$/W Costs of Thermoelectric Waste-Heat Recovery for Stationary Applications

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ABSTRACT

There are challenges related to cost and scalability of thermoelectric generators. Prior work investigated the costs and system performance factors that govern device efficiency and commercial feasibility of promising thermoelectric materials [1, 2]. Bulk thermoelectric materials can achieve costs below $1/W, and thermoelectric technologies are particularly advantageous for waste-heat recovery applications. System costs for heat exchangers and ceramic plates are substantial. In this work, we apply a cost-performance metric to determine how thermoelectric generators can be designed and implemented for three example waste-heat sources: gas turbines, glass annealing lehrs, and household water heaters. The results demonstrate thermoelectric waste-heat recovery can be a viable option to improve these energy systems and indicate which thermoelectric materials are most promising for these thermoelectric generators.

Keywords: thermoelectrics, thermoelectric cost, $/W, waste heat recovery costs

1 INTRODUCTION

Waste-heat recovery techniques are of vital importance for energy efficiency. The majority of energy consumed from resources goes unutilized, and it is mostly rejected in the form of heat. Coupled with the increasing demand for electricity, this waste-heat is a valuable resource if it can be used to generate electricity.

Thermoelectric generators convert heat into electricity and thus offer a means to achieve waste-heat recovery. Unlike other heat engines, thermoelectric generators are solid state devices without moving parts. Thermoelectric materials are typically semiconductors in which electrons move in response to a temperature gradient, giving rise to an electrical potential. When connected to a load resistance, electrical power is generated.

There have been notable advancements in the development of new thermoelectric materials, and reported materials figure-of-merit, *ZT*, values have crept upwards. However, the increase in material performance has not resulted in a comparable increase in device performance. There are a number of challenges with thermoelectric device engineering. As depicted in Figure 1, thermoelectric generators are composed of multiple components other than the thermoelectric material. Each layer and interface within the device adds sources of electrical contact and/or thermal resistance which hinder device performance. Moreover, these resistances can increase during operation as cracks and voids are created and grow due to stress concentration and expansion mismatch between layers. Heat exchangers are required to facilitate heat transfer to and from the thermoelectric material, so their effective heat transfer coefficients, or *U*-values, are critical. Material stability is also a concern since many candidate thermoelectric materials undergo oxidation and sublimation at high temperatures.

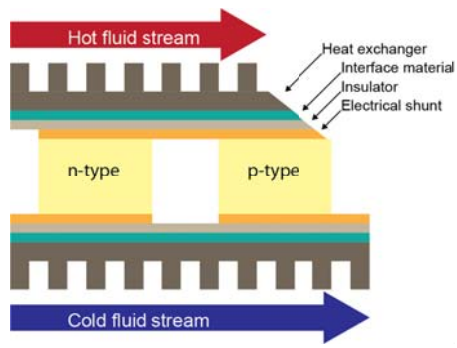

Figure 1. Schematic of a thermoelectric device showing a typical thermocouple composed of two legs made from semiconductor materials. The legs are thermally in parallel and electrically in series. Various interface materials are used to electrical isolate the leg assembly and thermally connect it to the rest of the device components.

Existing applications of thermoelectric generators are limited due largely to low efficiency. They have primarily been used to power space vehicles. Although typical device efficiency is about 5-10%, the high reliability and low maintenance attributes make thermoelectric generators ideal for remote space applications.

Given the abundance of waste-heat sources, it is reasonable to consider future applications for thermoelectric generators in waste-heat recovery [3]. Indeed, prototype thermoelectric generators have been developed for vehicle exhaust heat recovery [4]. There are significant challenges in such applications due to system size and location constraints as well as considerable vibrations and thermal cycling. On the other hand, stationary applications such as power plants and high temperature industrial processes may

be more favorable candidates for thermoelectric power generation [5]. Three examples of stationary applications are considered here: a gas turbine, a glass annealing lehr, and a household water heater.

