# Energy Harvesting Using Thermoelectric Microgenerators: Realistic Perspective or Utopian Idea? A Critical Analysis

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## Abstract

*Microstructured cell-arrayed thermoelectric power generators, which are able to convert (waste) heat into a few milliwatts or even watts of electrical energy, seem to be particularly attractive for the autonomous power supply of microelectronic circuitry and electronic or micromechatronic appliances without the use of batteries. However, the conversion efficiencies achieved so far are very small. A critical analysis shows that there is still a certain potential for improvements toward the theoretical limits, but that some expectations seem to be rather unrealistic and questionable in view of the physical and technological limitations.*

## INTRODUCTION

The need for regenerative decentralized small electric power sources comes along with the progress in microsystems technology in its various widespread application fields as, for example, wireless telecommunication and wearable appliances. Miniaturized thermoelectric power generators, which are able to convert waste heat into a few milliwatts or even watts of electrical energy, seem to be particularly attractive for the autonomous power supply of microelectronic or micromechatronic gadgets without the use of batteries. Microstructured (even CMOS-integrated) micro-thermoelectric generators (μ-TEGs) have been successfully demonstrated and are commercially available. However, the conversion efficiencies achieved so far are very small (less or much less than a few percent). But fortunately this is not decisive for many practical applications, where a heat source delivers the input heat for free (as waste heat) from an available heat reservoir at high temperature. Instead, other figures of merit have to be considered to assess the performance of μ-TEGs properly as discussed in the following.

## Basic theoretical considerations

### Thermodynamic efficiency

A thermoelectric generator (TEG) is a device through which heat is flowing from a heat source at high temperature $T_{in}$ to a heat sink at low(er) temperature $T_{out}$ (Fig.1). In an idealized view, it is assumed that the electric power $P$ delivered by the TEG is the difference between the inflow and the outflow of heat, $dQ_{in}/dt$ and $dQ_{out}/dt$ . The energy conversion efficiency is defined as

$$\eta = \frac{P}{\left(\frac{dQ_{in}}{dt}\right)} \tag{1}$$

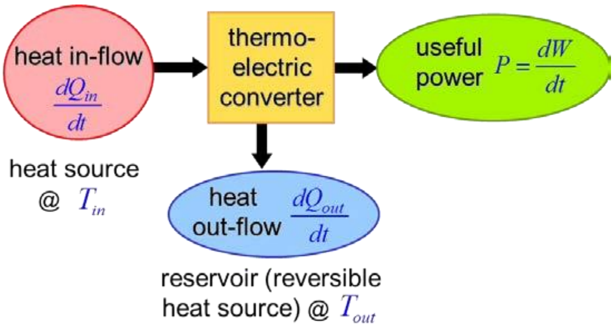

Fig. 1: Energy flow in an ideal thermoelectric generator.

By the second fundamental law of thermodynamics, $\eta$ is limited by the Carnot efficiency $\eta_C$; this means

$$\eta \le \eta_c = T_{out}\left(\frac{1}{T_{out}} - \frac{1}{T_{in}}\right) = 100\% - T_{out}/T_{in} \qquad (2)$$

Typical values of the maximum attainable efficiency at room temperature $T_{out} = 300K$ for different temperature drops $\Delta T = T_{in} - T_{out}$ are

| $\Delta T$ | $5K$ | $10K$ | $20K$ | $100K$ |
|---|---|---|---|---|
| $\eta_C$ | 1.6% | 3.2 % | 9.1% | 25% |

Unfortunately, due to effects inherent in thermoelectricity and design limitations, the converter efficiency attained in real µ-TEGs is drastically smaller (even by orders of magnitude) than $\eta_C$. On the other hand, even if the converter efficiency is very small, a µ-TEG may harvest a specified amount of electric output power, if the device area exposed to the heat flow is sufficiently large to collect the required inflow of waste heat (Fig. 2). As the latter comes for free, the crucial quantity determining the performance is the output power per active device area (see section 2.4), while the converter efficiency becomes quite questionable as measure of the device performance.

