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Thermoelectric generator for energy production from renewable sources

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Abstract. Thermoelectric generators (TEG) produce electrical energy from a temperature difference between the cold and hot side of TEG modules (Seebeck effect); in principle, they can be used at temperature differences greater than 3 K [1]. Thermoelectric energy generation is primarily known for supplying self-sufficient sensors or in exhaust systems of motor vehicle internal combustion engines [2], where high temperature differences of up to 700 K are used. In this paper, basic investigations are carried out in order to expand the power range of thermoelectric energy generation and their potential for the energy transition. To this end, the area of application should be expanded to include medium and small temperature differences. The output characteristic of a TEG module has a power maximum, which increases quadratically with the temperature difference and linearly with the module area. At a temperature difference of 40 K, an output of 250 W/m^2 can be generated. A solar module can generate 150 W/m^2 in full sunlight; this output is only available for 12 % of the year given the 1000 full-load hours of sunshine that are usual in our latitudes. A continuous thermoelectric energy source could provide energy all year. Under optimal conditions, an annual usage time of 5000 hours and a service life of 10 years, electricity production costs of around 10 Cents/kWh can be expected [3]. This price is quite comparable to other renewable energy sources (photovoltaics, wind) [4].

Key words. Thermoelectric power generation, TEG module, Energy harvesting, Seebeck, Peltier.

1. Introduction

Photovoltaic cells that use a charge separation between the p-doped (positively charged) layer and an n-doped (negatively charged) layer to generate electrical energy have been known for a long time and are currently on the mass market for commercial and private customers. One of the system-related problems in Northern Europe is the reduction of the working time window to the presence of sunlight. In northern and central Germany, the annual sunshine duration [5] is around 20 % to 30 %. This means that no energy is generated during around 70 to 80 % of the available time. Another system-related problem with photovoltaic systems is that energy is generated when the sun is shining and not when the energy is needed. This paper presents the preliminary work to answer the question: Is it technically possible and economically viable to use Peltier/Seebeck modules, which only require a temperature difference, to generate renewable energy instead of photovoltaic modules?

The first steps of our work are concerned with checking the manufacturer's specifications for commercially available Peltier/Seebeck modules. A test setup was designed for this purpose. This paper presents the test setup and shows the initial results.

2. Thermoelectric Generator Modules

In simple terms, Peltier/Seebeck modules are thermoelectric energy converters. A temperature difference generates electricity (Seebeck effect) and a flow of electricity generates a temperature difference (Peltier effect). From an electrical point of view, Peltier/Seebeck modules consist of a series connection of p-doped and n-doped semiconductors (thermocouples).

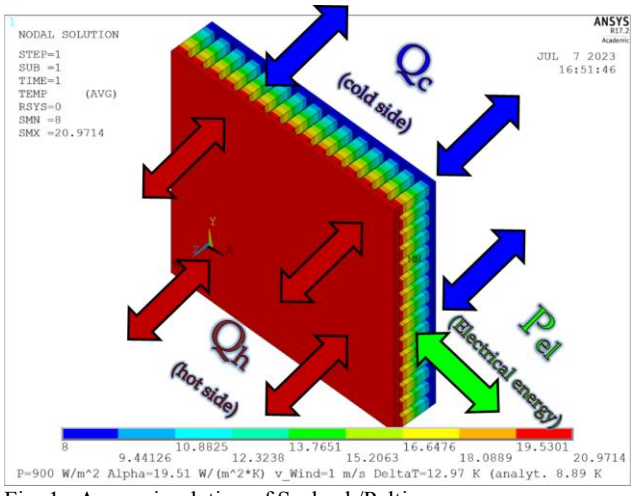

Fig. 1. Ansys simulation of Seebeck/Peltier.

This relationship is referred to as the Seebeck coefficient (α) or "thermal force" in equation (1), where dT is the temperature difference between hot and cold side, α the material specific Seebeck coefficient and U_{Thermo} the Seebeck voltage.

$$U_{Thermo}[V] = \alpha \left[\frac{V}{K} \right] \cdot dT[K] \quad (1)$$

A. *Measurement Equipment / Experimental Setup*

The criteria for the test setup were defined as follows:

a. a defined cooling option (cold side),
b. a defined possibility for heating (warm side),
c. a possibility to measure the temperatures for both sides independently of each other,
d. a possibility to place a TEG module to be tested (test object) reproducibly between the warm and cold side
e. a variable load resistance for the TEG to be tested
f. displays for the voltage and current generated by the test object

a., b.: Both the cold and the warm side should be freely adjustable within the temperature range and it should also be possible to realize a variable temperature through simple control, so the selection was made for simple, cheap electric Peltier coolers included air heat exchangers and electric fans.

c.: A referenceable measuring device with reference-able temperature sensors was selected for the temperature measurement of the hot and cold side.