Demonstrating the cost-effectiveness of thermoelectric generators is essential to garnering commercial interest and financial investment in the development and deployment of this technology. The benefit to recovering the waste-heat for electricity generation must warrant the expense of the device, so an appropriate metric for evaluating the market potential of thermoelectric generators is one which combines the device cost with the power output. A suitable metric has been developed and provides the cost of thermoelectrics in $/W by considering material, manufacturing, and system costs together with electrical power output [1, 2]. This work applies the metric to three waste-heat sources (gas turbines, glass annealing lehrs, and water heaters) to project the cost-competitiveness of thermoelectric waste-heat recovery and investigate which thermoelectric material candidates are most promising.

2 METHODS

2.1 Cost Metric

The cost metric used here integrates the device physics with the various costs [1]:

$$G = \frac{\left(\left(C_B + C_{M,B}\right)\rho L + C_{M,A}\right)AF + C_{hx}UA}{\eta_{TE} q_h} \quad (1)$$

where P_{gen} is the electrical power generated. The raw material cost C_b, manufacturing costs C_{mb} and C_{ma}, and heat exchanger costs C_{hx} are difficult to specify as they vary widely based on factors such as availability and equipment cost and throughput. The values used here are taken from a prior study which applied the cost metric using properties of thirty state-of-the-art thermoelectric materials, typical manufacturing approaches, and off-the-shelf system components. The cost is linked to thermoelectric leg parameters such as material density ρ, leg thickness L, total planar area A, and fill factor F which is the ratio of the thermoelectric area to the total area. The fill factor was set to 0.5 for the calculations of $/W reported here.

Manufacturing processes are enacted (1) on a bulk material with throughput depending on the mass of material processed (e.g. milling or hot pressing) and (2) on a planar area basis (e.g. dicing or metalization). The traditional thermoelectric device structure with the form depicted in Figure 1 require considerable assembly efforts which may be manual or automated (e.g. pick-and-place). The assembly cost is not included in the analysis here, but it could easily be incorporated into the cost metric by adding it into the areal manufacturing costs.

Since commercial feasibility will be based in part on cost minimization, the thickness of the thermoelectric material is optimized to minimize the overall cost in $/W for the approach presented here. There is a complex interplay between the electrical and thermal transport within the device and the optimized cost [2]. Nonetheless, sufficient net power output is still a critical goal, so the cost-optimized system cannot be sized too small to produce a meaningful amount of power.

2.2 Thermoelectric Materials

Thermoelectric materials are often classified by compound type [6]. Some key material groups are chalcogenides, silicides, clathrates, skutterudites, half Heuslers, and oxides. The differences between material groups and their optimum operating temperatures have been described extensively. Based on a survey of these materials, a limited group of materials were used in the analysis here. At least one material from each class was selected based on the highest reported *ZT* value for the application temperatures used here. Table 1 lists the material properties for the six materials considered. The properties were extrapolated using the material data reported by the original groups which developed and characterized the materials. Matched n- and p-type materials properties were assumed in the analysis; however, in practice it is challenging to develop both n- and p-type thermoelectric materials with matched properties.

Thermoelectric materials are sometimes categorized by material form (e.g. bulk or thin film), as well. For the high temperature applications considered here, bulk materials are the main candidates, so they are the only ones included here.

2.3 Applications

Three representative applications were analyzed and are summarized in Table 2. They represent multiple boundary conditions: medium and high temperature waste-heat exhaust streams and air- and water-cooled cold sides. There is a range of exhaust gas temperatures for each application, so a practical value of the heat source at the thermoelectric generator is given in the table and used in the analysis. For this analysis, the coolant temperature was taken as 50ºC for all applications.