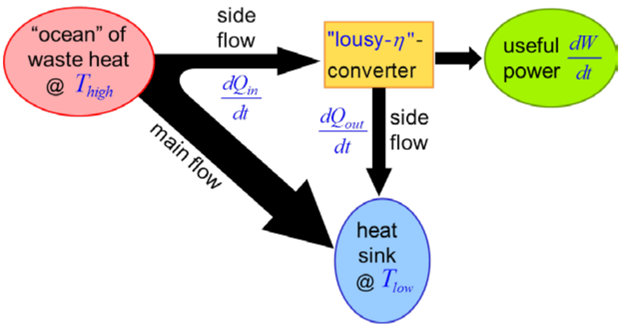

Fig. 2: Energy flow in a real "waste-heat-to-power" converter. The side flow of waste heat is proportional to the active area of the converter.

### Figure of merit ZT

A common approach to assessing the performance of TEGs is based on the transport equations governing the flows of heat and electric current in a thermoelectric material. It is assumed that the maximum deliverable electric power flux is determined by the electronic contribution $J_{Q,el}$ to the total heat flux $J_{Q,tot}$ according to the relation

$$\vec{J}_{Q,el} \approx (L + S^2)\frac{\sigma T}{\kappa}\vec{J}_{Q,tot} \qquad (3)$$

where $L$ is the Lorenz number, $S$ the (absolute) thermopower, σ the electric conductivity, and κ the thermal conductivity. This relation suggests that the dimensionless quantity

$$ZT := \frac{S^2\sigma}{\kappa}T \qquad (4)$$

κ may serve as a proper "figure of merit" for the thermoelectric performance. Measured values of $ZT$ vary over a wide range from $ZT \approx 10^{-3}$ for homogeneous bulk semiconductors to $ZT \approx 0.5\ldots1$ for commonly used high-efficiency thermoelectric materials like alloys based on bismuth in combinations with tellurium, antimony or selenium [2]. Current research focussing on nanostructured materials (superlattice, quantum dots etc.) has shown that $ZT$ values up to 4 are feasible. However, the relevance of high $ZT$ must be revisited in the light of the next section.

### Thermoelectric generator efficiency

A more detailed theory including the internal Joule and Peltier heating [1] shows that in a TEG the maximum attainable energy conversion efficiency $\eta$ is limited by the Carnot efficiency $\eta_C$ multiplied by a factor $\eta_{TE} < 1$, the so-called thermoelectric generator efficiency:

$$\eta = \frac{P_{el}}{dQ_{in}/dt} \le \underbrace{\frac{T_{in} - T_{out}}{T_{in}}}_{\eta_c} \cdot \underbrace{\frac{\left[(1+ZT_{av})^{\frac{1}{2}} - 1\right]}{(1+ZT_{av})^{1/2} + 1 - \eta_C}}_{\eta_{TE}} \qquad (5)$$

with

$$T_{av} = (T_{in} + T_{out})/2$$

The variation of $\eta_{TE}$ with the figure of merit $ZT$ is displayed in Fig. 3. Only for small $ZT << 1$ the generator efficiency is approximately a linear function of $ZT$, while it saturates for large values of $ZT$. Consequently, striving for ever higher $ZT$ is not rewarded by a proportional gain in efficiency, while other aspects in the optimization of real-world TEGs may have a much larger impact.

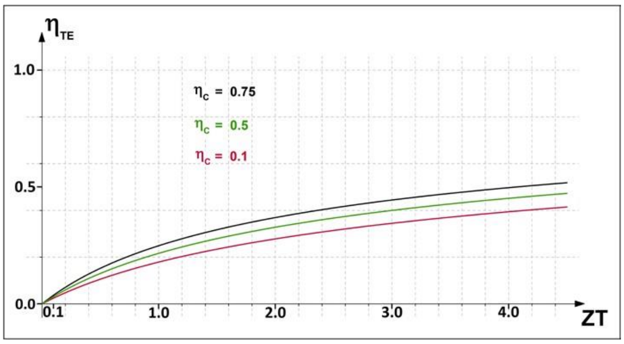

Fig. 3: Thermoelectric generator efficiency vs. figure of merit ZT

### Thermoelectric power factor

In the situation sketched in Fig. 2 the electric output power can be factorized as

