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FINAL PROJECT REPORT

Thermoelectric Generator Application and Pilot Test in a Geothermal Field

Gavin Newsom, Governor
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ACKNOWLEDGEMENTS

This research was conducted with financial support from the California Energy Commission (EPC-16-036), the contributions of which are gratefully acknowledged.

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

This is the final report for the Thermoelectric Generator Application and Pilot Test in a Geothermal Field project (Grant Number EPC-16-036) conducted by AltaRock Energy, Inc. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

Thermoelectric generators (TEG) are solid state devices that convert heat directly into electrical energy. A TEG produces electrical voltage when there is a different temperature on each side of the material. TEGs function like heat engines, though not as efficiently, but are less bulky and have no moving parts. TEGs are typically applied to power small devices, such as space probes and wine coolers. This project sought to develop a TEG apparatus that could produce electricity using heat generated form a geothermal field in The Geysers in northern California. While there have been many studies on TEG power output under varying conditions, there are no known studies of adapting TEGs to a geothermal resource. To this end, we designed a geothermal-TEG apparatus that has a modularized design to allow expanded power production by increasing the number of layers. After demonstrating the TEG's performance in the laboratory, the apparatus was tested in the field at a well located in the Bottle Rock geothermal field. A 6-layer TEG field-scale device could generate about 500 W electricity with a temperature difference of about 152 °C between the hot and cold fluid manifolds, while each individual TEG chip could generate about 3.9 W. The steam pressure at the inlet of the TEG apparatus was about 122 psi, close to the wellhead pressure of 125 psi. After optimizing the field infrastructure, the TEG device could generate electricity without any leak at the wellhead pressure of 125 psi and the temperature over 176 °C (349 °F). The field test of the TEG field device at Bottle Rock geothermal power plant was considered successful. The work demonstrated that geothermal-TEGs can produce electricity in an economically competitively range similar to solar PV panels when external factors such as capacity factor are considered.

Keywords: Geothermal, thermoelectric generator system, direct power generation, thermoelectric effect, thermal efficiency

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EXECUTIVE SUMMARY

Background

Geothermal energy is one of the largest sources of renewable energy according to the 2000 World Energy Assessment. Compared with solar and wind systems, geothermal energy has many advantages, including being impervious to weather changes, having a stable base load, and high thermal efficiency (for high temperature geothermal resource). However, the total capacity of installed geothermal power lags far behind solar and wind. In 2020, the nameplate capacities of PV and wind power installed in the US were 91 and 126 GW, respectively, but the total geothermal power installed in the US was still less than 2 GW. Factors that hold back expansion of geothermal energy production include high initial investment, high exploration risk, long payback and construction time, difficulty assessing resources, and difficulty to modularize. One strong potential solution to expanding geothermal may be the large-scale utilization of Thermoelectric Generator (TEG) technologies.

Increased attention has been recently paid to the application of low-temperature thermal resources for power generation. A noteworthy example is the ORC plant in Chena Hot Springs, Alaska, which produces 250 kW electricity from geofluids that are only 74 °C. However, recent research into the application of TEG have indicated that they could also be economical when used in these lower temperature resources. Most of the current commercialized thermal power-generation technologies, including geothermally-source power production, convert thermal energy to electric energy indirectly, doing mechanical work (for example, spinning a turbine) before producing electricity. Technology using TEGs can transform thermal energy into electricity directly, without moving parts, making TEG apparatus compact, quiet, and reliable.

TEG technologies can produce power without turbines or other moving parts. Because of these characteristics, TEG may make small-scale production and geothermally-sourced micro power grids both practical and affordable. Small (<5 MW) geothermal projects could provide consumers with the same distributed power flexibility provided by solar and wind production with the additional benefit of being a more reliable base-load source of electricity without intermittency. TEG technologies can also allow geothermal heat to provide balancing and grid support as well as using the earth's heat for storage.

TEG’s produce electricity through what is known as the Seebek effect, where an electromotive force is created across an electrically conductive material when one side of that material is hotter than the other. Depending on which direction that electromotive force moves (positive or negative), those thermoelectric materials are referred to as “P-type” and “N-type”. A typical TEG module is constructed of multiple pairs of P-type and N-type materials wired together in series; a typical TEG module design is 127 pairs in a flat 4 cm by 4 cm array. Applying a temperature gradient across the module causes charge carriers to diffuse towards the cold side which generates an electric voltage.

Many numerical and experimental studies have been published on the applications of TEG and the parameters affecting the TEG power. It has been shown that there is great potential to apply TEG in the direct conversion of waste heat to electricity (Crane and Jackson, 2003; Maneewan and Chindaruksa, 2009). The effects of the TEG dimensions and flow characteristics on the TEG power output and the thermal conversion efficiency are significant, based on the previous studies (Yu and Zhao, 2007; Bélanger and Gosselin, 2011; Wang et al., 2008; Liu and Li, 2014).