Gas turbine power plants have high exhaust gas temperatures. Thermoelectric generators may be a feasible waste-heat recovery option in small to medium sized, single cycle plants where an alternative bottoming cycle or recuperation scheme is too expensive or maintenance-intensive. Glass product manufacturing often requires an annealing process in which the glass passes through a lehr. The lehr is a kiln with a spatially controlled temperature variation that reduces thermal shock or mechanical stress concentration in the glass. Unlike other steps in the glass manufacturing process, the flue gas in a lehr is relatively free of contaminants and molten glass. In a gas-fired, tankless water heater the combustion gas stream passes through a compact heat exchanger to heat building water.

Table 1. A selection of materials from each of the main thermoelectric materials classifications. The figure of merit of each material is provided for relevant waste-heat recovery temperatures [7-12].

Classification	Material	*ZT* at T_h= 500ºC	*ZT* at T_h= 800ºC
Chalcogenide	$(Na_{0.0283}Pb_{0.945}Te_{0.9733})(Ag_{1.11}Te_{0.555})$	1.1	1.5
Silicide	$Mg_2Si_{0.6}Sn_{0.4}$	0.63	1.0
Clathrate	$Ba_8Ga_{16}Ge_{28}Zn_2$	0.43	0.48
Skutterudite	$Yb_{0.2}In_{0.2}Co_4Sb_{12}$	0.80	0.93
Oxide	$Ca_{2.4}Bi_{0.3}Na_{0.3}Co_4O_9$	0.085	0.13
Half Heusler	$Zr_{0.25}Hf_{0.25}Ti_{0.5}NiSn_{0.994}Sb_{0.006}$	1.1	1.4

Table 2. Exhaust flue gas temperature (heat source) and coolant fluid and temperature for thermoelectric generators if they were used for waste-heat recovery in three stationary applications: turbines, lehrs, and water heaters.

Application	Exhaust temperature	Coolant temperature	Cooling source
Gas turbine	500°C	50-100°C	Air
Glass annealing lehr	500°C	50-100°C	Closed-loop water chiller
Water heater	800°C	25-50°C	Building water

Since the combustion gas stream temperature is about 1400ºC, a thermoelectric generator embedded within the water heater system would still experience heat source temperatures near 800 ºC [13]. Some of the heat energy could be converted into electrical power while still achieving sufficient heating of the building water.

There are a key factors which influence the suitability of an application for thermoelectric waste-heat recovery. The composition of the flue gas is critical since particulate and contaminants can foul the generator's heat exchanger surface. Industrial processes in which raw materials such as metals and glass are heated in furnaces seem appealing for waste-heat recovery, but the practical device engineering required to cope with dirty flue gas may be prohibitive. The stability of the heat source influences the amount of thermal cycling the thermoelectric generator experiences. The cycling will affect the amount of power generated and cause wear and tear on the device due to varying thermal expansions. These considerations are important for combustion appliances like water heaters which turn on and off frequently.

The effectiveness of the thermoelectric generator's heat exchangers is critical to power output and cost. The heat exchanger *U*-value is its overall heat transfer coefficient and is influenced by the heat exchanger material (e.g. steel, copper, etc.) and the heat exchange fluids. For the two materials exchanging heat, the amount of heat transferred through the exchanger is limited by the material with the lower effective heat capacity (*i.e.* the higher thermal resistance). When a coolant flows through the heat exchanger, the effective thermal resistance can be lower by increasing the coolant flow rate, thus increasing the rate of heat transfer. However, mechanical work is required to flow fluid through the heat exchanger. The commercial value of a thermoelectric generator for waste-heat recovery is in the net power delivered from the system. The net power will decrease as the work required to boost coolant flow rate increases.

At the thermoelectric generator's hot side, the heat is exchanged between the exhaust gas and the solid thermoelectric. The *U*-value for the hot side heat exchanger was taken to be 50 W/m^2K. At the cold side, heat is exchanged between the solid and coolant gas or liquid. The thermoelectric generator cold side *U*-values for the turbine, lehr, and heater applications were set at 100, 1000, and 1000 W/m^2K, respectively [14].

