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Cost Estimation of Thermoelectric Generators

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ABSTRACT

Technology using thermoelectric generators (TEG) can transform thermal energy into electricity directly by using the Seebeck effect. TEG electricity generation technology has many advantages such as compactness, quietness, and reliability because there are no moving parts. One of the challenges to using TEG for power generation may be the cost. This study collected the costs of the main parts required to make a TEG power generation system. The total cost of such a TEG system has been estimated according to the costs of parts and the data of the field tests conducted at Bottle Rock Geothermal Power Plant, California, USA. The total cost was assessed at different temperatures. Higher temperatures lower the total cost of a TEG power generation system. We found that the cost of TEG generation at conditions such as at Bottle Rock would be less than that of solar photovoltaic panels if availability and capacity factor are considered.

1. INTRODUCTION

Thermoelectric generation (TEG) is a technology that can enhance electricity production (Ahmadi Atouei et al., 2017; Araiz et al., 2017; Atouei et al., 2018; Demir and Dincer, 2017a). TEG can transform different types of thermal energy or heat into electricity directly by using the Seebeck effect. TEGs have a lot of advantages, including longevity, easy maintenance, compactness, quietness, and reliability because there are no moving parts. Large scale utilization of TEG technology can play an important role in shaping the industry of electricity generation from thermal energies, including those from solar, geothermal, biomass, industrial waste heat, etc. (Kim et al., 2018, 2016; Wang et al., 2014). There have been many reports on the application and the improvement of TEG technology (Cao et al., 2018; Demir and Dincer, 2017b; Huang et al., 2018; Huang and Xu, 2017; Kane et al., 2016; Kim et al., 2017; Lv et al., 2017; Negash, 2017; Remeli et al., 2016; Tu et al., 2017). However, TEGs have not been widely marketed yet because of the higher cost and lower efficiency.

There have been a few studies and reports on the TEG cost for practical utilization. According to a case study about TEG unit for passenger automobiles, Kishita et al. (2016) indicated that it is necessary to reduce the current TEG price by 60-90% in order to reduce the life cycle CO_2 emissions to zero (Kishita et al., 2016). Kishita et al. also summarized the performance and cost of the TEG unit. The maximum output power and capital cost of the TEG unit were 480 W and \$2000, respectively. The capital cost per kW was over \$4000.

Bellos and Tzivanidis (2020) carried out an energy and financial investigation of a solar-driven thermoelectric generator in the climate conditions of Athens, Greece. In the default financial scenario with a 2% discount factor and \$1,214/kW specific investment cost, the payback period was found to be about 4.55 years and the levelized cost of electricity around \$0.0535/kWh (Bellos and Tzivanidis, 2020).

The cost, operating conditions, time, and scale of TEG will affect its market competitiveness. Yazawa and Shakouri (2013) optimized the energy consumption of thermoelectric power generators burning fossil fuel (propane). The results showed a lower initial cost compared with commercialized micro gas turbines but a higher operating cost per kW due to the moderate efficiency. The quantitative benefit of TEG on a price-per-energy (\$/J) basis lies in its scalability, especially at a smaller scale (<10 kW), where mechanical thermodynamic systems are inefficient (Yazawa and Shakouri, 2013). In the study of Yazawa and Shakouri, the power price of the TEG holds steady at about \$0.8/kWh with efficiency of 13.3% (assuming $ZT \approx 0.8$). Rinalde et al. (2013) reported a new TEG based on moderate-temperature (up to 175 °C) BiTe modules. The specific cost of about 55,000 \$/kW obtained for the 120 W prototype has been improved to \$33,000/kW for a 1 kW unit (Rinalde et al., 2013).

Based on direct ink writing (DIW), Shakeel et al. (2021) printed a TEG onto window glass in an economic way for solar thermal energy harvesting which shows the flexibility of the fabrication process. The overall material and manufacturing cost estimated was about \$120/W (Shakeel et al., 2021). Shakeel et al. used a geometrical approach to maintain a temperature gradient rather than the use of an expensive heat exchanger which is a dominant factor for reducing the cost of the TEG device. The cost of heat exchangers usually dominates the cost of the overall TEG system, which is difficult to escape. In order to achieve TEG system cost of \$1/W, it is necessary to achieve the heat exchanger cost of \$1/(W/ °C). Considering different cold temperatures, the cost of TEG ranged from \$13,500/kW to \$16,000/kW at 500 °C hot temperature and from \$10,000/kW to \$12,000/kW at 575 °C hot temperature (Hendricks et al., 2016).