Fig. 2. Cheap electric Peltier cooler and PCE T 330.

a., b., c., d., e., f: The entire experimental setup is shown in Fig. 3. All criteria (independent control and setting of the temperature for the cold and warm side) could be implemented with the measurement setup displayed.

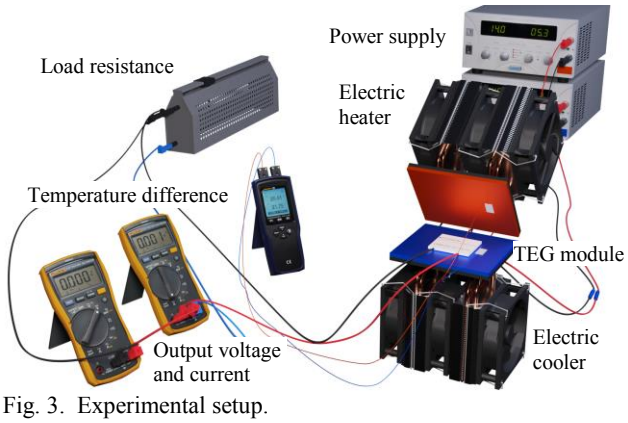

Fig. 3. Experimental setup.

B. *Output Characteristic of TEG Modules*

Fig. 4 shows the output characteristics of the thermo-electric generator (TEG) module GM250-127-14-16 for several temperature differences dT between cold side and hot side. The output current is set by variation of the load resistance. The output characteristic is characterized by an open-circuit voltage and an internal resistance (similar to that of a battery). The cold side temperature in this case is 30 °C, however other cold side temperatures result in nearly the same output characteristics. A higher temperature difference causes a parallel shift of the output characteristic, because of the temperature dependence of the open-circuit voltage. TEG modules are suitable for bipolar operation that means both polarities of the temperature difference produce electrical energy. Positive temperature differences generate positive output voltage and current and vice versa.

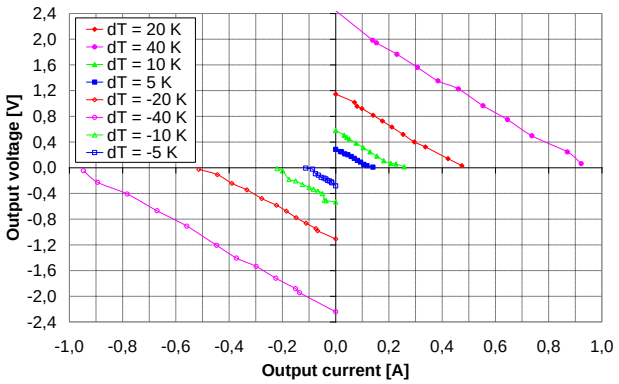

Fig. 4. Output voltage and current of GM250-127-14-16 for several temperature differences between cold side and hot side.

Fig. 5 shows the output power of the same TEG module. Each curve has a power maximum at the so called matched load resistance. In this case the load resistance is the same as the internal resistance. In bipolar operation both polarities of the temperature difference have nearly the same power maximum.

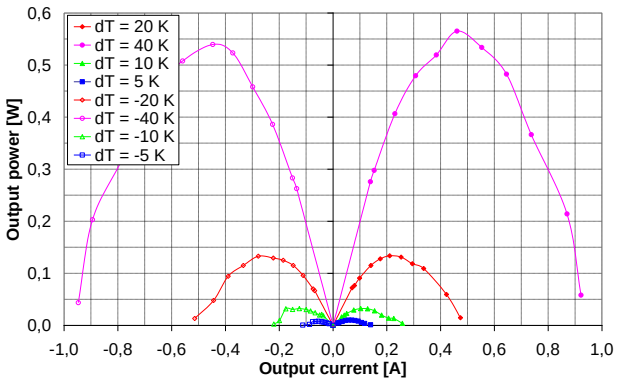

Fig. 5. Output power and current of GM250-127-14-16 for several temperature differences between cold side and hot side.

