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Techno-Economic Obstacles for a Hypothesized Thermoelectric Generation Power Plant (TEGPP)

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Abstract: A thermoelectric generator (TEG) is a solid-state semiconductor device that produces a direct current (DC) voltage when subject to a temperature difference, through a phenomenon known as the Seebeck effect. The TEG technology has been proposed for waste heat recovery, through generating electricity from a source of heat that is not otherwise exploited, such that the hot exhaust gas released from a vehicle engine. In this study, the concept of building a power plant using TEG modules was investigated, both technically and economically. The hypothesized thermoelectric generation power plant (TEGPP) is modular, consisting of a large array of electrically connected TEG units for generating clean electricity without greenhouse gas (GHG) emissions, noise, or hazardous solid wastes. The TEGPP considered here is assumed to utilize solar radiation as a heat source, and water as a heat sink. The viability of such a concept was examined here based on available specifications of a high-output TEG module in the market. Benchmarking was carried out considering a high-efficiency photovoltaic (PV) panel in the market, assuming that it operates under standard solar radiation of 1,000 W, and with a standard panel temperature of 25 °C. It was found that in order to have an electric power of a TEG unit similar to that of a PV panel of equal area, the temperature at the hot side of the TEG unit should be about 70 °C if the cold-side temperature is 30 °C. However; under this electric equivalence, the price of the TEG unit is about 90 times that of a PV panel of equal size. At an elevated hot-side temperature of 300 °C for the TEG unit (with the cold-side temperature still 30 °C), the TEG unit can generate power that is about 25 times the power generated by a PV panel of equal geometric size. This big boost in the output power still does not counteract the large cost difference between the TEG technology and the PV technology.

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1. Introduction

The Seebeck effect is a thermoelectric phenomenon where a temperature difference between the two points of contact of two different metals forming a closed circuit causes the metals to display magnetic properties due to an induced current and electric field. In other words, a temperature difference can result in a voltage difference and electricity [1].

The Seebeck effect is quantitatively expressed by the Seebeck coefficient (α), which is a proportionality factor relating the resulting voltage difference (ΔV) to the applied temperature difference (ΔT), over a narrow range of temperature [2].

$$\alpha = -\Delta V / \Delta T \quad (1)$$

The Seebeck coefficient is generally a function of temperature [3]. The Seebeck coefficient tends to be very small for metals, with no metal having a value above 100 μV/K (at 300 K). Furthermore, most metals have a Seebeck coefficient magnitude below 10 μV/K [4].

Despite being weak, the Seebeck effect was successfully utilized in temperature measurements through sensor elements called thermocouples [5]. In order to upgrade the Seebeck effect for use as a power source, magnification is performed through adopting semiconductor materials instead of metals, and through arranging many thermoelectric elements connected electrically in series while subject to a common temperature difference between two sides (hot side and cold side) [6]. This special design leads to a thermoelectric generator (TEG) module, which may be viewed as a portable direct current (DC) power source in the shape of a thick plate.

Small TEG-based power units were already produced commercially. These units may have a power rating of 10 W, converting heat (such as a flame of a camping gas canister) into direct current electricity (with 5 V or 12 V voltage levels) for low-power applications, such as lighting and charging mobile phones [8].

The use of TEG models for recycling waste heat was proposed in different applications such as combustion gases of an electric generator, and industrial furnaces [8,9].

This study investigates the suitability of electrically assembling an array of thermoelectric generator (TEG) modules so that the array becomes a candidate for a power plant, in a similar way that many solar photovoltaic (PV) panels can be assembled in an array and act a renewable energy power plant. The anticipated heat source here is direct solar radiation, and water cooling is needed. Such an imagined thermoelectric generation power plant (TEGPP) has several advantages, such as not having moving parts in the generation part (solid state devices), which eliminates requirements for lubrication, avoids noise, and improves reliability [10]. A TEG system can be classified as a clean alternative power source if its heat source does not cause harmful greenhouse gas (GHG) emissions, such as solar heat or waste heat [11].

2. Settings

This section describes various settings for a thermoelectric generator (TEG) module from which a TEGPP can be formed. The TEG module corresponds to a high-power model, which is TEG1-24111-6.0, produced by the Canadian manufacturer TECTEG, which is a division of the Thermal Electronics Corporation (TEC) [12]. Table 1 provides a summary of some conditions for the TEG module as well as selected operational conditions for the TEGPP.

Table 1. Settings for the thermoelectric generator (TEG1-24111-6.0), as a possible module in a TEGPP.