$$P = A_{heat} * \Pi * (\Delta T_{ext})^2$$

with $\qquad (6)$

$$\Delta T_{ext} = T_{high} - T_{low}$$

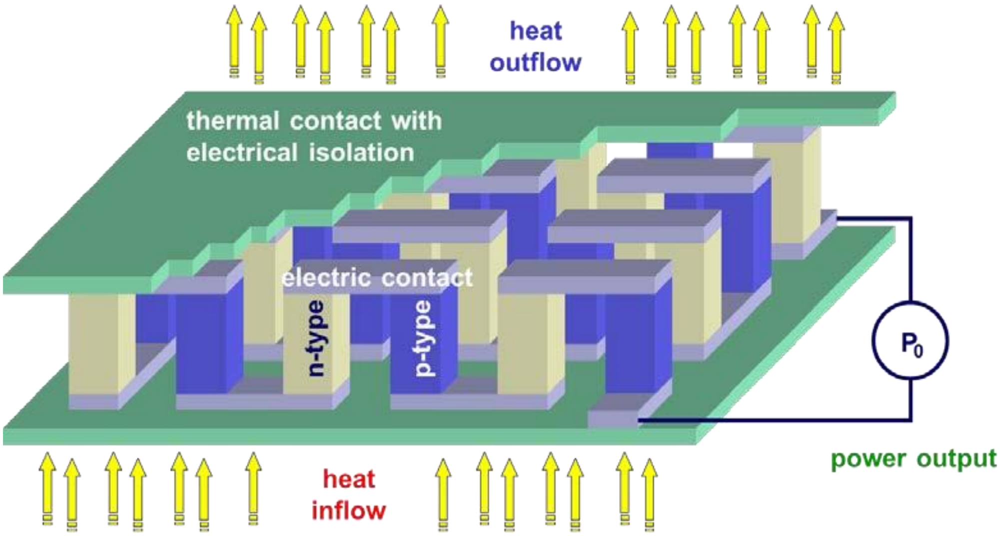

Fig. 4: Schematic view of a microstructured vertical thermopile.

Here $A_{heat}$ is the cross-sectional area of the TEG passed by the heat flow and $\Delta T_{\text{ext}}$ is the externally controlled (given) temperature difference between waste heat source and ambient heat sink. The thermoelectric power factor Π depends on the details of device geometry and package and involves the respective physical material properties $S$, σ, and κ. Hence, Π is the proper figure of merit for optimizing the performance of realistic TEGs including the effects of electrical and thermal contacts, thermal leakage, package etc.

## Optimized design of a microstructured thermopile

As an illustrative example, we derived the power factor for the model of a vertical thermopile consisting of a large number of microstructured thermocouples connected electrically in series and thermally in parallel. We include a thermal series resistance $K_S$ of the package, but neglect any electrical contact resistances. The crucial parameter is the length of the thermocouples $l_{TC}$. We find the asymptotic expressions:

For small $l_{\text{TC}}$:

$$\Pi = \frac{1}{16}\frac{A_{TEG}}{A}\cdot\frac{S_{TC}^2\sigma}{\kappa^2}\cdot\frac{l_{TC}}{(A_{TEG}\cdot K_S)^2} \qquad (7)$$

For large $l_{\text{TC}}$:

$$\Pi = \frac{1}{16}\frac{A_{TEG}}{A}\cdot S_{TC}^2\sigma\cdot\frac{1}{l_{TC}}$$

where $A_{TEG}$ and $A$ denote the thermoelectrically active and total chip areas, respectively, $S_{TC}$ the relative thermopower of one thermocouple, and σ and κ their respective electrical and thermal conductivity. As Π rises linearly with $l_{TC}$ for small values and falls with $1/l_{TC}$ for large values, Π shows a maximum value in between. For “real-world” design parameters, as encountered in an industrial CMOS-process, we find $l_{TC}$ in the range of some 10-100μm.

## REFERENCES

[1] G. J. Snyder and T. S. Ursell, Phys. Review Letters 91, no. 14, 2003, pp. 148301(4).
[2] D. M. Rowe, Int. J. of Innovations in Energy Systems 1, no. 1, 2006, pp.13-23.

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