3 RESULTS

The costs for thermoelectric power generation systems using six top-performing thermoelectric materials are provided in the figures below. Figure 2 shows the estimated thermoelectric generator cost for a water heater application. The cost is broken into two components, the raw material and manufacturing costs and the cost of the heat exchanger and ceramic insulator plates. The results for the clathrate and oxide sample materials demonstrate the need for a minimum materials performance level for a cost-effective device. For instance, oxides' low performance cannot compensate for their low cost. On the other hand, the silicide material does not have the highest *ZT*, but the low cost compensates to make its cost-performance similar to the higher *ZT* chalcogenide and half Heusler materials. These examples demonstrate the tradeoffs between material and manufacturing costs and performance. The cost breakdown also demonstrates the significant expense associated with system components other than the material. The ceramic insulators and heat exchangers provide essential functionality but at an expense that outweighs that of the thermoelectric material.

The generator material and manufacturing costs for three applications are show in Figure 3. The clathrate and

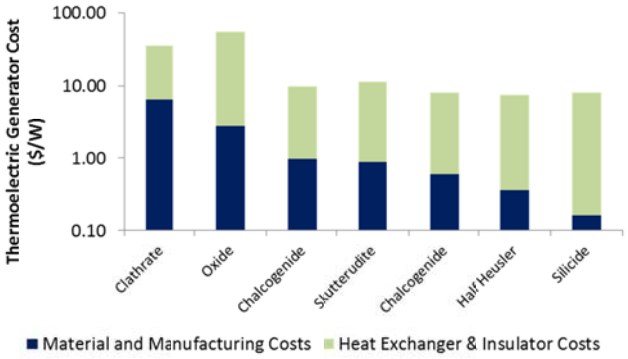

Figure 2. Cost breakdown for thermoelectric generators comparing (1) the impact of material type and (2) material and manufacturing costs with system components costs.

oxide material examples are omitted since their costs are an order of magnitude large than the other example materials. The benefit of more effective cooling with water rather than air on the device cold side is evidenced by the lower costs for the glass annealing lehr application compared to the gas turbine application. The low cost due to a large temperature difference and presence of water cooling in the water heater application makes the heater a good potential application for thermoelectric heat recovery. However, the minimal operation time might preclude most expenses related to heat recovery measures including thermoelectric generators. The cost of primary electricity generation methods are still generally lower than that of thermoelectrics generators [15]. The cost results demonstrate that thermoelectric generators could be cost competitive with organic Rankine cycle systems which are also used for waste-heat recovery but potentially have many more installation and maintenance challenges than thermoelectric generators [16].

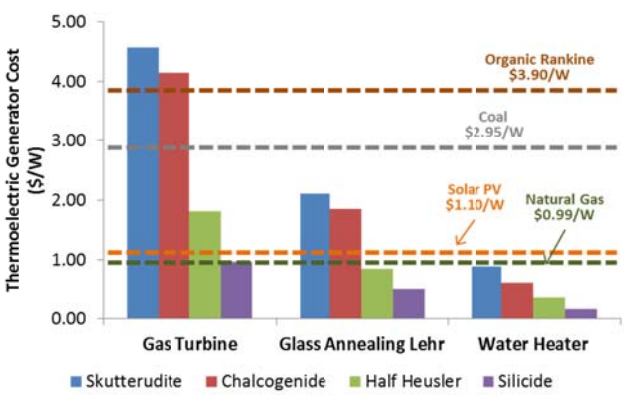

Figure 3. Materials and manufacturing costs for thermoelectric generators considered in three applications.

4 CONCLUSIONS

A cost-performance metric has been applied to thermoelectric generators for waste-heat recovery in three applications. This technology is most cost-competitive if water cooling can be incorporated without significant reduction in net power output. The costs of off-the-shelf system components are a critical pain point in thermoelectric generator costs.

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