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Cost–Performance Analysis and Optimization of Fuel-Burning Thermoelectric Power Generators

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Energy cost analysis and optimization of thermoelectric (TE) power generators burning fossil fuel show a lower initial cost compared with commercialized micro gas turbines but higher operating cost per energy due to moderate efficiency. The quantitative benefit of the thermoelectric system on a price-per-energy ($/J) basis lies in its scalability, especially at a smaller scale (< 10 kW), where mechanical thermodynamic systems are inefficient. This study is based on propane as a chemical energy source for combustion. The produced heat generates electric power. Unlike waste heat recovery systems, the maximum power output from the TE generator is not necessarily equal to the economic optimum (lowest $/kWh). The lowest cost is achieved when the TE module is optimized between the maximum power output and the maximum efficiency, dependent on the fuel price and operation time duration. The initial investment ($/W) for TE systems is much lower than for micro gas turbines when considering a low fractional area for the TE elements, e.g., 5% to 10% inside the module. Although the initial cost of the TE system is much less, the micro gas turbine has a lower energy price for longer-term operation due to its higher efficiency. For very long-term operation, operating cost dominates, thus efficiency and material ZT become the key cost factors.

Key words: Topping cycle, thermoelectric, energy production, energy cost

INTRODUCTION

A quarter of the world's population does not have access to sources of electric power.[1] Those people could take advantage of localized power generators by burning fuel for electricity. Even in power-rich countries, power shortages in the grid can impact modern lifestyles and have a significant negative social impact.[2] A significant increase of renewable sources must be considered for long-term social and human life sustainability in either of these situations. We have also studied the effective use of concentrated solar[3] and other renewable alternatives.[4] However, facing the above challenges, many populations need distributed power generation, even based on fossil fuels. For this purpose, we studied whether and how thermoelectric generators could work in this application when optimally designed. In previous work, we analyzed and optimized generic thermoelectric (TE) power generator systems for waste heat. We theoretically derived the cost impact of the element's geometry and the parasitic losses[5] to find the optimal trade-offs for cost effectiveness.[6] These effects were taken into account for "waste" heat ranging up to temperatures of 600°C.[7] Based on the same principle but also considering the cost of the heat source, we present herein an energy cost analysis for a TE power generator burning fossil fuel in comparison with micro gas turbines.[8]

The analysis considers the price per energy ($/J) for fuel as the operating cost and also considers the required initial investment. The currency in this article uses US $ and US ¢. The efficiency takes into account the useful energy output from the injected chemical energy from propane. A heat source temperature of 1980°C is used as the flame temperature.[9,10] Unlike waste heat recovery systems, the maximum power output from the TE

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generator is not necessarily equal to the economic optimum (lowest \$/kWh). The lowest cost is achieved when the module is optimized between the conditions for maximum power output and maximum efficiency depending on the fuel price.

MODEL AND CONDITIONS

Temperature settings are based on a natural-gas flame temperature of 1980°C for the hot-side source and an ambient air temperature of 25°C for the cold-side thermal ground. As discussed in Ref. 11, thermal impedance matching yields the maximum power output. In this analysis, the leg length d, the thickness of the thermoelectric element, is the key parameter. The optimum value for this parameter depends on the TE material properties, the thermal resistance of the TE substrate, the contact interface thermal resistances, and the thermal resistance of the external heat sink. For simplicity, this study is based on the assumption that the thermal resistance of the hot side and that of the cold side are the same or similar. The changes when the external thermal resistances are dissimilar were reported in Ref. 11.

Figures 1 and 2 show a conceptual schematic and the thermal network for this thermoelectric generator. The fuel gas must flow through the combustion chamber to achieve the necessary reaction with continuously supplied oxygen. Based on this reaction, constant convective heat transfer can be assumed for the hot-side surface of the thermoelectric module. A water cooling heat sink is placed on the cold side of the thermoelectric generator. The pumped water cooling is subject to a design trade-off. The drive power for pumping the water reduces the useful power output but increases the heat transfer coefficient so that the generator power output increases, see Eqs. 1 and 2. The water that removes heat from the cold-side heat sink receives the waste heat and brings it to the outside reservoir. This lower-grade heat can also be used as an input to a waste heat recovery system.