An attractive application of TEG technology is to generate electricity from enhanced geothermal systems (EGS). Catalan et al. (2019) built a prototype to experimentally analyze the feasibility of using TEG for EGS resources. The prototype was composed by a two-phase closed thermosyphon as a hot side heat exchanger and two thermoelectric modules. Different cold side heat exchangers were used: fin dissipators assisted by a fan and loop thermosyphons, both with various geometries. The experimental results have demonstrated that loop thermosyphons might be the best alternative due to their low thermal resistance, primarily, due to their lack of auxiliary consumption. They are leading to a maximum net power generation of 3.29 W per TEG module with a temperature difference of 180 °C, 54% more than those with fin dissipators.

Project Purpose

The current geothermal industry is conservative, risk-adverse, and firmly rooted in conventional technology, and as such is hesitant to implement new technologies such as TEG. The purpose of this project was to demonstrate that a thermoelectric generator (TEG) could be used at a geothermal resource to produce electricity and to understand whether such power production could be competitive in the marketplace. This pilot-scale project sought to prove both the feasibility of using TEG materials to produce electricity from a geothermal resource and the feasibility of deploying this technology in an operating field. The goal is to bring geothermal-TEG technologies to a pre-commercial stage. The results of this project could support the future design of a larger-scale demonstration project for appraisal of operational and performance characteristics and financial risks of utility-scale geothermal-TEG projects. This will help expand development of untapped and localized geothermal resources.

Project Approach

The project was led by AltaRock Energy, owners of the Bottle Rock Power project located near Cobb, California. Bottle Rock is a part of the larger Geysers geothermal resource area, currently the largest geothermal field in the world. AltaRock Energy served as the project lead, point of contact with the CEC, and technical contributor. Bottle Rock Power provided the field site for demonstration of the geothermal-TEG operations. Bottle Rock provided use of geothermal steam from its Coleman 3-5 well as well as the staff and infrastructure to install and operate the geothermal-TEG in the field. Stanford University conducted data collection, and analysis of both the laboratory-scale experiments and the field-scale demonstration.

Challenges to the project were twofold: 1) how to scale up a TEG from benchtop to field scale, and 2) how to deploy and operate a TEG in an operating geothermal field within the physical and regulatory confines of that project. TEGs are a direct heat to electricity technology which relies on the utilization of the thermoelectric effect without the need to develop power using mechanical energy. This project was a direct extension of successful laboratory-scale proof-of-concept experiments which have demonstrated that the technology works. A demonstration-scale TEG unit was built for testing at geothermal fields to help determine how TEGs could be used to develop usable-scale distributed energy production from a variety of geothermal resources. The goal of applying this technology is to explore the scalability from laboratory power size to field pilot size and to reduce the cost of generating electricity using geothermal resources with different temperatures while increasing its distribution and power generation flexibility.

Geothermal resources produce a flow of enthalpy (e.g., energy) as hot water and/or steam, and geothermal power production efficiency is expressed as mass flow per kilowatt (kW). Phase 1, therefore, started with lab testing that expanded on lessons from previous lab-scale experiments. TEG generator output and efficiency were determined as a function of flowrate, temperature gradient (across the TEG), ratio of TEG mass to heat flow mass, and apparatus generator design. TEG efficiency was compared to conventional geothermal power generation equipment such as organic Rankine cycle binary systems and flash-steam turbines. Design parameters were determined in Phase 1 for a field-scale device operation in Phase 2. TEG field device parameters included number of TEG cell layers, type of insulator materials, need for and types of engineered cooling system, and the magnitude of geofluid flows needed to be supplied at the different testing fields. Phase 2 was also concerned with developing a deployment process which tested the regulatory notification and permitting process, proving the concept that geothermal heat could be supplied to a TEG apparatus, and demonstrating whether a heat exchanger would provide adequate cooling using ambient temperature water to create enough of a temperature differential across the larger TEG apparatus. The geothermal-TEG was then installed and operated at the Bottle Rock geothermal field to demonstrate how well it could operate under field conditions. Field operations were important to understand the regulatory and operational procedures for operating a geothermal-TEG. Data was collected in real time during the operation of the TEG to analyze its efficiency and cost of power production.

