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Potential Impact of ZT = 4 Thermoelectric Materials on Solar Thermal Energy Conversion Technologies †

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State-of-the-art methodologies for the conversion of solar thermal power to electricity are based on conventional electromagnetic induction techniques. If appropriate ZT = 4 thermoelectric materials were available, it is likely that conversion efficiencies of 30−40% could be achieved. The availability of all solid state electricity generation would be a long awaited development in part because of the elimination of moving parts. This paper presents a preliminary examination of the potential performance of ZT = 4 power generators in comparison with Stirling engines taking into account specific mass, volume and cost as well as system reliability. High-performance thermoelectrics appear to have distinct advantages over magnetic induction technologies.

Introduction

According to the Energy Information Administration of the Department of Energy (DOE), the world net electric power generation in the world in 2008 was about 19 560 TWh (1.956×10^{13} KWh, Figure 1). This number is projected to increase to 31 780 TWh by 2030, of which the U.S. would consume about 5323 TWh. To meet this demand, significant efforts need to be made to develop renewable energy technologies. Solar energy has the ultimate potential of providing 120 000 TW globally. The solar radiation intercepted in an hour by earth therefore equals world power needs for a year. In practice, perhaps as much as 600 TW of solar energy can be converted to electricity.

Photovoltaic and solar-thermal are two conversion technologies receiving a great deal of attention. Solar-thermal conversion uses the full solar spectrum and generates electricity by conventional electromagnetic induction methods. There are three solar-thermal technologies that are currently attracting worldwide attention: tower receiving systems using Brayton or Rankine engines; parabolic trough systems that also use Brayton or Rankine engines; and dish collector systems using Stirling engines. Although each solar-thermal system has its own advantages, dish-Stirling systems claim to outperform the other two systems. According to Southern California Edison & Sandia National Laboratory, prototype dish-Stirling systems are said to be capable of an annual energy density of about 629 kWh/m^2, followed by central-tower with 327 kWh/m^2, parabolic-trough with 260 kWh/m^2, and tracking-photovoltaic with 217 kWh/m^2 as is shown in Figure 2.[1] Under otherwise identical conditions, the dish-Stirling system if it performs according to projections would require the least land area for solar collectors. Another dish-Stirling company, Infinia Stirling Engine Technology, claims that their dish-Stirling system would produce 1.5 MW of power on a 3 acre site versus 13.5 acres required for generating the same amount of power using photovoltaic-based systems. In addition, it is claimed that dish-Stirling systems are

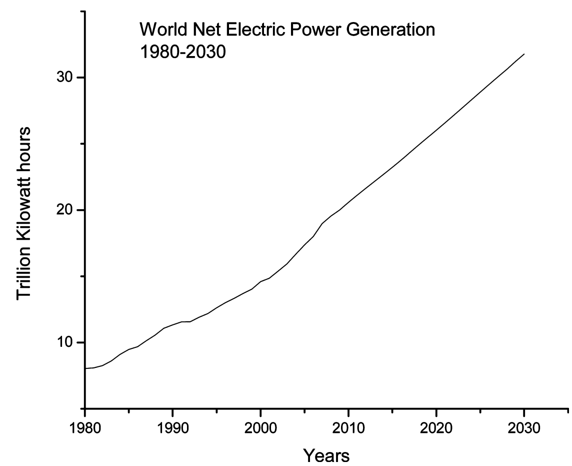

Figure 1. World net electric power generation from 1980 to 2030. Sources: Energy Information Administration of the U.S. Department of Energy (2009).

easy to install due to large-scale modularization and are relatively easy to replace.[1] Dish-Stirling systems can in principle achieve high-operating temperatures, leading it is claimed to high Carnot-efficiencies. Thus SunCatcher claims to hold the world's highest solar energy to grid quality electricity peak conversion efficiency of 31.25%.

The proposed SES Solar One project would be a nominal 850 MW Stirling engine project with construction planned to begin in late 2010. The primary equipment for the generating facility would include the approximately 34 000, 25 kW solar dish Stirling systems, their associated equipment and systems, and their support infrastructure. Plans are for this project to be constructed on an approximately 8230 acre site located near Barstow, California. Another project called Solar Two, which at present is 750 MW with options to go to 900 MW, is planned at Imperial Valley, CA under an agreement with San Diego Gas & Electric (see Figure 3).

