Thermoelectric and thermophotovoltaic micro renewable power systems for home use

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Terrestrial mass-market needs for off-grid power generators offer applications and challenges for space research. Synergy between research on extraterrestrial in situ resource exploitation, and research on terrestrial mass-market needs for standalone power generators, offers avenues to advance both, with large potential impact on the quality of life. The technologies have been shown to work. However, closing the business case for such devices requires careful definition of requirements and attention to a wide array of issues. In this paper, two systems derived from space technology are discussed. The first is a thermoelectric generator for use with rudimentary wood stoves. This is designed to produce enough power for a fan to augment air flow through the stove, a DC LED floodlamp for steady lighting, and an ultraviolet LED water purifier. The power budget for this system will close well under the 10-watt level that is projected for a single semiconductor thermoelectric generator; however serious challenges remain in active thermal control. The second system is a thermophotovoltaic generator for use with trash incinerators sized for middle class families or neighborhoods. Radiation from ceramic emitters placed in the incinerator is concentrated and filtered into a set of photovoltaic cells tuned to the radiation spectrum. Power levels of several tens to hundreds of watts have already been demonstrated from such systems.

I. Introduction

A common refrain heard among researchers on extraterrestrial in situ resource utilization (ISRU) techniques, is that government space agencies are unable to provide the sustained funding levels that they need, especially as missions to other planets and asteroids get pushed back. This creates a mismatch between the supply of new technological advancements, and the demand for these. On the other hand, hundreds of millions of people on our planet would benefit from micro renewable energy devices that are portable, or sized for a single family, or from viable systems to clean the air and provide lighting and drinking water to off-grid communities. Despite decades of strong interest, such devices have not been successful in the mass market, primarily (in the opinion of the lead author) because they are not really viable in the marketplace, they fail to achieve the advertised effectiveness as stand-alone systems, and cannot exploit synergies due to fear of predatory competition. The present venture capital model for commercializing space program spinoffs usually requires inventors to push a single technology with great speed as a miracle device into marketplaces that may require long-term education and slow percolation by example. Multiple ISRU technologies incorporated into these devices with the same seriousness that is shown in planning a payload for an interplanetary mission, could make a difference in maximizing their effectiveness. At the same time, mass market success could provide the huge increase in funding that is needed to take ISRU research to the levels needed for spacefaring civilizations. A few points are listed below:

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1. Support for space ventures must come from a much broader base of the population than what the present national space programs manage to garner. Today most people are asked to support space exploration on the arguments that we must explore the origins of our Universe and of Life, and that space technology and the sight of brave people cavorting in inflated suits will inspire K-12 students to learn calculus. Rightly or not, most taxpayers can imagine less expensive and more direct ways of achieving these objectives.

2. A close synergy between extraterrestrial ISRU systems and micro renewable energy systems (MRES) that people use at home, will enable a much better understanding of the value of advanced research in both arenas. It will at least provide a source of growing support to develop the elements needed for a Space-based economy.

3. Venture capital models of funding for MRES have not been successful, and with good reason. Devices such as micro wind turbines are only now catching the attention of consumer watchdog agencies and organizations. The fact that many vendors advertise performance well beyond what the laws of physics will allow, is not difficult for such entities to realize. In the case of the systems of interest in this paper, the end-use customers in the mass market are not likely to be able to afford such systems at the beginning. Instead, governments and non-governmental organizations would have to fund them based on a business model where the cost of the devices is traded off against the opportunity costs of delaying education, healthcare and information access to the end-users. These are issues calling for the employment of talents and expertise from well beyond traditional aerospace engineering.

Dudley-Rowley and Gangale,1,2 in wide-ranging papers, have pointed out the need to consider sustainability as part of long-term exploration missions, raising concerns about funding stability. While cautioning against over-reliance on in situ resource utilization technologies at the expense of backup resource planning, they also recognize that much of the innovation required for multi-year sustained long-duration space missions is along the lines of the same kind of innovation needed to respond to worsening environmental conditions and their unexpected consequences. They also argue for efforts involving global cooperation to develop long-term missions including comprehensive human factors considerations. Marsh and Rygalov 3 point to the need for self-sustainable behaviors and activities to increase the stability of closed ecological life support systems. Pass et al.,4 in describing humanity’s cultural imperative to colonize Space, points to the difficulties in recognizing the spinoffs from the Space programs to terrestrial applications.