The following equation gives the maximum power output per unit area of the TE module, $w_{\max}$ [W/m^2]:

$$w_{\max} = \frac{mZ}{(1+m)^2}\frac{(T_s - T_a)^2}{4X}, \tag{1}$$

where

$$X = \left(1 + \frac{Z}{2(1+m)^2}((2m+1)T_h + T_c)\right)\frac{\Psi_h}{\sum\psi} + \left(1 + \frac{Z}{2(1+m)^2}(T_h + (2m+1)T_c)\right)\frac{\Psi_c}{\sum\psi} \tag{2}$$

and

$$d_{opt} = X\beta F\sum\psi(F). \tag{3}$$

m is the electrical resistance ratio given by $R_{load} = mR_{internal}$, Z is the figure of merit [1/K], and $\Sigma\psi$ is the sum of external thermal resistances [K/W] including spreading resistances, thus $\Psi_h = \psi_h + \psi_{sh}$ and $\Psi_c = \psi_c + \psi_{sc}$. The spreading thermal resistances are weak functions of the fill factor. T_s is the heat source (flame) temperature, and T_a is the coolant temperature. d_{opt} is the optimum leg length [m], and β is the thermal conductivity [W/mK] of the thermoelement. $\Sigma\psi$ can be decreased by increasing the power to pump the coolant.

Based on Ref. 12, micro gas turbines are priced from \$700/kW to \$1000/kW, ranging from 25 kW to 500 kW capacity, with energy efficiency from 20% to 30%; the operating and maintenance (O&M) cost is found to be \$0.005/kW to \$0.016/kW with a maintenance interval of 5000 h to 8000 h.[13] Since this information is based on commercialized equipment, we assume that the operating condition was already optimized to be cost effective.

We picked efficiencies of 20% for a 25-kW engine and 30% for a 500-kW engine. Similarly, we

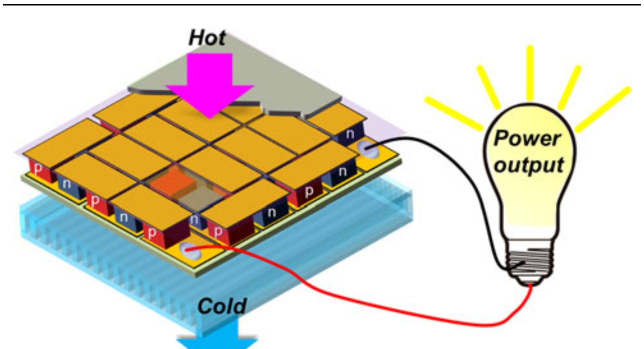

Fig. 1. Conceptual schematic of the modeled TE generator system.

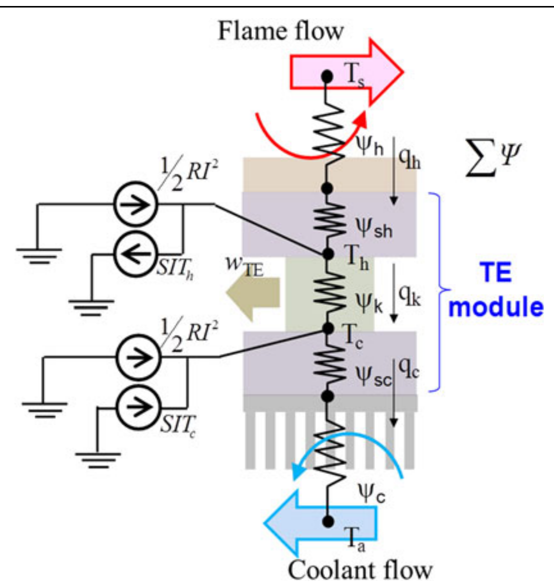

Fig. 2. Diagram of the thermal network of the TE generator system.

assumed the equipment price per power as \$1000/kW for a 25-kW system and \$700/kW for a 500-kW system. We used this O&M cost for the comparison since the O&M cost for thermoelectrics is not known for long-term operation. Since the TE module itself is all solid state and does not have any moving parts, it is anticipated that the O&M cost could be reduced.

ENERGY COST ANALYSIS

The energy price [\$/kWh] includes the one-time initial investment [\$/W] for the overall equipment (overnight cost) and the running cost of fuel [\$/kWh]. The overnight cost is evenly divided across the time duration of power production. This is dissimilar to the financial accounting depreciation method, but is simple and suitable from an engineering viewpoint.