Project Results

The project was considered a successful demonstration of how TEG technology can be used to generate electricity using a geothermal resource. Originally the project was designed to deploy a 20-kW geothermal-TEG apparatus. To that end, three smaller geothermal-TEG apparatus were built and tested in the field: a 200 W unit built by Stanford University, a 240 W unit built by Hi-Z, Inc., and a 500 W unit also built by Stanford University. Field testing of each of these generators provided key data for developing design parameters for larger geothermal-TEG units. However, ultimately the project was not successful in building a 20-kW geothermal-TEG apparatus due to insurmountable delays to the project schedule cause by inclement weather, changes in project administration, and changes in project staffing that left the team without resource needed to complete the build.

The project was, however, particularly successful in troubleshooting the deployment process by testing the regulatory notification and permitting process, providing a proof-of-concept for supplying geothermal heat to a TEG apparatus, and demonstrating whether a heat exchanger would provide adequate cooling using ambient temperature water to create enough if a temperature differential across the larger TEG apparatus. Of the lessons learned the most surprising was the regulatory challenges of applying a new generation technology to an established geothermal field.

According to the field test results, one layer with 24 chips could generate about 100 W per layer without any leak at the wellhead pressure of 125 psi and temperature over 176 °C (349 °F). Therefore, about 40 layers (960 chips) are needed for one TEG unit to generate 4 KW. It is very difficult to put 40 layers in one unit of the design. One of the main challenges is how to achieve good thermal contact with both the cold and hot plates in all of the TEG chips in one layer, which requires that all the chips have exactly the same thickness. However, the thickness of the commercially available TEG chips is often not the same, and chips need to be screened before assembling them. It may be possible to develop a method or a device to do the chip screening automatically. Of course, the best solution to this problem would be to have the chips with exactly the same thickness, but this is not within the scope in this project as the TEG chips are received from suppliers in whatever format they make them.

The second challenge to building 40 layers (720 chips) into one TEG unit is the electric connection. In this project, all of the chips in the same layer were connected in series, but a series connection will not function at all if even one chips fails. Therefore, future designs should connect all of the layers in parallel. The electricity generated by the TEG system is direct current (DC), which can be transformed to alternate current (AC). The solar PV industry has developed very good commercial transformers from DC to AC. We can just buy such units on the commercial market.

It was estimated that the cost per kW would be around $13,900 with the TEG apparatus design used. The total cost of the 20 kW TEG would be around $280,000, and the volume of a 20 kW TEG device would be around 1 m^3. These costs are very attractive compared with solar photovoltaic (PV) panels. The average cost of installing solar panels is $3.05 per watt ($3,050 per kW). The capacity factors of solar PV are between 10 and 25%, and they average about 20%, due to nights and cloudy days. 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. At a scale larger than 20 kW, the cost per kW of a 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 fluid.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The results, analyses, findings, and conclusions have been presented in three geothermal industry meetings (one Stanford University geothermal workshop and two Geothermal Resources Council conferences) and two peer-reviewed publications (International Journal of Heat and Mass Transfer, Journal of Power Sources). The publications and presentation were well received, and inquiries have been received from electrical technology enthusiasts in the US and Canada. The findings can be used to design and build remote, hands-off electrical generation systems in remote areas that are of the gird or could otherwise afford significant investment in transmission infrastructure. Near-term markets for TEG-geothermal technology could include remote communities adjacent to orphaned geothermal resources that are too small or too far removed from transmission to be economically attractive to the state-wide electrical market. If geothermal-TEGs become commercially available, both their cost and size will reduce while efficiency is improved as the technology matures with subsequent generations of generators. If commercial geothermal-TEGs can reach their theoretical performance, they will compete with binary Organic Rankine Cycle geothermal power technology. Optimizing TEG performance to be an effective and practical large scale energy producer requires a temperature difference (ΔT) of 200 °C, stronger TEG module framing than is currently commercially available, and colling-side heat exchangers that work well enough that they don’t overwhelm the generator itself in size and capital cost. In that case, the >90% less maintenance needed by geothermal-TEGs will make them more attractive for widespread adoption by the power industry. The biggest challenge to commercializing geothermal-TEGs is the fact that the geothermal industry is a small and niche player in California's power market. Until the demand for geothermally-source electricity grows, there will not be a great demand for new and unconventional power generation technologies like TEGs. It has been estimated that the potential power that could be generated in California from small geothermal resources that have been ignored by larger power producers could be on the scale of up to 2 GW. These tend to be resource that are too far from power markets or adequate transmission to be economically attractive for utility scale power production. The reduced infrastructure need and maintenance requirements of geothermal-TEG technology could make developing these orphaned resources more attractive, especially for nearby off takers.