Omer et al. (2020) studied the dependence of TEG cost on temperature difference (ΔT). Their results show that the payback time rapidly decreases with the increase in ΔT. The ΔT-dependent payback time was calculated assuming a warranty time of 5 years, a cost of \$1250/kW, and a revenue of \$0.133 per kWh. When ΔT = 100 °C, 152 W of power is achieved and the payback time is estimated to be 7 years in this case (Omer et al., 2020).

In this study, the costs of the main parts required to make a TEG power generation system were collected. The total cost of a TEG system has been estimated according to the costs of parts and the data of the field tests conducted at Bottle Rock Geothermal Power Plant, California, USA. The total cost was also assessed at different temperatures.

2. OUTLINE OF FIELD TEST

Many factors affect the cost of a TEG apparatus. One of the main factors is the power output per TEG chip at a specific temperature difference. It is more accurate to estimate the cost based on field test data than that based on lab experiments. The field test that used for the cost estimation in this paper is briefly discussed as follows. The details could be referred as to Li et al. (2020).

The six-layer-TEG apparatus used for field tests is shown in Fig. 1 and has a dimension of 75 cm (length) X 24 cm (width) X 18 cm (height). The TEG device can withstand high pressure better, without leak, if the pressures on the cold and hot sides of the TEG chips are approximately equal to each other.

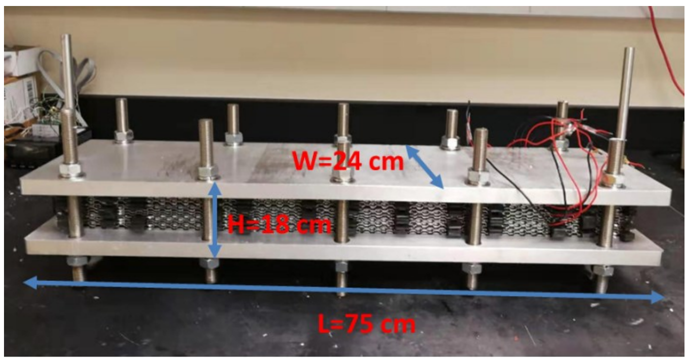

Fig. 1: The photo of the six-layer-TEG device used for field test (Li et al., 2021).

The six-layer TEG apparatus was installed at Bottle Rock geothermal field, as shown in Fig. 2. We conducted the tests and measured the power output at different steam pressures (or steam flow rate) using the steam from this geothermal production well and at different pressures of cold water (or water flow rate). The field test began on September 27, 2019 and ended on September 29, 2019.

(a) The new six-layer TEG apparatus installed for field test at Bottle Rock geothermal field (Li, et al., 2021).

(b) The field test site at Bottle Rock geothermal field.

Fig. 2: The TEG apparatus and the field test site at Bottle Rock geothermal field.

The total power for the six-layer TEG apparatus is shown in Fig.3. The total estimated power reached about 560 W at a steam flow rate of 120 lb. per hour.