This power maximum is shown in Fig. 6 as function of temperature difference for various cold side temperatures Tc. It depends approximately quadratically on the temperature difference, according to equation (2). However this power maximum doesn`t depend on the cold side temperature.

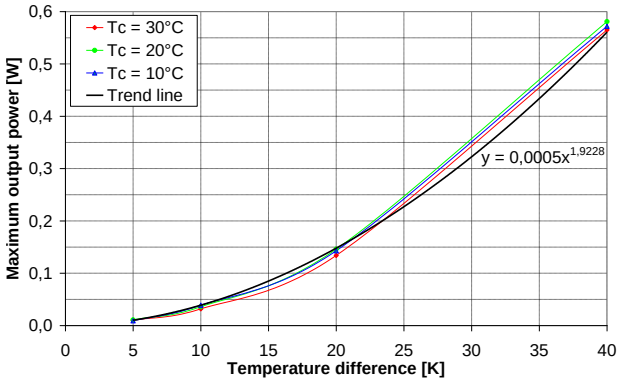

Fig. 6. Maximum output power of GM250-127-14-16 as function of temperature difference for various cold side temperatures.

$$P_{max}\left[W\right] = 0{,}0005 \cdot \left(dT\left[K\right]\right)^{1{,}9228} \tag{2}$$

Fig. 7 contains the matched load resistance for maximum output power for various temperature differences. The matched load resistance is nearly constant for all temperature differences and cold side temperatures. This knowledge simplifies the intended maximum power point (MPP) tracking for thermoelectric generator systems, because no temperature measurement is necessary.

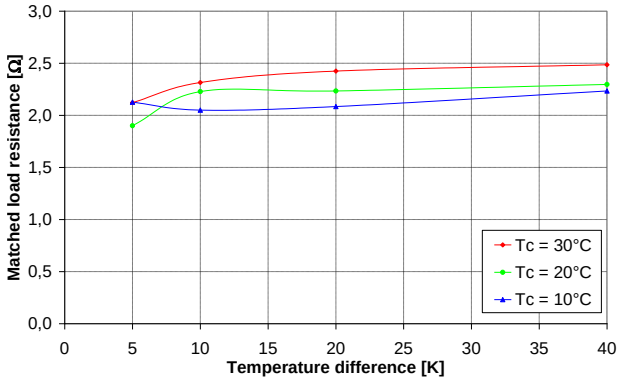

Fig. 7. Matched load resistance for maximum output power of GM250-127-14-16 as function of temperature difference for various cold side temperatures.

C. Comparison of different TEG Modules

Table 1 contains selected TEG modules with an area of 40 x 40 mm for further measurements.

Table 1. – Specifications of TEG modules

Type	Max. temperature	Costs
Seebeck modules		
GM250-127-14-16	250 °C	57 €
SP1848	150 °C	4 €
Peltier modules		
QC-127-1.4.-3.7	200 °C	34 €
TEC1-12706	138 °C	3 €

Fig. 8 shows the maximum output power per square meter as function of temperature difference for the selected TEG modules (Tab. I). The cold side temperature in this case is 30 °C. GM250-127-14-16 has the best performance but also the highest price. The TEC1-12706 has only 5 % of the price, however the output power is only reduced by 34 %. Therefore the TEC1-12706 is chosen for further investigations.

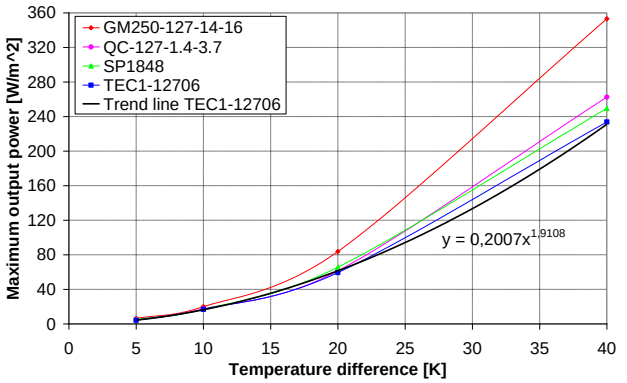

Fig. 8. Maximum output power per square meter as function of temperature difference for selected TEG modules.

3. Electrical Equivalent Circuit

The steady-state model of a TEG module is based on the electrical equivalent circuit in Fig. 9. It contains the open-circuit voltage (U_q) and the internal resistance (R_i). U_K is the output voltage and R_a the load resistance.