Benefits to California

Growth of the geothermal industry has been held back by the need for large and costly power plants and large-scale infrastructure to produce geothermal electricity on an economic scale. Typically, a geothermal project cannot produce electricity economically at a scale less than 5 MW and there is a very large economy of scale for projects above 30 MW in size. TEG technologies, however, have the potential to produce geothermal electricity without all the infrastructure – turbines, steam piping, etc. – thus making small scale production and geothermally-source micro power grids both practicable and affordable. Small (<5 MW) geothermal projects could provide consumers with the same distributed power flexibility provided by solar and wind production with the additional benefit of being a more reliable base load source of electricity. TEG technologies can also allow geothermal heat to provide balancing and grid support as well as using the earth's heat for storage. TEG is direct generation that makes geothermal more like solar but available and dispatchable at any time of day. Research is on-going in the development of various TEG materials and metal interconnects. For this project, the scale up from the watt-level in the lab to use in a geothermal reservoir has the capacity to produce 10 kW to 100 kW and 500 kW in easily replicated steps.

This project demonstrated the applicability of thermoelectric generation (TEG) technology which can expand the production of electricity from renewable resources in the State of California. Geothermal-TEG can expand use of low temperature and stranded geothermal resources in the state which have not traditionally been used to produce electricity. TEG generating from geothermal can supply peaking power and balancing of intermittent renewable resources like wind and solar at much lower cost than batteries without relying on power supplied by the grid. Because TEG allows direct electrical generation from the heat of the earth, there is no safety risk from large rotating equipment and lower risk of accidental discharge of geothermal fluids.

California has a very large potential for geothermal resource development, with over 2000 MW currently supplied to the state grid. However, smaller resources in remote areas without grid connectivity may not be developable due to scale and lack of support for development. Use of TEG technology can enable development of these resources to supply small communities or off grid uses such as providing direct heat with small scale power. Because this technology can operate unattended, it can provide power to follow local demand reducing reliance on balancing for areas at the end of long transmission lines.

A premise of the project is the offset costs associated with adding renewable power to an existing facility. The other component of this work is that the techniques developed at this field can be used at other underperforming geothermal resources to create lower cost power. Prior to stopping power production, Bottle Rock Power plant at The Geysers emitted approximately 183 g/kWh of CO_2. This compares with a natural gas power plant which emits more on the order of ~450 g/kWh. Use of TEG technology should compare favorably with battery storage costs while allowing completely dispatchable power at any time of day. TEG can also provide power on demand for off grid use or for grid support. For projects providing combined heat and power, TEG technology can use heat directly to generate power on demand while also providing heat for direct use such as heating, cooling, green-housing, food or wood drying, brewing or distillation. Costs will be significantly reduced due to the low operating cost which are similar to solar.

CHAPTER 1: Introduction

Background

Increased attention has been recently paid to the application of low-temperature thermal resources for power generation. Most of the current commercialized thermal power-generation technologies, including geothermally-source power production, convert thermal energy to electric energy indirectly, doing mechanical work (for example, spinning a turbine) before producing electricity. Technology using TEG (thermoelectric generator) can transform thermal energy into electricity directly by using the Seebeck effect. Because of the above feature, TEG apparatus is usually compact, quiet, and reliable.

TEG technologies can produce power without turbines or other moving parts. Because of these characteristics, TEG may make small-scale production and geothermally-sourced micro power grids both practical and affordable. Small (<5 MW) geothermal projects could provide consumers with the same distributed power flexibility provided by solar and wind production with the additional benefit of being a more reliable base-load source of electricity without intermittency. TEG technologies can also allow geothermal heat to provide balancing and grid support as well as using the earth's heat for storage.

While most storage technologies require power from the grid to charge, TEG power uses the stored heat in rock at depth and is thus independent of grid power. This technology not only means added flexibility but also enables the operation of geothermal-TEG to supply another major market segment: off-grid or island power. Communities in remote areas or areas with interruptible connection to the grid can benefit from the ability of geothermal-TEG to supply power on demand, dropping down to base-load at night and then ramping up to supply peak power when needed.

A TEG module is usually constructed of many (usually 127 pairs for a 4x4 cm size) p- and n-type thermoelectric legs fastened between two ceramic plates. When a temperature gradient is applied across p- and n-type legs over two ceramic plates, a voltage is induced due to the Seebeck effect. There have been many studies, both numerical and experimental, on the applications of TEG and the parameters affecting the TEG power. It has been shown that there is great potential to apply TEG in the direct conversion of waste heat to electricity (Crane and Jackson, 2003; Maneewan and Chindaruksa, 2009). The effects of the TEG dimensions and flow characteristics on the TEG power output and the thermal conversion efficiency are significant based on the previous studies (Yu and Zhao, 2007; Bélanger and Gosselin, 2011; Wang et al., 2008; Liu and Li, 2014).