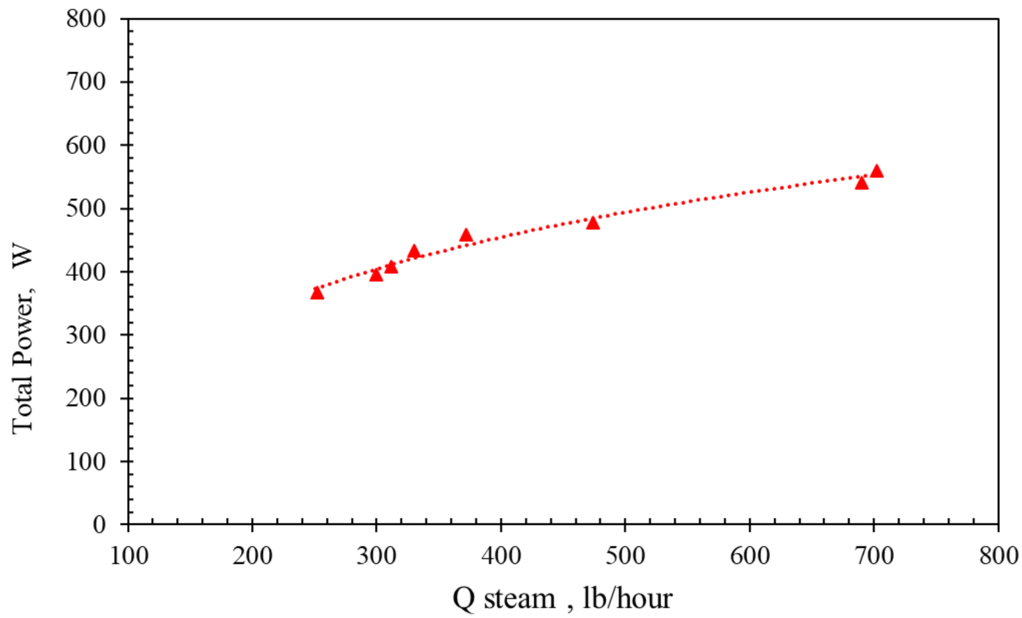

Fig. 3: The total power estimated for the six-layer TEG apparatus in field tests

The volumetric power density of the TEG apparatus was estimated based on the field test results. A device with a physical volume of 50 cubic meter could generate about 1 MW of electric power, which is very attractive.

3. BASIC DATA AND FACTS FOR COST ESTIMATION OF TEG

The main data required for the cost estimation is the number of TEG chips that could make 1 kW electricity, which depends on the temperatures at the inlet and the outlet of the TEG apparatus. The cost of one TEG chip can be obtained from the vendors. Then the cost per kilowatt of TEG chips can be estimated. Note that the costs of other parts such as frames that hold the TEG chips should be included in the cost estimation of the entire TEG apparatus.

The cost estimation of TEG was based on the results of the field tests conducted at Bottle Rock geothermal field in The Geysers, CA, USA, as discussed in the previous section. The field test data used in the cost analysis in this paper are listed as follows.

(1) TEG device: six layers with 144 chips (size: 4x4 cm). (2) Temperature at the inlet of the TEG apparatus: 176 °C (349 °F). (3) Steam pressure at the inlet of the TEG apparatus: about 122 psi. (4) Wellhead pressure: 125 psi. (5) Temperature difference: 152 °C between the hot and cold fluid manifolds. (6) Power generated: about 500 W electricity.

4. PRELIMINARY COST ANALYSIS

According to the analysis of the results of the field test and the costs of single TEG chips, heat exchange plates, and other parts in the TEG device, it was estimated that the cost of the 6-layer TEG device would be around $13,900/kW at a temperature difference of 152 °C between the hot and cold fluid manifolds. The payback period at the specific temperature difference is about 8.4 years. The electricity price of California in 2019 (US EIA, 2019) was used to calculate the payback time.These costs are very attractive compared with solar photovoltaic (PV) panels. The costs per kW and payback period of TEG systems also depend on the temperature difference. The ΔT-dependent costs per kW and payback period were calculated and shown in Fig. 4. Both the cost and the payback time of the TEG systems decrease with the increase in temperature difference.