Conversion Efficiencies and Costs of State-of-the-Art Thermoelectric Materials

In the present paper, a concept is described that would replace Stirling engines with thermoelectric modules. It is based on the

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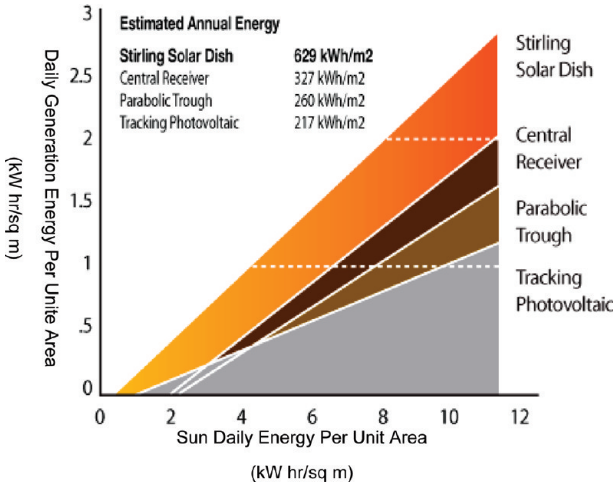

Figure 2. Estimated annual energy for different solar-thermal technologies and tracking photovoltaic. Sources: Southern California Edison & Sandia National Laboratory.

assumption that a suitable thermoelectric material with ZT=4 can be developed. Such a material can be projected to have a conversion efficiency of 30−40%. A thermoelectric converter is a totally solid state direct energy conversion device, not requiring pressurized fluids or rotating machinery.

In the past four decades, thermoelectric unicouples made of silicon germanium (SiGe) or lead telluride (PbTe) alloys have been used in more than 35 radioisotope thermoelectric generators (RTGs), to convert thermal power generated by a radioisotope reactor to electricity for deep-space missions. Their maintenance free operation has been established over a 30 year period, for example, in the Voyager spacecrafts. El-Genk et al. examined the feasibility of using thermoelectric converters for a scaled-up 20 kW space power system,[2] and concluded that either PbTe or SiGe thermoelectric converters would have better overall performance compared to the He−Xe Brayton turbo-alternator. Clearly, the application of thermoelectric power generators has been limited so far to RTGs for space missions because state-of-the-art thermoelectric materials with ZT values near unity limit conversion efficiencies to ∼8−10%. Figure 4 shows the manner in which conversion efficiencies of thermoelectric materials depend on ZT when plotted as a function of heat source temperatures, under the assumption that the temperature of the cold side is maintained at 300 K. To compete with state-of-the-art solar-thermal technologies based on the electromagnetic induction method, the conversion efficiency of thermoelectric materials must be 30%−40%. This requires ZT ≥ 4 and a large temperature differential between the hot and cold ends of a thermopile. Remarkable progress toward achieving high ZTs has been made in the past few years. A ZT near 2 has been seen in nanostructured-SiGe, Zintl compounds, and LAST.[3−5] However, devices based on these materials have not yet been reported.

Even if higher ZT would be achieved, the costs of materials currently being favored are probably too high for large scale application. For example, the cost of BiTe and PbTe is about \$140/kg and \$99/kg, respectively, and SiGe is from \$270/kg to \$660/kg depending on the elemental ratios in the alloy.[6] Tellurium, a most important element in thermoelectric materials, is also sought after as a constituent of solar cells. Current refinery production of tellurium worldwide is 128 000 kg per year, too small even for large scale automotive applications,[7] let alone for TW power generation. Constraints on germanium production have led to increases in the price for polycrystalline zone-refined germanium from \$500/kg in 2003 to about \$1000/kg in 2007[8] due to increasing demands for this element by the fiber and IR optics, electronics, and solar cell industries. It is clear that thermoelectric power generation on the TW scale will require more abundant, less expensive and environmentally benign elements as candidate materials. Resource and environmental impact considerations will play an increasingly important role in reaching decisions concerning the practicality of thermoelectric power generation systems.

Potential Performance of ZT = 4 Thermoelectric Power Generators

From a historical perspective, solar thermoelectric generators were proposed as long ago as 1954 but they had very low efficiency.[9] Chen et al. made a thermodynamic analysis of a solar thermoelectric generator based on a thermally insulated flat plate collector[10] and H. Naito et al. developed a solar-powered thermionic/thermoelectric converter by using a parabolic mirror.[11] With the development of solar-tracking technologies, especially for solar-dish systems, we thought it worthwhile to revisit the feasibility of solar thermal conversion on the assumption that a breakthrough thermoelectric material with ZT = 4 can be developed. Dish systems can be designed to have high-concentrating ratio from 800 to 15 000, which allows one to achieve temperatures at which Carnot efficiencies of 70−75% can be reached. A parabolic dish with a collector area of ∼90 m^2, and a focal length of ∼7.45 m can reach near 1000 K over a diameter of ∼20 cm. A comparison of the performance of thermoelectric generators with that of Stirling engines will be made on the basis of specific mass, volume, and cost, as well as reliability. All of these considerations are based, as has already been stated, on the supposition that ZT = 4 can be reached. Lastly, we will briefly address the advantages of high-voltage DC transmission.