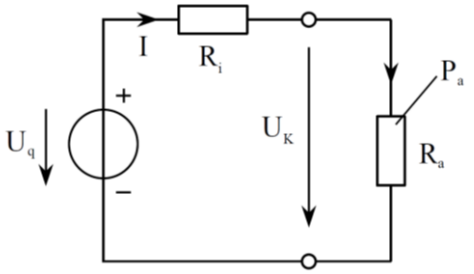

Fig. 9. Electrical equivalent circuit of a TEG module.

Fig. 10 shows the output characteristics of the TEG module TEC1-12706 for several temperature differences with the associated straight line equations. This contains the relationship between output voltage U_K and output current I, according equation (3).

$$U_K = -R_i \cdot I + U_q \tag{3}$$

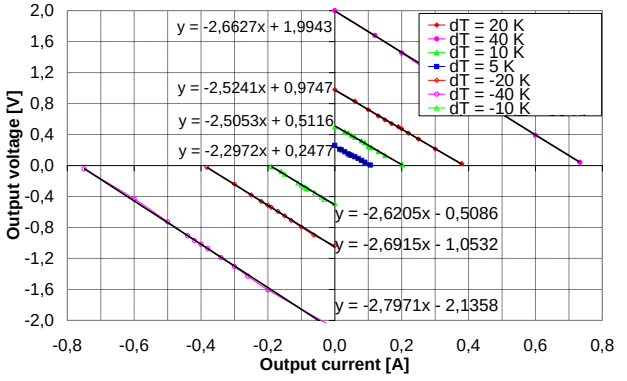

Fig. 10. Output voltage and current of TEC1-12706 for several temperature differences between cold side and hot side.

The open-circuit voltage and the internal resistance for each temperature difference are contained in Table 2. The open-circuit voltage is nearly proportional to the temperature difference, but the internal resistance is nearly constant.

Table 2. – Electrical equivalent circuit parameters

dT [K]	U_q [V]	R_i [Ω]
40	1,9943	2,6627
20	0,9747	2,5241
10	0,5116	2,5053
5	0,2477	2,2972
-10	-0,5086	2,6205
-20	-1,0532	2,6915
-40	-2,1358	2,7971

The output power (P_a) is calculated in equation (4) as function of load resistance (R_a). The maximum output power ($P_{a\,max}$) is achieved with power adjustment in equation (5). In this case the matched load resistance (R_a) is as large as the internal resistance (R_i).

$$P_a = U_K \cdot I = \frac{U_q^2 \cdot R_a}{(R_a + R_i)^2} \tag{4}$$

$$P_{a\,max} = \frac{U_q^2}{4 \cdot R_i} \quad ; \quad R_a = R_i \tag{5}$$

Fig. 11 shows the output power of the TEG module TEC1-12706. The maximum output power is achieved with the matched load resistance. All measured power maxima are compared with the calculated in Table 3.

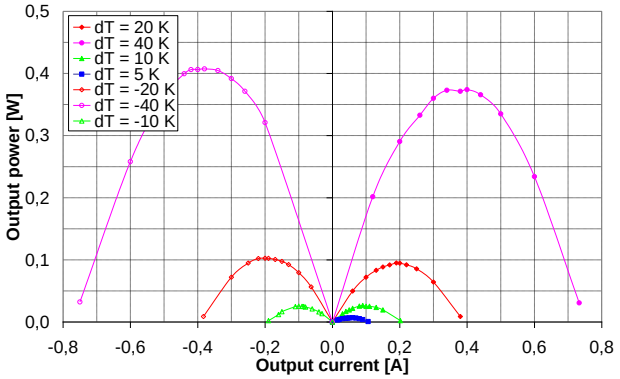

Fig. 11. Output power and current of TEC1-12706 for several temperature differences between cold side and hot side.

Table 3. – Calculated and measured maximum output power

dT [K]	$P_{a\,max}$ [W] calculated	$P_{a\,max}$ [W] measured
40	0,373	0,374
20	0,094	0,095
10	0,026	0,027
5	0,0067	0,0068
-10	0,025	0,025
-20	0,103	0,103
-40	0,408	0,406

4. Series and Parallel Connection

For higher output power, an interconnection of many TEG modules is necessary, either in series or in parallel, to obtain a thermoelectric generator.