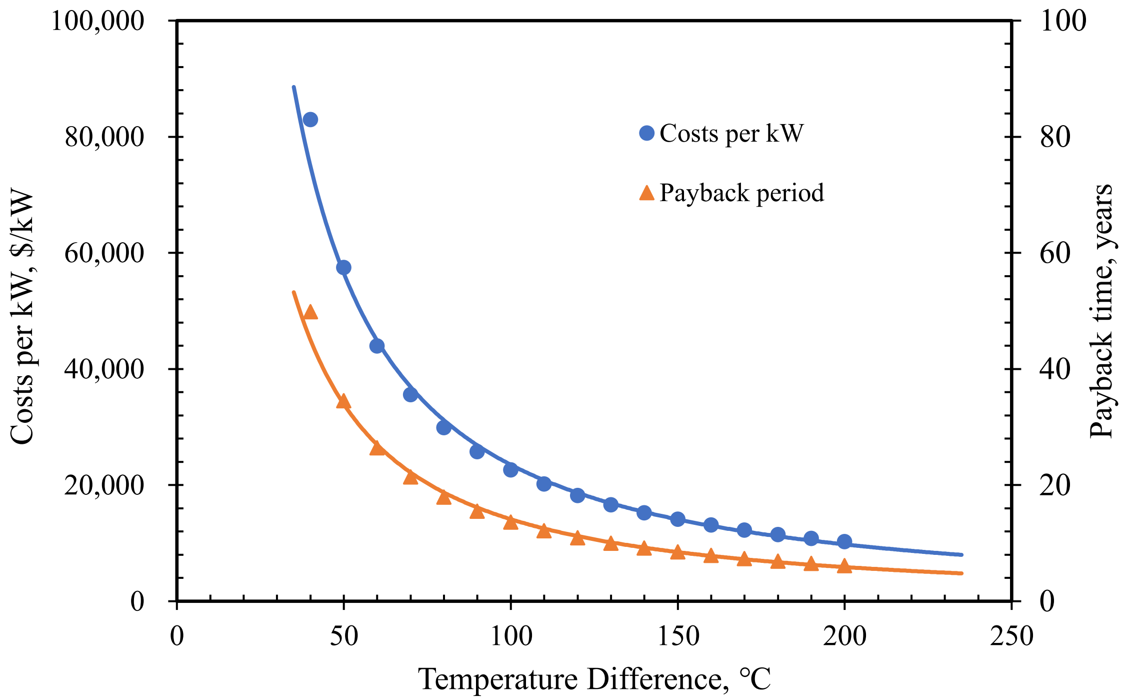

Fig. 4: Cost per kW and payback period depend on temperature difference.

The average cost of installing solar panels in 2019 is $3.05 per watt ($3050 per kW) according to solar comparison-shopping marketplace EnergySage (White, 2020), as shown in Fig. 5. The capacity factors of solar PV are between 10 and 25%, and they average about 20%, due to nights and cloudy days (Li et al., 2015). The cost of solar PV panels is greater than that of TEGs if capacity factor is considered. TEG devices have a capacity factor of ~99%, and so the net cost of solar PV panels at a capacity factor comparable to a TEG system would be about $15,250/kW.

Note that the cost comparison of TEG with solar PV is actually unfair to TEG. This is because the cost of TEG is estimated at a very small scale but the cost of PV is the current price at a very large scale.

At a scale larger than 20 kW, the cost of per kW TEG could be less than $13,900. TEG devices may also be cost competitive with binary geothermal power generation technology because TEG does not need turbines and does not need the binary fluids which may need to be refilled from time to time.

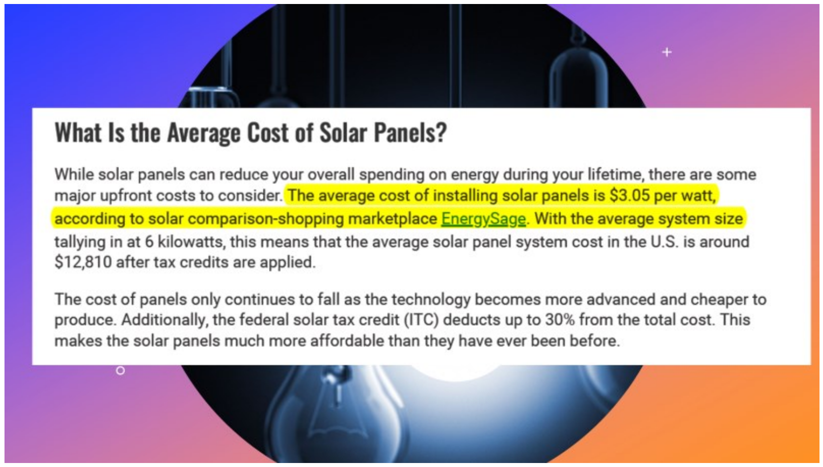

Fig. 5: The average cost of installing solar panels, (White, 2020).

5. DISCUSSION ABOUT DECREASING TEG COST

TEG technology is very promising according to the preliminary cost analysis shown in last section. It is surprising that current academic and industry attention has been dominantly focused on PV technology. Comparatively, less interest has been dedicated to TEGs. Note that the value of figure-of-merit ZT (= S2σT/κ) of the thermoelectric material used in this field test was about 1.0. A good thermoelectric material should have a good Seebeck coefficient (S) that is usually the feature of semiconductors, high electrical conductivity (σ) as that of copper metals, and also very low thermal conductivity (κ) like most heat insulation materials (for example, glass fibers). It is difficult to find a single material that has all of the ideal features to realize high thermoelectric performance. However the advancement in thermoelectric materials is excellent in terms of increasing the values of ZT as shown in Fig. 6 reported by Tan et al. (Tan et al., 2016).

