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A temperature-variant method for performance modeling and economic analysis of thermoelectric generators: Linking material properties to real-world conditions

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HIGHLIGHTS

- A numerical method predicts power and financial costs of a thermoelectric generator.
- Temperature-dependent, experimental materials properties and variable heat sources are used.
- Sensitivity analyses show improvements can be made by choosing higher temperature heat sources.
- Optimizing the choice of heat exchanger lowers cost.
- A higher figure of merit improves performance and lowers cost.

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ABSTRACT

A new methodology for the systematic study of thermoelectric generator (TEG) design and economic analysis is presented, with the objective of assessing the performance and financial feasibility of small-scale TEG installations, for 4 leading candidate thermoelectric materials. Temperature of a steam trap pipe surface were measured at the University of California Davis Pilot Brewery, and device performance was modeled using the finite-element modeling software ANSYS. The model integrated temperature-dependent material properties from leading candidate thermoelectric materials and experimental time-variant temperature data. Calculated power outputs were utilized in a net present value (NPV) framework to assess the financial feasibility and economic implications of small scale TEG installations, as well as to address the aspects of TEG research, design and implementation which have potential for rapid and substantive improvement. This model, along with case study results, provides a powerful platform for analyzing the performance of real-world systems and can be used to predict where further technological development on TEG materials and devices would be most effective. It is found that a *BiSbTe* based TEG generated the highest power output at the measured temperatures and consequently resulted in the highest NPV at the end of 25 years. Sensitivity analysis of the NPV revealed a strong dependence on the heat-exchanger cost, highlighting the importance of efficient heat transfer design. The *zT* necessary for a 7-year payback period as a function of the capital cost and hot-side temperature was also calculated for a *SiGe* based TEG.

1. Motivation

Thermoelectric installations can provide a source of green electricity, especially when in high-value on-site applications, but financial viability is highly sensitive to source temperature, device efficiency, maintenance cost, and projected device lifetime [1–4]. The integration of TEGs may also facilitate added functionality that would not be possible without their use: for instance, self-powered furnaces and co-generation systems [4–7] for use in remote regions, waste heat recovery from automobile exhausts [8,9], building-integrated power generation [10], and wearable electronics that may be powered indefinitely by harvesting body heat [11–13]. And a variety of other energy applications [14–18].

Recent studies for module-level TEG performance have assumed constant hot and cold-side temperatures, and operation

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Nomenclature

ρ	density, $\frac{\mathrm{kg}}{\mathrm{m}^3}$
C	specific heat capacity, $\frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}}$
T	absolute temperature, K
$\dot{q}$	heat generation rate per unit volume, $\frac{\mathrm{W}}{\mathrm{m}^3}$
$\vec{\boldsymbol{q}}$	heat flux vector, $\frac{\mathrm{W}}{\mathrm{m}^2}$
$\vec{\boldsymbol{J}}$	electric current density vector, $\frac{\mathrm{A}}{\mathrm{m}^2}$
$\vec{\boldsymbol{E}}$	electric field intensity vector, $\frac{\mathrm{V}}{\mathrm{m}^2}$
$\vec{\boldsymbol{D}}$	electric flux density vector, $\frac{\mathrm{C}}{\mathrm{m}^2}$
$\boldsymbol{\lambda}$	thermal conductivity matrix, $\frac{\mathrm{W}}{\mathrm{m}\cdot\mathrm{K}}$
$\boldsymbol{\sigma}$	electrical conductivity matrix, $\frac{\mathrm{S}}{\mathrm{m}}$
$\boldsymbol{\alpha}$	Seebeck coefficient matrix, $\frac{\mathrm{V}}{\mathrm{K}}$
$\Pi = T\boldsymbol{\alpha}$	Peltier coefficient matrix, V
$\boldsymbol{\varepsilon}$	dielectric permittivity matrix, $\frac{\mathrm{F}}{\mathrm{m}}$

Thermal stiffness matrix $\boldsymbol{K}^{TT} = \int \nabla \boldsymbol{N} \cdot [\lambda] \cdot \nabla \boldsymbol{N} dV$
Electric stiffness matrix $\boldsymbol{K}^{\varphi\varphi} = \int \nabla \boldsymbol{N} \cdot [\sigma] \cdot \nabla \boldsymbol{N} dV$
Seebeck stiffness matrix $\boldsymbol{K}^{\varphi T} = \int \nabla \boldsymbol{N} \cdot [\sigma] \cdot [\alpha] \cdot \nabla \boldsymbol{N} dV$
Thermal damping matrix $\boldsymbol{C}^{TT} = \rho \int \mathrm{C} \boldsymbol{N}\boldsymbol{N} dV$
Dielectric damping matrix $\boldsymbol{C}^{\varphi\varphi} = \int \nabla \boldsymbol{N} \cdot [\varepsilon] \cdot \nabla \boldsymbol{N} dV$
Thermal stiffness matrix $\boldsymbol{K}^{TT} = \int \nabla \boldsymbol{N} \cdot [\lambda] \cdot \nabla \boldsymbol{N} dV$