On the other hand, people all over the world are demonstrating that they can use the products of technological innovation, without worrying about how they work. New applications for technology are coming up everywhere as people get access to these devices, and many of these uses are far from what the initial developers anticipated, because their frame of reference was far from that of many present users. We reason that bottom-up empowerment of people to develop their own stand-alone renewable energy solutions is the best way to encourage rapid adoption of renewable energy, and reduction of fossil fuel usage. This provides a contemporary public imperative to develop the synergy between aerospace technology and the market for MRES.

II. Thermoelectric and thermophotovoltaic generator systems

In a paper at SPESIF2010,5 our team presented the opportunity for synergy between ISRU research and the mass market for renewable power generators sized for a single family. We made the point that people who do not have access to the electric power grid pay extremely high costs per unit power, since they have to depend on batteries or fossil-burning generators. Our approach to this issue is to work at the interface between the technology innovators and the mass market users. We have developed five testbeds which are being refined through analysis, simulation and testing. In this paper two such concepts are discussed.

Many families around the world must do their cooking using rudimentary wood-burning stoves made of three stones or bricks, burning whatever wood scraps they can gather. These stoves are inefficient. With no more than natural convection for exhaust removal, they generate high levels of pollution. This leads to a high incidence of health problems. With mothers having to attend to cooking, their children must do their homework sitting in the same kitchen, with poor lighting and air quality. A high possibility of bacterial
infection from drinking water is also a reality. In the communities where they live, outdoor burning of trash generates high levels of smoke and air pollution.

The relevance of Space technology to the above situation is examined in this paper using two simple examples. The first device is a thermoelectric converter. This is suitable for small heat sources with moderate temperatures. Earlier bimetal strips have given way to more compact semiconductor devices with higher efficiency and mass-specific power. They find application primarily as a source for small amounts of electric power on long-duration space missions. The heat source in the Space mission case is the radioactive decay of nuclear isotopes, but more recently such devices are finding use in extracting power from the exhaust pipes of luxury automobiles. While the efficiency is very low, on the order of 5 to 6 percent, the simplicity of the device enables a useful amount of power to be extracted without much expense. Coupled with other technologies that use little power, it is shown that the system design will close at least at the conceptual stage, with excellent prospects for economic viability when mass-market economics and socio-economics of public policy are brought into the equation, rather than depending on venture capital schemes alone.

The second is a more involved system, and a bit further away in market readiness. It depends on the space technology of pyrophotovoltaics. Here a high-intensity, high-temperature heat source (the short-duration firing of a rocket engine in the case of space applications, a home garbage incinerator for the mass market) is used to heat up a suitable object placed in the exhaust, so that it emits strong radiation. The emitter is chosen so that its emission in the relevant temperature range is preferably with a sharp spectral peak, focusing the radiation onto a narrow-band photovoltaic cell array with high conversion efficiency in that spectral band. A Thermophotovoltaic (TPV) system concept shown later in the paper has two photovoltaic cells. One is for the infrared band, and one for the visible band of radiation, and they are separated by a dichroic mirror. This has the advantage of locating the converter some where it can be insulated from the high temperatures, and allows use of short-duration flames. This system may be more suitable for village-level landfill burnoffs or waste incinerators. In both types of systems, the involvement of the aerospace community in articulating the socio-economics and policy implications, is argued to be essential at least until mass-market acceptance ignites. A corollary offshoot of the above is a low-cost version where ceramic elements are used to generate broad-band radiation, with inexpensive broadband solar cells used to generate electricity.

II.A. Prior Work on Thermoelectric Conversion

Thermoelectric generators (TEG) have been considered as general heat engines by Gordon. Previously, thermoelectric generators have been used in conjunction with nuclear thermal sources. In the case of the Transit Satellites 4A and 4B, each thermoelectric generator (one per satellite) produced 2.7 Watts of electric power at the beginning of the mission by using a radioisotope heat source. These radioisotope thermoelectric generators (RTGs) known as SNAP-3B in 1961 were among the forerunners to current thermoelectric technologies.