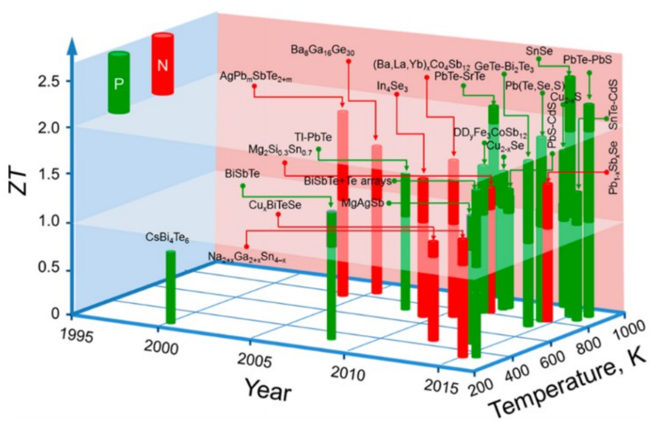

Fig. 6: Current state-of-the-art bulk thermoelectric materials: the thermoelectric figure-of-merit ZT as a function of temperature and year illustrating important milestones. Green cylinders represent the p-type materials, while red cylinders represent the n-type ones (Tan et al., 2016).

Remarkably, a large dimensionless figure of merit ZT exceeding 400 has been reported by Byeon et al. (2019), as shown in Fig. 7. This exceptional behavior might be brought about by the self-tuning carrier concentration effect in the low-temperature phase assisted by the high-temperature phase, as Byeon et al. (2019).

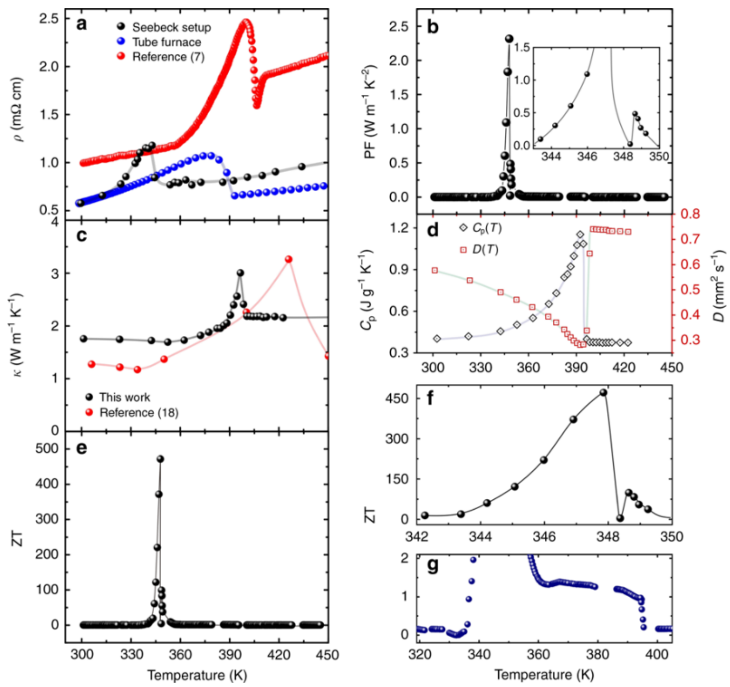

Fig. 7: Temperature dependences of thermoelectric properties of Cu_2Se, from (Byeon et al., 2019).

With the continuous increase in the figure of merit ZT, the cost of the power output per kW by TEG will be reduced significantly. We speculate that the TEG power generation technology may be able to replace binary or even traditional geothermal power generation technologies when the thermoelectric materials with a ZT value greater than 4.0 are available at a large scale.

6.CONCLUSIONS

According to the field test results, the following conclusions may be drawn on the cost of TEG apparatus at a small scale:

(1) The TEG device with 6 layers and 144 chips would cost around $13,900/kW at a temperature difference of 152 °C between the hot and cold fluid manifolds.
(2) The payback period of the TEG device tested at Bottle Rock Geothermal Power Plant, California, USA is about 8.4 years at a specific temperature difference of 152 °C.
(3) The cost of TEG systems, even at a small scale, is less than that of solar photovoltaic (PV) panels if availability and capacity factor is considered.
(4) A TEG system with a volume of 50 m^3 could generate about 1 MW electric power. Such a unit is comparable in size to a 1 MW diesel-powered generator and could supply a thousand homes.
(5) With the continuous increase in the figure of merit ZT due to the improvement of thermoelectric materials, the cost of the power output per kW by TEG will be reduced significantly. We speculate that the TEG power generation technology may be able to replace binary or even traditional geothermal power generation technologies when the thermoelectric materials with a ZT value greater than 4.0 are available at a large scale.

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