1. Specific Mass. Specific mass is defined as the power W generated per kilogram of material. High-specific mass clearly lowers loadstress on dish structural members and lowers power requirements for tracking machines. Seon-Young Kim et al. presented preliminary designs and specific power estimates of high efficiency, free-piston Stirling engines for 5, 10, and 25 kWe outputs.[12] Their calculations indicated the 25 kWe dual opposed Stirling engine (with alternator) has the highest specific power of about 220W/kg. In addition, NASA began a new project with Auburn University to develop a 5 kW single converter (with alternator) for potential use in a lunar surface reactor power systems. The goals of this development program include reaching a specific power in excess of 140 W/kg at the converter level.[13]

On the other hand, thermoelectric power modules using $Si_{0.8}Ge_{0.2}$ on RGTs have a specific mass of 230 W/kg.[14] We have arrived at our own estimate of the specific mass for a commercial thermoelectric generator module based on bismuth telluride (BiTe) with ZT ∼ 1 (Custom Thermoelectric Company). This module generates output power of 14.7 W with a hot side at 200 °C and the cold side at 0 °C. The mass of the module is 48 g without leads, which includes the hot and cold plates, and BiTe assembly. This gives a specific mass of 300 W/kg. If ZT = 4 can be achieved, the mass of thermoelectric material would be reduced by a factor of 3−4 leading to a specific mass of 700−900 W/kg for an equivalent power output.

We estimate that the weight of a separate thermoelectric module could be 5 times less than that of an equivalent Stirling engine/alternator, thus greatly reducing the load on dish structural members with a consequent reduction in the overall

Figure 3. Prototype SunCatcher will be used for 850 MW Solar One and 900MW Solar Two. Sources: Sandia National Laboratory

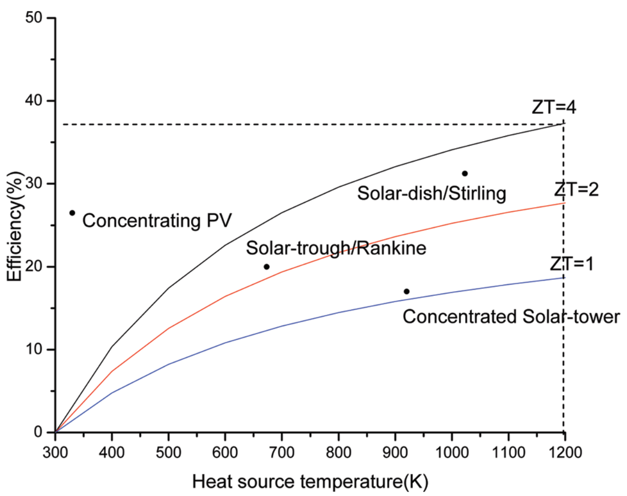

Figure 4. Thermoelectric conversion efficiencies as a function of temperature differentials for different values of ZT. Conversion efficiencies for several state-of-the-art technologies are also indicated for comparison purposes.

weight of the dish structure. The resultant significant reduction in collector cost could substantially benefit the cost of solar thermal power. Mancini et al. concluded that initial costs of Stirling dish systems are distributed with 40% in the concentrator and controls, 33% in the power conversion unit (PCU), and the remaining 27% in the balance of the system.[15] Using a thermoelectric module is anticipated to have a dramatic effect on lowering overall cost of a dish solar collector system, but quantitative evaluation of cost impacts is beyond the scope of this paper.

2. Specific Volume. The dimensions of the Stirling Engine Systems (SES) dish Stirling system power conversion unit (PCU) with 25 kWe output power are approximately 213 cm long by 152 cm wide by 91 cm high[16] of which the Stirling engine and alternator occupy at least half of the volume. Therefore, the specific volume of the Stirling engine is about 0.02W/cm^3.

Comparison with a ZT = 4 thermoelectric material of density 3 g/cm^3 (similar to that of $Si_{0.8}Ge_{0.2}$) and specific mass of 700 W/kg shows a very large advantage for the thermoelectric. For a 25 kW power generator, 36 kg of material is required leading to a specific volume of 2−3 W/cm^3.