Setting	Type	Value
Cold side temperature	Assumption	30 °C
Hot side temperature	Assumption	70 °C
Power mode	Assumption	Matched load (maximum power)
Load resistance	Performance curve	2.9 Ω (approximately)
Voltage difference	Performance curve	1.4 V (approximately)
Current	Calculated (voltage difference ÷ load resistance, with performance curve validation)	0.48 A
Power	Calculated (voltage difference × current, with performance curve validation)	0.672 W
Dimensions	Data sheet	0.056 m × 0.056 m
Area	Calculated (length × width)	0.003136 m^2
Power density	Calculated (power ÷ area)	214.3 W/m^2
Modules per m^2	Calculated (1 m^2 ÷ area)	318.878
Price of 1 module	Online, by manufacturer	USD 49.0
Cost per m^2 of module	Calculated (price of 1 module ÷ area)	15,625.0 USD/m^2
Cost per W of output	Calculated (price of 1 module ÷ power)	72.9167 USD/W

The above module price reflects a discount for bulk orders (50 or more TEG modules). For small orders (from 1 to 9 TEG modules), the price increases to USD 56.0.

For benchmarking, a high-efficiency photovoltaic solar panel is considered here for comparison with the TEG modules. This panel (SPR-MAX3-400) is the model Maxeon 3 by the American company

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SunPower, having a nominal power of 400 W. It has a nominal solar-to-electric energy conversion efficiency of 22.6%.

Table 2 list some features of that PV panel, based on manufacturer's data sheet and the selling price provided by an online supplier [13].

Table 2. Settings of the SunPower Maxeon 3 solar photovoltaic panel (SPR-MAX3-400).

Setting	Type	Value
Power mode	Assumption	Standard test condition (1,000 W/m² solar radiation, 25 °C panel temperature), and maximum power
Voltage difference	Data sheet	65.8 V
Current	Data sheet	6.08 A
Power	Calculated (voltage difference × current, with data sheet validation)	400 W
Dimensions	Data sheet	1.690 m × 1.046 m
Area	Calculated (length × width)	1.76774 m²
Power density	Calculated (power ÷ area)	226.3 W/m²
Panels per m²	Calculated (1 m² ÷ area)	0.565694
Price of 1 panel	Online, by a European supplier (in Lithuania)	EUR 346.0 (equivalent to USD 337.18 as of 8/October/2022)
Cost per m² of panel	Calculated (price per panel ÷ area)	190.74 USD/m²
Cost per W of output	Calculated (price per panel ÷ power)	0.84295 USD/W

3. Results

The analysis in the previous section suggests that the TEG modules and the PV panels can give similar DC electric power output per unit surface area under their optimized operations. When comparing 214.3 W/m² for the TEG module with 226.3 W/m² for the PV panel, the magnitude of the relative difference is below 6%.

However, the cost of power is significantly different for the two technologies. The cost of a unit power in the case of the TEG technology is about 86.5 times its value for the PV technology (72.9167 USD/W compared to 0.84295 USD/W). This does not even take into account added expenses of the cooling system for the TEG modules.

4. Discussion

The manufacturer of the investigated TEG module has a recommended operational condition of 30 °C for the cold side, and 300 °C for the hot side (which is near the maximum allowed limit of 320 °C). In that intense mode, the heat flow density across the module is about 96,000 W/m², which is 96 times the standard solar radiation power of 1,000 W/m². This is an enormous heating requirement, which also demands excessive cooling at the cold side.

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The electric power density (with a matched load) under this TEG intense condition is 5,612.2 W/m² (24.8 times the power density of a PV panel under its standard condition). With a needed heat flow density of 96,000 W/m², the heat-to-electricity conversion efficiency for the TEG module in that case is only 5.85%.

The estimated cost per watt under such an intense TEG operation drops by a factor of 26.19, from 72.9167 USD/W to 2.7841 USD/W. Despite this big decline, this cost is still 3.3 times higher than the estimated one for PV panels (0.84295 USD/W).

5. Conclusions

Based on assessment of the power generation capability and its economic aspect, this study concludes that a thermoelectric generation power plant (TEGPP) is far from being realistic. Such a TEGPP cannot compete with a solar photovoltaic power plant, primarily due to the large cost gap that cannot be bridged by intensifying the operational conditions to a level near the maximum allowed temperature.

However, thermoelectric generators (TEG) are still successful in energy harvesting through converting waste heat into useful electricity.

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