$\vec{\boldsymbol{Q}}$	vector of combined heat generation loads

Peltier heat load vector $\vec{\boldsymbol{Q}}^{P} = \int \nabla \boldsymbol{N} \cdot [\Pi] \cdot \boldsymbol{J} dV$
Electric power load vector $\vec{\boldsymbol{Q}}^{e} = \int \boldsymbol{N}\mathbf{E} \cdot \mathbf{J} dV$

under steady-state conditions [18–20]. However, many potential heat sources show significant temperature variation during the course of operation, and given the strong temperature dependence of all material properties that contribute to the thermoelectric figure of merit zT [19,21], understanding the temperature and time variance of the potential power generation of a particular TEG system is critical to accurately modeling its real-world performance. Previous financial analyses [1–3] while thorough and robust within the model conditions, do not account for temperature variation, and rely on similar approximations of device performance that may be refined with the inclusion of time- and temperature-variant device performance modeling. Financial forecasting and sensitivity studies indicate that TEG installations provide a feasible source of green electricity but are highly sensitive to source temperature, device efficiency, discount rate, and projected device lifetime.

This analysis integrates real-time hot side temperature data, gathered from the pilot brewery at the UC Davis August A. Busch III Brewing & Food Science Laboratory, with a model that was formulated using finite-element software ANSYS to accurately predict the expected power outputs from various thermoelectric materials given the hot side temperature conditions. Thermoelectric material properties are a function of temperature, and during operation there is a temperature gradient across the TEG device (Fig. 1). It is therefore important that a model take into consideration the variation in material properties along the length of a thermoelectric leg. The model used in this paper accounts for such variations caused by the temperature gradient and thus provides a more accurate prediction of the power output as compared to simplified analytical models that assume a constant temperature during operation [8,9]. The power output results are fed into an economic model that calculates the Net Present Value (NPV) of TEG installations given realistic cost and income parameters (See Methods). This methodology is generalizable to a range of different TEG materials, systems, and operating conditions, wherever the material properties are known and operating temperatures can be measured, and is especially useful in systems with widely varying input temperatures for which more simplistic models are not sufficiently powerful.

2. Theoretical background

Finite element modeling (FEM) has become an extremely valuable solution technique for coupled-field (for example, thermal-electric) analyses in many areas of engineering and physics. FEM is versatile in its applicability to arbitrarily shaped structures, complex materials, and various loads and boundary conditions. ANSYS, the FEM software used in this study, has a large library of elements that support structural, thermal, fluid, acoustic, and electromagnetic analyses [22]. Below is a brief summary of the equations of thermal-electric analysis utilized by ANSYS [22].

The equation for heat flow in thermoelectric analysis is:

$$\rho C \frac{\partial T}{\partial t} + \nabla \cdot \vec{\boldsymbol{q}} = \dot{q} \tag{1}$$

And of continuity of electric charge:

$$\nabla \cdot \left(\vec{\boldsymbol{J}} + \frac{\partial \vec{\boldsymbol{D}}}{\partial t} \right) = 0 \tag{2}$$

Those 2 equations are coupled by the following constitutive equations of thermoelectricity:

$$\vec{\boldsymbol{q}} = \boldsymbol{\Pi} \cdot \vec{\boldsymbol{J}} - \boldsymbol{\lambda} \cdot \nabla T \tag{3}$$

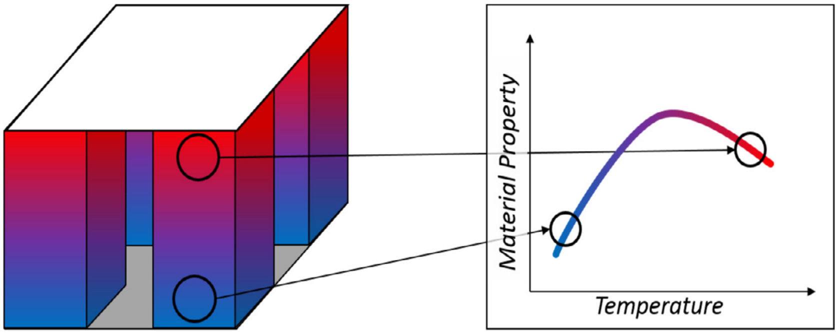

Fig. 1. Schematic illustration of a multi-leg thermoelectric device (left) and how material properties, such as the Seebeck coefficient, may vary with temperature within a thermoelement leg.