-generating crops [26]. The MRES issue is how to integrate algae cultivation with other uses of land and resources, and to enable urban dwellers or residents of small village homes to participate in a distributed algae biodiesel enterprise. Centralized processing at one place in a village makes sense because several processing steps are involved in the biodiesel production, including drying, crushing and distillation, which require too much specialized equipment to be installed in each home. Collecting and transporting the wet bales of algae from each home to the processing station is as simple as an "inverse newspaper route" involving a tricycle carrier or at most a pickup truck powered by biodiesel.

LED Plant Growth - An interesting technology for directly using mechanical energy from wind turbines is to drive pumps. The REDOX system was developed by NASA Lewis Research Center in the 1960s as an alternative to lead acid batteries. A newer version, the Fe-Cr or "I" REDOX system has also been developed.

Micro or "Pico hydel" - The efficiency of small hydroelectric generation systems is estimated to reach 55% on average. This is best suited to installations with high dynamic head. Designing turbines for small hydro electric applications poses challenges.

9. Efficiency Comparisons

The above examples illustrate the fact that even in the Space program, there is a place for systems that operate with low thermodynamic efficiency compared to those of jet engines and large utility power plants, if there are compelling advantages when the overall system requirements are taken into account. Conversion efficiency is only a part of the story, but is useful as an exercise to start system design considerations. The comparisons are useful when one realizes that at these small size scales, the "high-efficiency" options typically considered, are no better, and may be fundamentally far more complicated. Radioisotope thermal generators have been highly refined for spacecraft long-duration power applications. The power conversion parts of these systems (typically thermoelectric) are suitable for adaptation to this market. Thermoelectric systems achieve roughly 4% conversion efficiency, but can operate with temperature differences much less than 250 C, and are extremely simple devices. Their mass availability is improving since the major automobile companies are adopting them to extract heat from the exhaust and power auxiliary systems. Since the heat sources with which they operate will be otherwise wasted, the primary issue here is to reduce acquisition cost and improve durability. As seen above, this compares quite well with the efficiency that is achieved by small Rankine cycle heat engines [27] which have relatively complex machinery.

A hub-mounted bicycle dynamo can convert mechanical to electrical power with 66% efficiency [28] even at low power levels of 6 watts at 12 volts. At a much larger power level, automobile alternators are claimed to operate with 90% conversion efficiency using electromagnets, and the new hybrid systems have enjoyed the research and development needed to operate efficiently over wide ranges of power, speed and load. Again this should be compared to traditional alternatives. A heavy but portable diesel generator typically provides only 15% efficiency of conversion from the thermal energy contained in the hydrocarbon fuel to electric power. It does so with vastly greater mechanical complexity and need for maintenance than the systems discussed above.

Micro wind turbines, though relatively simple, pose installation issues and operational safety hazards, and may not survive weather conditions that are quite probable at least once every year. Many small commercial wind turbine models come with "rated power" values that exceed the physical limits of kinetic energy flux through their swept areas at the "rated wind speed." As may be expected, the reality of their operational performance is nowhere near these claims. The mechanical figure of merit on most such systems, compared to the theoretical Betz efficiency of 59% of the kinetic energy flux for horizontal axis machines, is on the order of 10%. The electrical conversion efficiency is also low because of the wide range of torque and power encountered. It turns out upon careful investigation that the marketers of such devices, unlike those of large wind turbines, are not obliged to cite the rated power ***at*** the rated wind speed. The rated wind speed (typically around 12 m/s) is just a number suggested by the government. The rated power is what the manufacturers claim at the maximum wind speed (perhaps 40 m/s) that they claim the device will survive! Given that power is proportional to the cube of wind speed, one can easily calculate the consequences to optimistic customers who buy these systems. This is clearly an area where rigorous research and standards that will come with increased interest from Space researchers, would serve the community well. Solar Stirling engine systems offer greater efficiency than Rankine cycle engines for the modest temperature gradients encountered in most solar thermal systems. However, the net efficiency is still on the order of 20% even for spacecraft applications (Pisacane, 2005) where the cold side is exposed to the vacuum of space, and there is substantial mechanical complexity.

The conclusion from the above considerations is that solutions from space technology and elsewhere, should be actively developed for the application of micro renewable power systems. The competing “solutions” do not scale well at the low power levels that are appropriate to bring the first power swiftly to off-grid areas where people live in poverty. The cost-efficiency figures advertised by several providers of traditional solutions such as small wind turbines, are nowhere near the reality of actual operations. The alternatives available to people in such areas for the first few watts or watt-hours of electric power, are extremely expensive, and can be superseded by well-designed devices from the Space research community.

10. Some Suggested Solutions

To increase the cost-effectiveness of MRES, one approach may be to develop integrated hybrid systems that combine several different technologies and functions. The optimum combination may vary from one region or family to another, so the true challenge is to develop systems with a flexible architecture. The major benefit is likely to be in developing common power management systems that can handle a variety of generation technologies and operating conditions. This is conceptually no more difficult than using a standard spacecraft bus to build a variety of spacecraft depending on the mission. However, the pioneers will encounter high cost, as inventor Kamen [29] has experienced in developing a control system for a multi-faceted renewable power system for his island home. Some combinations of technologies are suggested below.