D. Interconnection for the same temperature difference

In series connection, both the open-circuit voltages (U_q) and the internal resistances (R_i) of all TEG modules are added, according to equation (6) and (7), where n is the number of series connected modules and U_{qG} the output voltage of the thermoelectric generator.

$$U_{qG} = n \cdot U_q \tag{6}$$

$$R_{iG} = n \cdot R_i \tag{7}$$

In parallel connection, the open-circuit voltage (U_q) remains the same but the internal resistances (R_i) of all TEG modules are connected in parallel, according to equation (8) and (9), where n is the number of parallel connected modules and U_{qG} the output voltage of the thermoelectric generator.

$$U_{qG} = U_q \tag{8}$$

$$R_{iG} = \frac{R_i}{n} \tag{9}$$

The maximum output power of the thermoelectric generator ($P_{a\,max\,G}$) as well as in series and parallel connection is the same (equation (10)).

$$P_{a\,max\,G} = \frac{(n \cdot U_q)^2}{4 \cdot n \cdot R_i} = \frac{U_q^2}{4 \cdot \frac{R_i}{n}} = n \cdot \frac{U_q^2}{4 \cdot R_i} = n \cdot P_{a\,max} \tag{10}$$

Table 4 contains the measured maximum output power per square meter for series and parallel connection of 4 modules. The interconnection produces 4 times the power of a single module. The missing data in the table were not measured.

Table 4. – Maximum output power of 4 modules TEG1-12706 for series and parallel connection

dT [K]	1 module [W/m^2]	4 modules series [W/m^2]	4 modules parallel [W/m^2]
5	4,4		
10	16,9	75,6	
20	62,5	267,5	241,2
40	247,5		

E. Interconnection for different temperature differences

Unfortunately, in most applications the TEG modules cannot be operated with the same temperature difference. The interesting question is therefore what effects variable temperature differences have on the operating behavior.

Series connection

Fig. 12 shows the series connection of n modules with full temperature difference (U_{q1}, R_{i1}) and k modules with reduced temperature difference (U_{q2}, R_{i2}), where dT_{ref} is the nominal temperature difference and dT the reduced value. The resulting open-circuit voltage (U_{qG}) and the internal resistance (R_{iG}) of the complete thermoelectric generator are determined in equation (14), where z is the number of all modules.

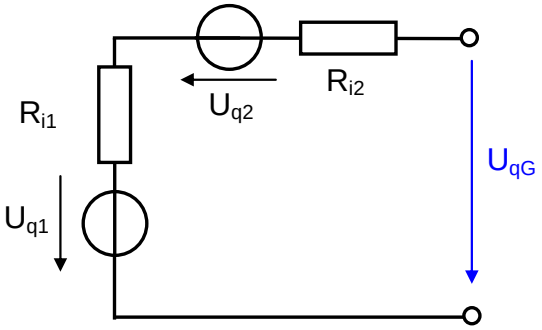

Fig. 12. Series connection of TEG modules with different temperature differences.

$$U_{q1} = n \cdot U_q \quad ; \quad R_{i1} = n \cdot R_i$$
$$U_{q2} = k \cdot U_q \frac{dT}{dT_{ref}} \quad ; \quad R_{i2} = k \cdot R_i \tag{11}$$

$$U_{qG} = U_{q1} + U_{q2} = U_q \left(n + k \frac{dT}{dT_{ref}} \right) \tag{12}$$
$$R_{iG} = R_{i1} + R_{i2} = R_i (n + k)$$

$$n + k = z \quad ; \quad x = \frac{k}{z} = 0 \ldots 1 \tag{13}$$

$$U_{qG} = z \cdot U_q \left(1 - x + x \frac{dT}{dT_{ref}} \right) \quad ; \quad R_{iG} = z \cdot R_i \tag{14}$$

Parallel connection

Fig. 13 shows the parallel connection of n modules with full temperature difference (U_{q1}, R_{i1}) and k modules with reduced temperature difference (U_{q2}, R_{i2}). The resulting open-circuit voltage (U_{qG}) and the internal resistance (R_{iG}) of the complete thermoelectric generator are determined in equation (17).