Although thermoelectric generators currently have lower specific volumes due to the spaces between each thermoelectric segment, the state-of-the-art thermoelectric generators already have a relatively high specific volume of about 1.42 W/cm^3 (14.7 W power output in a package of dimensions 5.6 cm × 5.6 cm × 0.33 cm, Custom Thermoelectric Company). One anticipates that a ZT = 4 thermoelectric generator will have a volume 2 orders of magnitude lower than that of a Stirling engine with comparable power output.

3. Specific Cost. Although the Stirling engine was conceived in 1816 and has been under development ever since, cost is an important factor that has prevented large scale applications so far. The cost for a kinematic Stirling engine can be as high as $10,000/kW, and for the free piston Stirling engine it is about $35,000/kW. Projected cost estimates are ~$1,000/kW if large scale production can be achieved.

At present, the price of $Si_{0.8}Ge_{0.2}$, the best studied of the current generation high temperature thermoelectrics, is about $660/kg. A 25 kW thermoelectric generator would require 36 kg $Si_{0.8}Ge_{0.2}$ in the unlikely event that ZT = 4 could be achieved for this material. This will give a slightly lower specific cost than the projected price of a Stirling engine. Thermoelectric generators, like photovoltaics, require DC-to-AC inverters and their cost per solar-dish must be considered. The DOE goal for the cost for such inverters is $40−100/kW. Even with this additional cost added to that of, for example, a projected $Si_{0.8}Ge_{0.2}$ thermoelectric unit, the price would still comparable to that of a Stirling engine. The specific cost could eventually be greatly reduced by advanced thermoelectric materials that are based on more abundant and inexpensive elements.

4. Reliability. Most solar power stations will likely be built in deserts or desertlike regions where the environment is harsh and difficult to access. Low-maintenance requirements are mandatory to reduce the total cost of a solar power station. Stirling engines are said to require little maintenance and have been redesigned for greater efficiency and performance. Such engines have received hundreds of thousands of hours of on-sun testing on all subsystems, and over 50 000 h of complete system on-sun testing at Sandia National Laboratories in Albuquerque, New Mexico as well as at other locations. Experience with thermoelectric modules in space shows that RTGs have averaged lifetimes of over 10 years in part because they do not require pressurized fluids or rotating machinery. In fact, RTGs based on SiGe or PbTe modules have been providing power to deep-space probes for over 30 years and can therefore be said to be a proven and highly reliable technology.

STM Power Inc., a company based in Ann Arbor, Mich., recommends preventive maintenance for Stirling engines, including lube and fluid check, every 1000 h and a longer procedure every 10 000 h. Major maintenance consists of replacing piston rings, rod seal cartridges, and other components in a procedure that takes about 16 h.[17] If this were to turn out to be the case in an actual application, a system such as Solar One with its projected complement of 34,000 Stirling dish systems, would require 544,000 h of full preventive maintenance to be accomplished by an estimated 226 workers working on a basis of 8 h/day and 300 days/year. Such maintenance costs would likely have to be considered part of the specific cost of Stirling engine solar dish installations.

5. DC or AC. Historically, the grid has been used primarily to transmit AC power. Recently, the cost of high voltage DC (HVDC) equipment for long distance DC transmission has fallen below that of comparable AC equipment. For example, 800 kV DC transmission is now said to be one-third cheaper than AC for a 750 mile transmission line.[18] In addition, DC does not introduce a reactance into the line and susceptance along the line, has lower line resistance than AC systems, and has no frequency variation to monitor since its frequency is zero. More and more, long-distance HVDC transmission systems are being installed around the world.[18] However, high megawatt power inverters are still under development. Silicon carbide (SiC) has been considered an enabling material to replace conventional silicon (Si) components for future MW power inverters, since SiC enables higher switching frequencies at higher operating temperatures and voltages.

Summary

In this paper, we briefly describe the commercial photovoltaics and solar-thermal technologies, and point out solar dish-Stirling systems outperform other technologies from the point view of energy density, modality, and easy maintenance. The history and the state-of-the-art thermoelectric power generators are also reviewed in this paper. In addition, we conclude that thermoelectric power generation on the TW scale will require more abundant, less expensive and environmentally benign elements as candidate materials. Lastly, we presents a preliminary examination of the potential performance of $ZT = 4$ thermoelectric power generators in comparison with Stirling engines, taking into account specific mass, volume, and cost as well as system reliability. High performance thermoelectrics appear to have distinct advantages over magnetic induction technologies.

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