Many investigations have been conducted to improve the power performance and decrease the self-energy consumption of TEG systems in recent years. The main technologies that have been utilized to do so are the thermosyphon heat exchanger with phase change (Araiz et al., 2017), heat pipe (Atouei et al., 20180; Cao et al., 2017), evaporative cooling (Boonyasri, 2017), tube heat exchangers directly covered with thermoelectric materials (Demir and Dincer, 2016; Demir and Dincer, 2017), and the optimized temperature range (Huang and X. Xu, 2017). It is also helpful to increase the TEG output by enhancing the heat transfer rates between hot/cold fluids and the TEG surfaces. One of the technologies used to enhance the heat transfer is the installment of fins with different shapes such as rectangular and circular tube fins. The experimental results reported by Kane et al., 2016) demonstrated the effectiveness of the fins and also showed that rectangular fins were more efficient than circular tube fins in terms of heat transfer efficiency because of the geometric features.

Interestingly, Remeli et al., 2016) built a bench-top TEG prototype for waste heat recovery. The maximum generated electric power was around 7 W. Although the TEG system had a relatively low conversion efficiency that had limited its power generation, the overall system might still be considered as economically viable because the energy input was from free waste heat.

Printed circuit heat exchangers (PCHEs) were employed to improve the compactness of a TEG device. The TEG system manufactured with PCHEs provides a power density of 233.1 kW/m3 at inlet temperatures of 448.15 K (hot side) and 293.15 K (cold side), which was claimed to be the highest value in literature for a low-temperature TEG (<505.15 K hot side). Such a design on the TEG with PCHEs might be helpful to manufacture more compact TEG systems and to expand the applicability of TEG for waste heat recovery (Lee and Lee, 2018).

Another attractive application of TEG technology is to generate electricity from enhanced geothermal systems (EGS). Catalan et al. (2019) built a prototype to experimentally analyze the feasibility of using TEG for EGS resources. The prototype was composed by a two-phase closed thermosyphon as a hot side heat exchanger and two thermoelectric modules. Different cold side heat exchangers were used: fin dissipators assisted by a fan and loop thermosyphons, both with various geometries. The experimental results have demonstrated that loop thermosyphons might be the best alternative due to their low thermal resistance, primarily, due to their lack of auxiliary consumption. They are leading to a maximum net power generation of 3.29 W per TEG module with a temperature difference of 180 °C, 54% more than those with fin dissipators.

According to the above description, the power output of the TEG systems reported in most of the publications is less than 100 W. The main problem yet to be solved for TEG electricity systems is the expandability to a large power capacity. To find a solution to this problem, a 5-layer TEG laboratory apparatus for electricity generation has been designed, built, tested, and optimized in this paper. The TEG system was designed such that it could be expandable in the number of layers while the temperature gradient cross over each layer (from inlet to the outlet) could be kept closely the same. Using this device, the laboratory experiments were conducted to measure the voltage, the power output, and the efficiency at different flow rates of water, temperature, and temperature differences between the hot and cold sides. Note that some of the results were presented at the Stanford Geothermal Workshop (Li et al., 2019).

Objectives

The current geothermal industry is conservative, risk-adverse, and firmly rooted in conventional technology, and as such is hesitant to implement new technologies such as TEG. The purpose of this project was to demonstrate that a thermoelectric generator (TEG) could be used at a geothermal resource to produce electricity and to understand whether such power production could be competitive in the marketplace. This pilot-scale project sought to prove both the feasibility of using TEG materials to produce electricity from a geothermal resource and the feasibility of deploying this technology in an operating field. The goal is to bring geothermal-TEG technologies to a pre-commercial stage. The results of this project could support the future design of a larger-scale demonstration project for appraisal of operational and performance characteristics and financial risks of utility-scale geothermal-TEG projects. This will help expand development of untapped and localized geothermal resources.

The objectives of this Agreement were to:

- Determined the flow of heat required to supply a geothermal-TEG with enough enthalpy to produce electricity economically
- Perform a proof-of-concept in a geothermal field to validate the technical feasibility of a geothermal-TEG, identify potential stumbling blocks, and determine the scope and level of customization necessary to commercialize this technology