In this analysis, the price of the burned fuel is based on the market price of natural gas per mass [\$/kg]. The calculation requires the energy extraction from unit mass of fuel [W/kg] by combustion—converting the chemical potential energy into heat energy with the help of oxygen in this case.

The fuel prices per volume of gasoline and propane as liquefied petroleum gas (LPG) are different, but interestingly, the price per energy contained [\$/MJ] shows very similar values for both. Table I presents a summary of this comparison. The data were extracted from the table based on US Energy Information Administration (EIA) data.[14] Based on this calculation, the source energy price is approximately 3.0 cents per MJ.

Since propane is the most popular fuel for micro gas turbines, the analysis assumes the properties of propane and the cost analysis is based on the energy price of LPG for both micro gas turbines and thermoelectric generators.

Figure 3 shows the results of the energy cost analysis. These values are based on an artificially defined thermoelectric material with $ZT \approx 0.8$, for this high-temperature application. We used electrical conductivity of 3.7×10^4 1/Ω m and Seebeck coefficient of 3.0×10^{-4} V/K as the thermoelectric properties. Alumina (Al_2O_3) substrates and a heat sink made of copper for the cold side are assumed. The analysis is based on a design for maximum power output. The material market prices are assumed to be \$500/kg for the thermoelectric material, \$5/kg for alumina, and \$20/kg for copper. The price of the studied thermoelectric material follows the information we used in our past analysis on Bi_2Te_3, since this is the only material in large-volume production, although this does not mean that the analysis is based on a particular material. The fractional area ratio F of the element with respect to the substrate (fill factor) is set to F = 10%. This is an aggressive value compared with

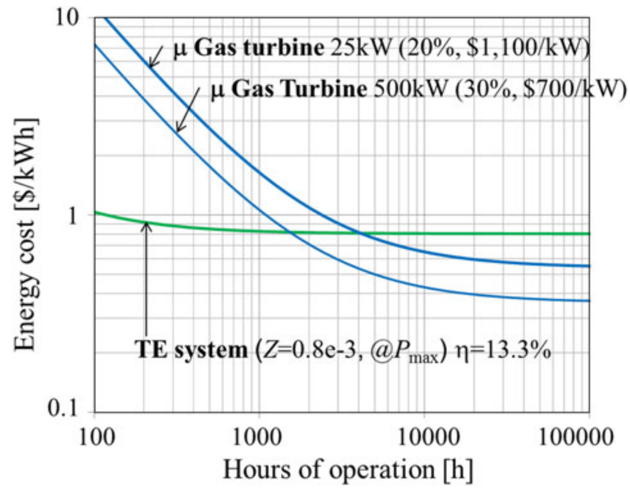

Fig. 3. Energy price versus hours of operation of the generators. The TE system is optimized for maximum power output. The material properties of the thermoelement are thermal conductivity of 4.1 W/mK, electrical conductivity of 3.7×10^4 1/Ω m, and Seebeck coefficient of 300 μV/K. The efficiency at maximum power is 13.3%.

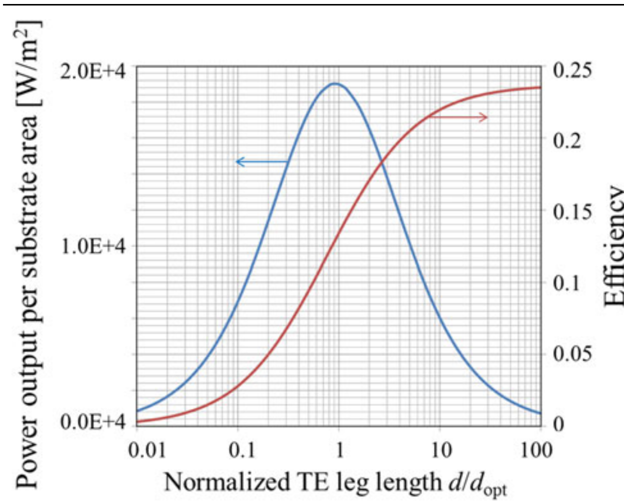

Fig. 4. Power output and efficiency changing only the leg length d normalized to the optimum leg length d_{opt}.