In 1972, the next iteration of RTGs, the SNAP-19, was designed for the Transit Triad series under the same program. The RTG was not sealed. Excess heat was radiated to thermoelectric panels to provide additional power. The new RTG succeeded in the mission objective of providing 30 We at the end of a 5 year mission at a minimum of 3 V.. The SNAP-19 then powered the Nimbus-3 Meteorological Satellite. Two SNAP-19 RTGs were combined to provide 56.4 We after 1 year in orbit, comprising about 20% of the total power supply. The SNAP-19 also went on the Pioneer missions to Jupiter and Saturn and on the Viking Mars Landers. Variations of the RTGs on the Viking Landers have been on every interplanetary mission, either as a supplemental power supply or, as the main power supply.

Bass et al. describe a 1-kilowatt thermoelectric generator for terrestrial diesel engines. Ikoma et al reported a generator to use with gasoline engines. Snyder and Ursell discuss the design of systems with segmented and cascaded generators. The application of thermoelectric generation to power micro-devices has been explored beyond the Space power application. Schaevitz and Stordeur and Stark describe applications to microsystems. Nuwayhid et al. discuss a low-cost stove-top thermoelectric generator. Bulls describes the invention of thermoelectric modules where the addition of trace amounts of thallium to bismuth telluride increases the conversion efficiency of bismuth telluride thermoelectric modules from roughly 6% to...
The most common thermoelectric materials are composed of some combination of bismuth, telluride, and antimony. Efficient thermoelectric materials exhibit high values of $ZT$, shown here as equation 1, where $S$ is the Seebeck coefficient, $\sigma$ is the electrical conductivity, and $\kappa$ is the thermal conductivity. At 300K, $ZT$ of .003 is obtained using $\text{Bi}_2\text{Te}_3$. Combinations of Bismuth, Antimony, and Telluride can yield a $ZT$ as high as 1.2 at 300K.

$$ZT = \frac{S^2\sigma}{\kappa}T$$

II.B. Prior Work on PyroPhotoVoltaic Conversion

Green and Baillie have reported a solar cell with 43 percent efficiency, splitting the sunlight into spectral bands, sent to different types of cells. Barnett et al. have reported a design where the split solar spectrum is directed to very high efficiency conversion modules in the UV and IR portions, while a low-cost silicon cell is used for the mid-band. Sunlight passes through a front lens and hollow pyramid concentrator on to a dichroic prism. The low energy part of the spectrum below 1.4 eV passes through. The middle band between 1.4 and 2.4EV is directed on to a mid-energy solar cell. The concentrator transmitted over 93% of the incident solar energy. At 20X concentration, the design targets 53.5% total efficiency, out of a total thermodynamic efficiency of 64.2%. Thermophotovoltaic generators based on the Gallium Antimonide (GaSb) cell, which is sensitive to the infrared band of the spectrum include a 1.5 kWe residential combined heat and power thermophotovoltaic generator, a 100 W generator combined with a 25,000 BTU stove, and a 20 watt Butane-fed portable generator. Their system achieves a power to mass ratio of 942 Wh per kg compared to only 145 for a Lithion Ion battery. Chen and Goldstein describe a man-portable TPV generator that produced 112 watts of electric power using atmospheric combustion of propane, and a ytterbia emitter mantle. A fused silica absorption filter and 12 water-cooled silicon concentrator arrays were used, with a fuel-to-electric conversion of 1 to 2%. Khvostikov et al. have discussed TPV generators based on Gallium Antimonide. They showed 19 percent conversion from the emission spectrum of tungsten. With the emission spectrum truncated to be above 1870nm, 27 percent conversion was shown, and the optimum temperature range of tungsten emitters was given as 1800-2000K. Bitnar describes high-efficiency TPV systems using Yb2O3 selective emitters and Si or SiGe PV cells.

Azorin has reviewed the thermoluminescence properties of materials for the emitter part of the pyrophotovoltaic system. Desired emitter characteristics are high thermal conductivity, mechanical stability in the operating temperature range, selectivity of the emission spectrum and compatibility with the PV cell sensitivity spectrum, and stability to thermal shocks. Tantalum and Silicon Carbide have been preferred for high radiation environments. To avoid oxidation, emitters have been placed in vacuum or inert gas atmospheres. For the case of a fire, a ceramic piece such as aluminum oxide would be appropriate, being commonly available and able to withstand the highest temperatures that are likely to be encountered. One difficulty is that the emitted spectrum changes substantially with temperature, so that it will fluctuate with a time scale on the order of several seconds. Saxton studied emitter candidate materials to work with a T-58 naval gas turbine. Materials had to withstand a 1573K combustion gas environment and thermal shocks, and have an emissivity of 90 percent. He concluded that C/SiC with a SiC overcoat, and SiC/Si were the most viable emitter candidates.