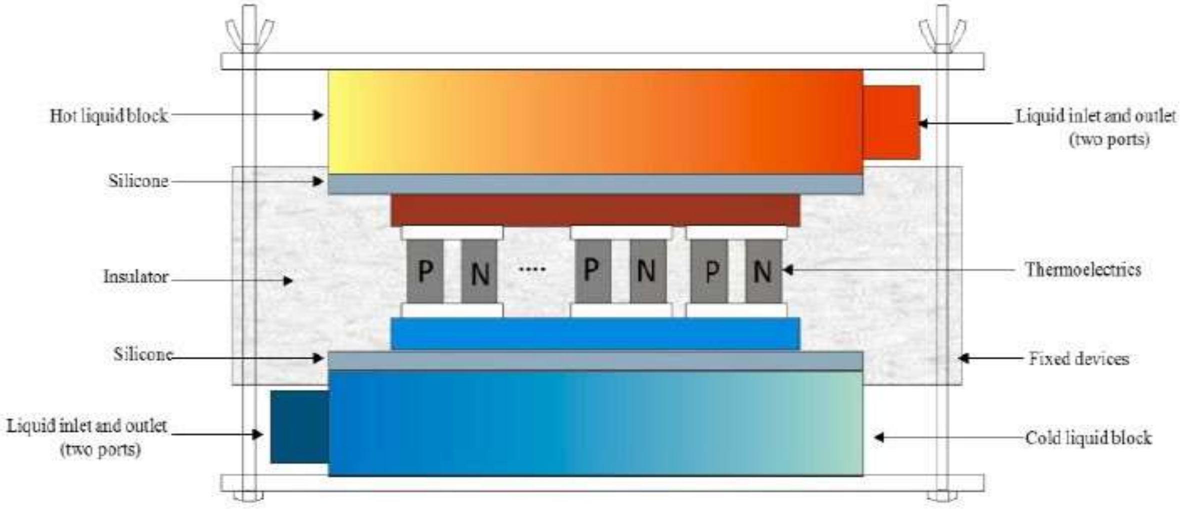
CHAPTER 2:
Project Approach

Techniques, Approach, and Methods

Phase 1 – Lab-Scale Design and Test

Tasks in Phase 1 were designed to empirically determine the flow of heat required to supply a geothermal-TEG with enough enthalpy to produce electricity. Work was guided by an experimental plan developed to conduct a series of laboratory experiments on a bench-scale TEG apparatus (Figure 1). These experiments measured TEG electrical power efficiency and output as a function of the temperature gradient across the TEG and the enthalpy flow rate through the lab apparatus.