Table I. Fuel cost

Fuel	Energy Vol. (MJ/liter)	Price (\$/G)	Price (\$/liter)	Energy Price (\$/MJ)
Gasoline	34.2	3.83	1.0119	0.02959
LPG	25.3	2.87	0.7583	0.02997

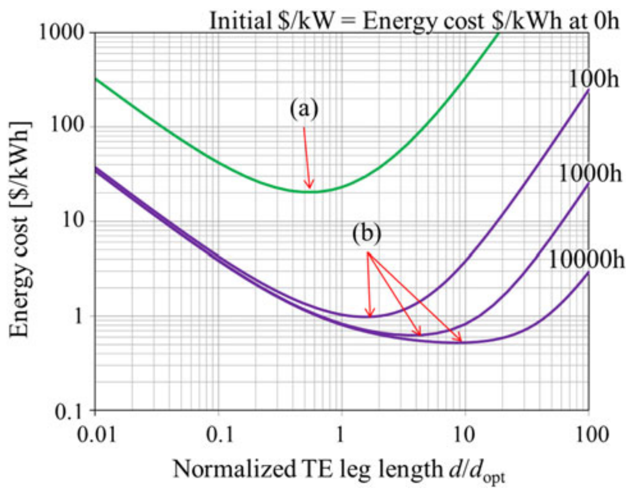

Fig. 5. Energy cost versus hours of operation of the TE generator with variation of element thickness d/d_{opt}: (a) initial cost (at 0 h), and (b) energy cost at various operation times (100 h, 1000 h, and 10,000 h).

current off-the-shelf TE generators, thus the initial cost (approximately $23/kW) is significantly lower than for TE modules currently on the market. At 100 h in Fig. 3, the energy cost is already in the range of $1/kWh.

Although the energy price for the TE system is lower for smaller numbers of hours of operation, for longer-term ($\gg$1000 h) operation it is higher than for the micro gas turbine. This is because the fuel cost dominates in the longer term, where the initial investment has little impact. The energy conversion efficiency matters the most for long-term operation.

The above discussion is based on the optimum design to extract the maximum power output. This characteristic does not necessarily yield the best long-term energy production cost [$/kWh]. Figure 4 shows the power output and system efficiency versus the thermoelement (leg) length, d. The performance of the heat sink is fixed. A thicker element yields higher efficiency since the higher thermal resistance limits the heat flow.

For thermoelectric generation of electricity by burning fuel, the steady-state approach may be limited for applications, which involve short-lived or one-time usage. A more obvious benefit of the thermoelectric generator is the system scalability from the millimeter range to the more than meter range by designing unit cell array modules. A smaller unit provides another advantage by making the response time very quick, since the time constant is directly related to the mass of the materials. Transient response to electricity demand will be studied in future work.

EXERGY CONSERVATION AND WASTE HEAT RECOVERY

Since the optimum design for maximum power output yields a thermal impedance match between the heat engine and the external thermal resistances,[11] the cold-side temperature of the thermoelectric still contains heat energy potential. This means that 100% of the chemical energy originally contained in the fuel cannot be used for conversion to electricity due to irreversible heat losses. Thus, from an exergy conservation viewpoint, waste heat should be recovered. We could add a secondary cogenerator for waste heat recovery. Higher cogeneration efficiencies can be achieved if the waste heat can be harnessed for a heating or cooling application (Fig. 5).

CONCLUSIONS

Based on this study, the initial investment for a TE system is lower than for a micro gas turbine, when considering a low fractional area of TE elements (e.g., 5% to 10% fill factor). For the first few thousand hours of operation, the power cost ($/Wh) of the TE system is lower. However, the micro gas turbine is better for longer-term operation, while the power price of the TE generator holds steady at about $0.8/kWh with efficiency of 13.3% (assuming $ZT \approx 0.8$). Unlike a TE waste heat recovery system, the maximum power output does not necessarily provide the lowest energy production cost. The minimum is observed between the maximum power output and the maximum efficiency (zero output), depending on the conditions. The results based on changing the thermoelement (leg) length demonstrate this economic trade-off. With current state-of-the-art TE material, the fuel-burning TE power generator is beneficial on a smaller scale ($<$10 kW), whereas mechanical thermodynamic systems are inefficient on this scale.

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