III. Concept Designs

III.A. The EduKitchen Prototype: Thermoelectric generator for fuel efficiency, pollution control, lighting and safe water

Our TEG system uses a bismuth telluride alloy module, placed in an aluminum envelope suitable for inserting directly into a home 3-brick stove along with firewood. The aluminum envelope is made from recycled soda
cans. A thermocouple monitors the temperature, while a DC fan powered by a 12-volt battery drives air into the fire through a flat nozzle, also cooling the sink side of the TEG. The battery powers the fan, a 5-watt DC LED floodlight, and a milliwatt level narrow-band LED operating in the deep UV band of 254-274 nm as part of a water purification system modeled on the UV WaterWorks 40-watt blacklight device developed by Gadgil at LLNL, based on the early experiments by General Electric corporation. These studies showed that 254 nanometer far-ultraviolet radiation effectively killed well over 99 percent of bacteria present in water, quickly enough to permit installation of the blacklight over slowly-flowing water. More recent studies have suggested that the range of radiation between 260 and 270 nm, centered probably at 264 nm, is much more effective, since this includes the resonance wavelengths of the DNA of these bacteria. The power budget is seen to close with the levels of heat available from home stoves. The DC fan takes roughly 5 watts, the floodlamp takes about 3 watts and the water purifier less than a watt, bringing the total well within the capability of a single thermoelectric module. Figure 1 shows the concept graphically. The module is sized to fit at the edge of a wood-burning stove. The DC floodlamp is sized to provide steady white illumination, sufficient for a child to read and write under. Thus the EduKitchen system is intended to revolutionize the family’s living environment, providing clean-burning and fuel-efficient cooking stoves, efficient electric lighting and clean, safe drinking water. The technical and socio-economic challenges in perfecting such a device are formidable and span several disciplines. It opens a long-term research portfolio with immediate application to the test bed.

While the prototype will contain only a dial to turn the airflow up and down, the ultimate goal for the device is to be self-powered and self-monitored. A feedback loop should be able to sense the ideal temperature and adjust the airflow accordingly to achieve ideal combustion. The key to the loop will be coding chemical equations into MATLAB or other similar languages in such a way that reduces the inputs required from the user. An ideal device would need only to be plugged in, and sensors should be able to ascertain the wood type and ideal combustion conditions.

A side view of the fan/nozzle/thermoelectric generator device that is the crux of the full system is shown below as Figure 2. Here, the clamps apply a pressure of at least 5 psia, which is needed to improve the performance of the thermoelectric generator. The fan exhaust is shown in green, and is to convect away the heat passing through the TEG, as well as augment the oxygen flow through the fire.
Figure 2. Fan/Nozzle/Generator Schematic (side view)
IV. ThermoElectric Module

A 22 Watt TEG from Custom ThermoElectric Inc achieves its theoretical capacity when the hot side of the module is at 300°C and the cold side is maintained at 25°C, resulting in a temperature difference of 275°C. However, it is useful to mention that most commercial devices won’t be able to sustain power generation at a temperature in excess of 200°C due to thermal interface degradation on the hot side.

Performance tests using an electric iron are being used to develop the integrated device. Transient experimental results are shown in Figure 3. The iron was heated to operating temperature, and placed on the TEG. The electric power output rises rapidly and reaches a maximum near 1.2 watts, corresponding to the expected power for the temperature difference between the iron and the cold side of the TEG ($\approx 50^\circ$C). The wattage begins to drop as the temperature equalizes.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{power_vs_time.png}
\caption{ThermoElectric Generator Standalone Test Results}
\end{figure}

V. Measuring Fan Flow Rate to Augment Combustion

A setup, shown in Figure 4 was used to measure the flow rate. The flow was measured at 5 points at the exit: the center, the left side, the right side, the top, and the bottom. Figure 5 shows the variation of speed with respect to voltage for the different positions. Results on mass flow rate variation with fan voltage are shown in Figure 6.