Figure 1: Schematic of a Bench-Scale Geothermal-TEG Testing Unit

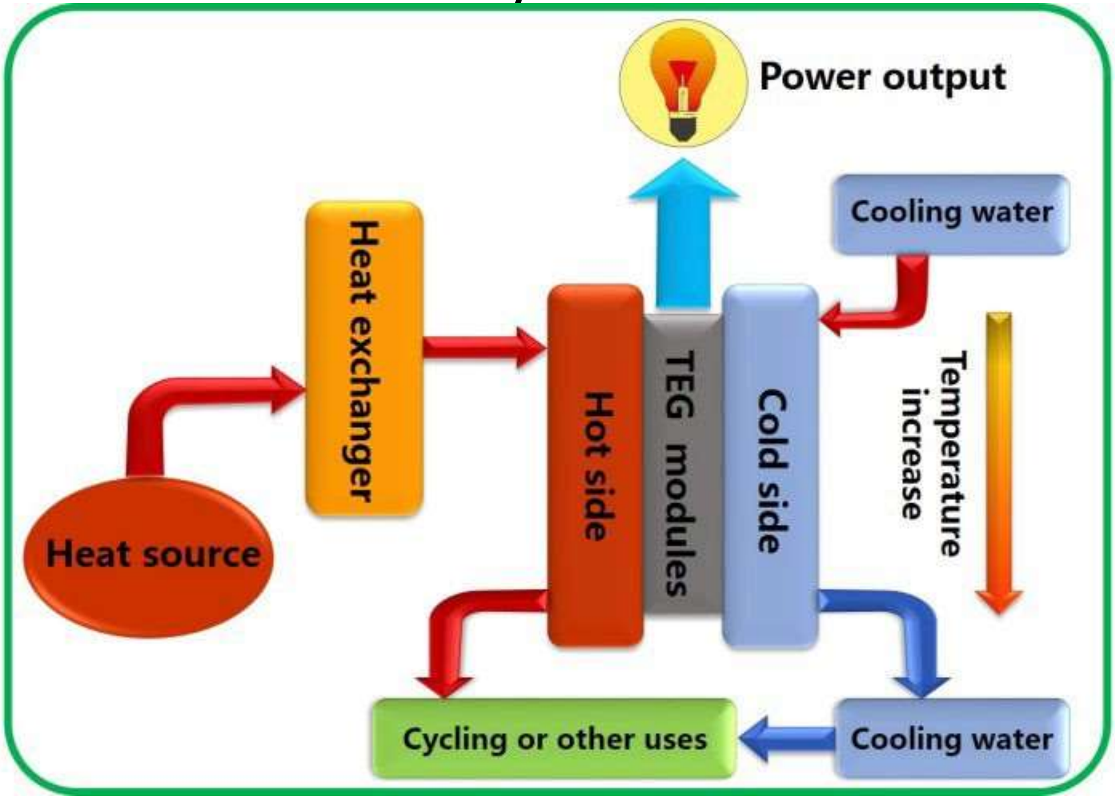


Phase 1 was intended to develop utility scale project economics including sourcing thermoelectric materials, geothermal well costs and cooling source costs. Various cooling sources were considered such as air source, evaporative cooling and aquifer geocooling. Based on experimental results and economic study, parameters were developed for design of 20 kW field-scale test TEG apparatus. These parameters include the number of layers in module, thickness and type of insulator material, need for heat exchanger, best type of cooling system, and geothermal flows required for low and high temperature field test.

Phase 1 Experimental Design

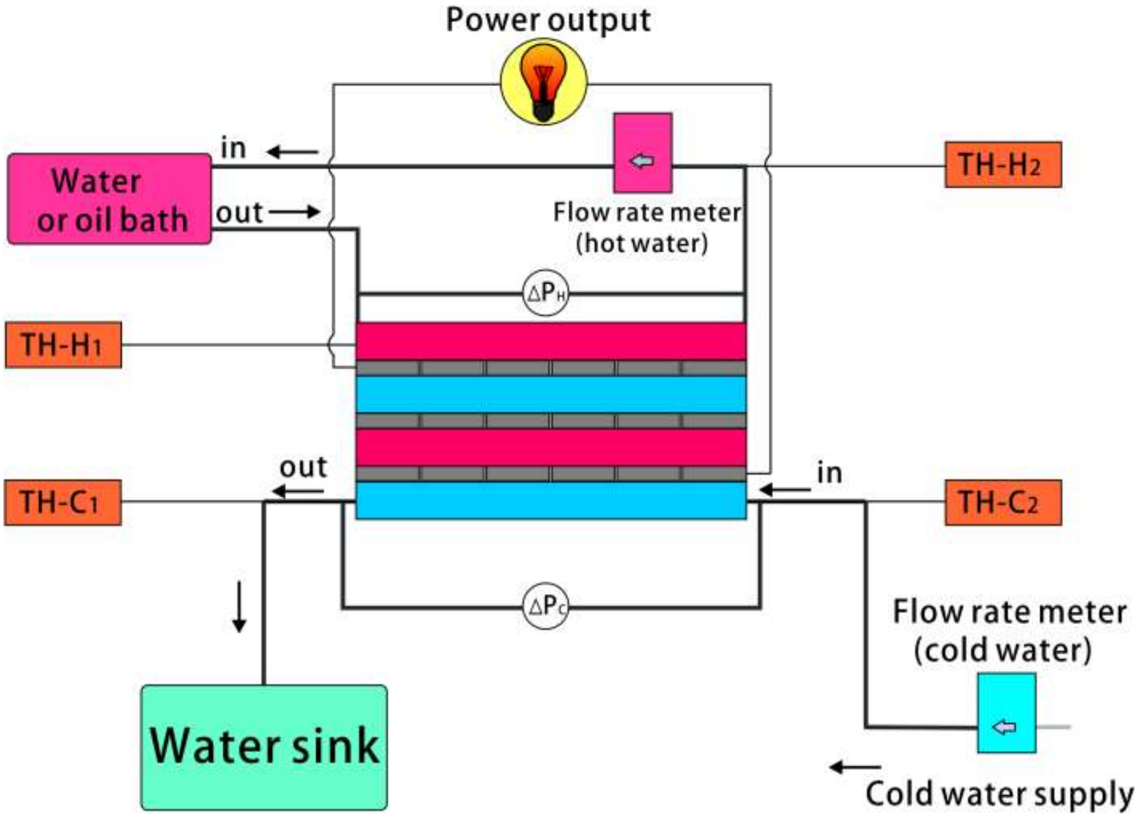
According to our review and analysis on some of the existing TEG technologies, we designed a lab-scale TEG apparatus. The process diagram is shown in Figure 2. The TEG power generator is composed of three parts: 1) heat sources, 2) TEG modules and assembly, and 3) cold sink. Water served as the heat transfer fluid in this study.

Figure 2: Process Diagram of the Lab-Scale Thermoelectric Power Generation System



It is usually necessary to test a single TEG module before assembling for quality check and other purposes. A schematic of the single TEG module test apparatus is shown in Figure 1. The schematic of the lab-scale TEG apparatus is shown in Figure 3. The hot water was provided by an electric heater. The TEG modules were placed in between hot and cold sides in containers with hot and cold water. The values of temperature at both inlet and outlet of the cold and hot sinks were measured. The power output of the TEG apparatus and its change with temperature differential and flow rate were measured too. All of the experimental data were sampled using LabView data acquisition hardware and software.