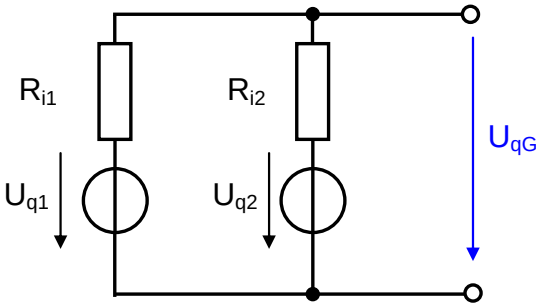

Fig. 13. Parallel connection of TEG modules with different temperature differences.

$$U_{q1} = U_q \quad ; \quad R_{i1} = \frac{R_i}{n}$$
$$U_{q2} = U_q \frac{dT}{dT_{ref}} \quad ; \quad R_{i2} = \frac{R_i}{k} \tag{15}$$

$$U_{qG} = U_{q1} \frac{R_{i2}}{R_{i1} + R_{i2}} + U_{q2} \frac{R_{i1}}{R_{i1} + R_{i2}} = U_q \frac{n + k \frac{dT}{dT_{ref}}}{n + k} \tag{16}$$
$$R_{iG} = \frac{R_{i1} \cdot R_{i2}}{R_{i1} + R_{i2}} = \frac{R_i}{n + k}$$

$$U_{qG} = U_q \left(1 - x + x \frac{dT}{dT_{ref}} \right) \quad ; \quad R_{iG} = \frac{R_i}{z} \tag{17}$$

The same output power of the thermoelectric generator ($P_{a\,max\,G}$) results for both series and parallel connection (equation (18)). If the temperature difference has the nominal value ($dT = dT_{ref}$), then the maximum output power $P_{a\,max\,Gref}$ is reached.

$$P_{a\,max\,G} = \frac{U_{qG}^2}{4 \cdot R_{iG}} = \frac{z \cdot U_q^2 \left(1 - x + x \frac{dT}{dT_{ref}} \right)^2}{4 \cdot R_i} \tag{18}$$
$$P_{a\,max\,G_{ref}} = \frac{(z \cdot U_q)^2}{4 \cdot z \cdot R_i} = \frac{z \cdot U_q^2}{4 \cdot R_i}$$

At reduced temperature difference the reduction of output power is calculated in equation (19) and illustrated in Fig. 14 for different percentage of modules and temperature difference. For reduced temperature differences (dT) only the open-circuit voltage of the thermoelectric generator (U_{qG}) changes, however the internal resistance (R_{iG}) remains constant. That means that the load resistance does not have to be adapted to changing temperature differences for both series and parallel connection.

$$\frac{P_{a\,max\,G}}{P_{a\,max\,G_{ref}}} = \left(1 - \frac{k}{z} + \frac{k}{z} \cdot \frac{dT}{dT_{ref}} \right)^2 \tag{19}$$

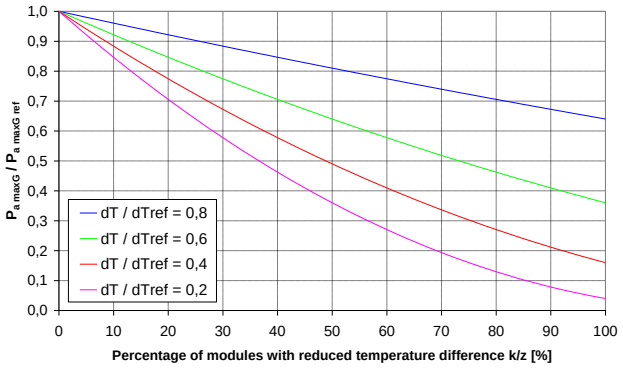

Fig. 14. Reduction of output power at reduced temperature difference.

5. Conclusion

Suitable thermoelectric generator modules are commercially available. An experimental setup for measurement of different Seebeck and Peltier modules was build. The output characteristic of a TEG module is characterized by an open-circuit voltage and an internal resistance (similar to that of a battery). The open-circuit voltage is nearly proportional to the temperature difference between cold and hot side, but the internal resistance is nearly constant. The output power of a TEG module has a power maximum when the load resistance is chosen to be as large as the internal resistance. This power maximum increases quadratically with the temperature difference and linearly with the module area. To create a thermoelectric generator, many TEG modules must be connected together, either in series or in parallel. In most cases the TEG modules cannot be operated at the same temperature difference. At reduced temperature difference also the output power will be reduced, however the load resistance does not have to be adapted to changing temperature differences.

Thermoelectric generators have a significant potential for the energy transition. Possible applications can be found in the natural environment (geothermal energy, solar thermal energy, deep heat), on buildings (roofs, facades), and on large-scale process plants (waste incineration plants, CHP plants, heat pumps, chimneys).

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