1. Horizontal axis wind turbine with a pico water pump and REDOX storage system, connected to a photovoltaic panel and a water purifier.
2. Solar thermal collector-concentrator with high temperature photovoltaic cells on the flow tube, connected to a Stirling cycle mechanical pump and electrical generator, as well as a hot-water circulation pump system for household needs, and a thermoelectric generator to charge the control system battery.
3. Thermophotoelectric generator with heat engine, for a scrap wood stove. Thermoelectric generators on exhaust pipe, powering LED lighting system through a battery.
4. Algae biodiesel tanks with mushrooms grown underneath, combined with a greenhouse and solar PV system and high-intensity LED lighting, with controllers.
5. Suburban compost methane generator with membrane gas separator and methane and hydrogen compression.
6. Robotic gardener and lawnmower powered by compost-generated methane generated from Robot-accumulated yard waste.
7. Solar thermoacoustic refrigerator combined with drinking-water generator and water purifier.
8. Solar PV/ thermal collector-concentrator and biogas fuel cell with microwave generator for microwave drying.

11. Efforts to Develop Learning Resources and Testbeds

This section discusses efforts at the first author’s school and laboratory to develop a Micro Renewable Energy Systems Laboratory and a set of courses that prepare engineers for these opportunities. The realization of the need for such an effort came through the discussions that led to the “Eighth Continent Chamber of Commerce” project at the Colorado School of Mines. 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 effort by Komerath and Komerath [30] studied the viability of a micro renewable energy architecture in the context of the Indian energy market. This used a Net Present Value approach taking into account the value of secondary employment, and elimination of the large-turbine infrastructure cost and delay, to show the benefits of the micro renewable architecture. 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. In turn, this led to the creation of two courses. 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 a predominantly technological campus, who had reached junior level. 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 thus 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 structure and teaching experience with the course, as well as its implications for opening international collaborations, are discussed in Komerath [31, 32]. The policy aspects of micro-renewable energy systems are discussed in Komerath, Venkat, Phillip and Halka [33].

Micro Wind Turbine - The vertical axis micro wind turbine testbed is shown in Figure 3. This 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. One issue is the smallest viable size of such machines. The 1-meter diameter, 1-meter tall machine has generated up to 62 watts of mechanical power, but only at 18 m/s wind speed, showing that there is a long way to go in Figure of Merit. A 2m x 2m version is projected to reach a kilowatt and operate under Pacific Coast winter winds. 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 is from easily available materials such as PVC pipes, plywood and roof flashing, enabling people anywhere on the planet to take ownership of repair and maintenance. 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.

Solar Thermal Generator - A second testbed is a solar thermal generator sized for a footprint compatible with roof terraces in the developing world – or an American urban high-rise balcony. It uses a reflective trough of aluminum sheeting formed by a simple wooden truss, covered with 99% reflective Mylar and coated with “Saranwrap” heat-resistant, non-polluting plastic sheeting, to focus sunlight onto copper tubes that form the heating element of a gaseous heat engine. Here the emphasis is again on minimizing cost and construction complexity, and then obtaining the best Figure of Merit consistent with those decisions. Thus, tracking motors and exotic collector shapes are avoided. In future, this testbed is to accommodate high-intensity photovoltaic cells along the collector pipes, different types of compressors and turbines, and photo-electric extraction from the waste heat. Versions of standalone solar thermal systems for the Moon are being considered.

Figure 3: Vertical Axis micro Wind Turbine testbed the Georgia Tech 42" Wind tunnel.

EduKitchen - A strong need in economically deprived communities is for cooking stoves that can operate efficiently with a variety of low-grade fuels such as scrap wood and dried leaves, without causing undue pollution. The Darfur Stove developed by a student team led by Lawrence Berkeley laboratory researchers [34] helped refugees in wind-swept, arid Darfur to do their cooking with much less fuel and better wind resistance than was needed with prior alternatives. This reduction in fuel was projected to have the life-saving impact of reducing the need for refugee women to go hunting for fuel in a region infested with human predators. A much more commonplace application would be to improve the efficiency and reduce the pollution of the typical camp-fire stone stoves that are used in millions of homes every day for lack of anything better.

Accordingly, 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 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 then successful because the recipients felt that food cooked on the shiny new devices lacked the "flavor" that came from their old "stoves."

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.

12. Conclusions

This paper has started exploring synergizes between extraterrestrial in situ resource exploitation technologies, and the terrestrial mass market for micro renewable power devices. It argues that many innovations and advancements in the space arena are indeed applicable to the systems that can solve the energy crisis at the mass-market level. Specific conclusions are listed below.

1. A large body of technical experience and innovation is documented in the archives of the STAIF and Space Resources conferences and in the NASA technology transfer office.
2. While many individual innovations have been spun off into the commercial sector, many others await integration into multiple uses.
3. The terrestrial mass market for single-family renewable power generators provides an excellent opportunity for space technology spinoffs.
4. The value of alternative sources of the first few watts of capacity, and watt-hours of energy, is up to 4 orders of magnitude above the marginal cost of urban grid-delivered electric energy.
5. The efficiency of micro renewable energy systems is comparable to that of low-power systems used in spacecraft.
6. Focused effort to develop common buses or other architecture could lead to a suite of integrated hybrid systems sharing common control and output infrastructure, thus improving the cost effectiveness of micro renewable power devices.
7. The appetite and capacity of the public, even in remote underdeveloped parts of the world to handle technically sophisticated equipment packages, is underestimated and under-appreciated. This provides a window of opportunity.

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