Assuming a completely uniform fuel (we used black spruce wood due to the availability of chemical composition), we can predict how much air is needed to completely combust a kilogram of wood. Using an assumed value for the heat release of the wood, we can figure out how much heat is released per kilogram of wood, which can then be extended to how much heat is released per 16.275 moles of air, given a fuel rich environment. This analysis is shown as Figure 7 and shows that we can add up to 20 kJ/sec of heat just by using the fan alone. The specific stoichiometric equations and analysis are left for an appendix. The fan capacity is more than sufficient to vary the equivalence ratio of the combustion in a typical home stove over the entire range of flammability.

Recent work has been focusing on the larger problem of using the fan flow to remove heat from the backside of the TEG. A contoured nozzle was set up under the TEG with the electric iron used to heat it. Figure 8 shows an increase in peak power, and the power remains higher than in the case without the fan. However the heat removal rate is nowhere near adequate, and methods of increasing the heat removal by an order of magnitude are being considered such as a stronger fan, or even possibly redesigning the system to allow the cold side of the TEG to be water-cooled.
Figure 9 shows one prototype of an EduKitchen system, with a DC Cyclone Blower fan being run. This fan comes integrated with a 90-degree turn of the flow, compatible with building the insert and permitting a substantial reduction in size from the initial prototype.
V.A. Pyrophotovoltaic System

A second societal problem in many nations is urban garbage, and the air pollution that results from uncontrolled open-air burning of garbage and fallen leaves. A simple incinerator with a gas starter and a chimney,
is beginning to catch on as an effective solution to this problem. We propose to add an electricity generator to such incinerators in order to power simple needs such as lighting in the surrounding area, and again, a forced convection fan to optimize flame equivalence ratio. Here the power need and the potential for power generation are both an order of magnitude larger than those of the home TEG.

A pyrophotovoltaic (PPV) system is appropriate for this application. As presently conceived, this consists of a set of emitter rods, probably of a ceramic material, that is placed in the fire and hence glow with substantial radiant emission. Narrow-band filters are used with an array of narrowband photovoltaic cells, giving high conversion efficiency. Where the power requirement is smaller, a more cost-effective approach is to use a ceramic emitter and a broadband solar cell. The generated power may have several applications specific to the community. These may include powering controlled air flow through the incinerator to optimize heat release and minimize pollution, street lighting, public telephone kiosks, purification of drinking water for public fountains, pumping water for public use, irrigation systems or low-voltage lighting for gardens, to name a few. The net benefits of such a system extend beyond disposing of garbage, to eliminating one of the worst sources of air pollution in many cities around the developing world. The markets for both types of devices run into the millions, perhaps hundreds of millions for the ”Edukitchen” application.

![Figure 10. Schematic Sketch of a Thermophotovoltaic system](image)

### VI. Conclusions

In the above we show that a conceptual design for a thermoelectric generator can close. In the case of the thermophotovoltaic generator, there are already several devices in the general specification range of the intended application to domestic and urban garbage incinerators. However neither of these applications is widely seen today, and the market for such devices has not developed. In the case of the integrated thermoelectric device, that is because the intended customers most certainly do not have the disposable income to afford such devices, otherwise they would not be living in conditions where the device is needed. A recreational version could be designed to cater to people going on camping trips in developed nations, but this is not likely to capture enough of a market to justify the investment. In the case of the TPV system, various applications have been identified, but mass-market success does not appear to have arrived. The argument for such devices includes their positive effects to the environment, public health, children’s education, and the opportunities opened for economic participation of more people. Accounting for such aspects requires incorporation of social and public policy considerations. Specific conclusions at this writing are:

1. Even 10 watts of power generated by a thermoelectric module should suffice to close the design of a system to achieve stoichiometric combustion in a home woodburning stove sized for a single family, power a DC LED floodlight, and a UV water purifier.

2. An initial configuration of an EduKitchen thermoelectric generator system has been constructed and is undergoing testing.
3. Convective heat removal from the sink side of the thermoelectric generator appears to pose a substantial problem in generating sufficient power.

4. Solutions for this problem are being investigated, and may require further infusion of advanced spacecraft active thermal control technology.

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VII. References


26 “JX Crystals ThermoPhotoVoltaics,” October 2011.