Figure 3: Schematic of the Lab-Scale Thermoelectric Power Generation System



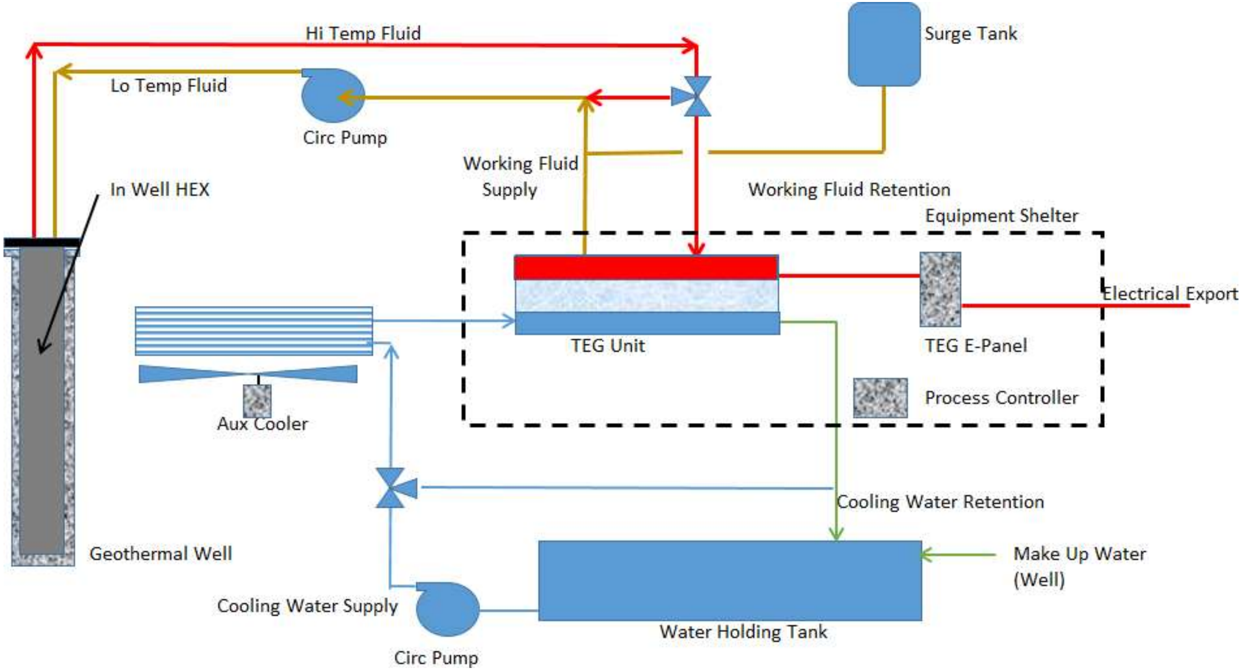
One of the challenges for TEG to be used for power generation is large-scale utilization, even at the scale of kW. To this end, we designed a TEG system that can be installed with modularized units and expanded in power, something similar to solar PV. Such a system was constructed as a layered structure, expandable by adding more layers. We built a 5-layer TEG apparatus, as shown in Figure 4. 90 TEG modules with a size of 4x4 cm were assembled in the 5-layer TEG lab apparatus shown in Figure 4. Each layer had 18 TEG modules.

Figure 4: Photo of the Lab-Scale Thermoelectric Power Generation System

Phase 2 - Design and Build Field Apparatus

Phase 2 tasks were to build and test field-scale test TEG-geothermal apparatus and perform a proof-of-concept using a TEG to produce electricity in a geothermal field. In the original Project Approach design, the field test was to include design integration of 20 kW field-scale geothermal-TEG apparatus into the test site infrastructure (Figure 5). The project design was modified and three smaller geothermal-TEG apparatus were first built and tested in the field to demonstrate the geothermal-TEG process: a 200 W unit built by Stanford University, a 240 W unit built by Hi-Z, Inc., and a 500 W unit also built by Stanford University. Field testing of each of these generators provided key data for developing design parameters for larger geothermal-TEG units. However, ultimately the project was not successful in building a 20 kW geothermal-TEG apparatus due to insurmountable delays to the project schedule cause by inclement weather, changes in project administration, and changes in project staffing that left the team without resources needed to complete the build. Field test protocols followed a Project Description submitted to and approved by the Lake County Air Quality Management District (LCAQMD) and the California Division of Oil, Gas, and Geothermal Resources (DOGGR).

Figure 5: Conceptual Schematic of a Field-Scale Geothermal-TEG Apparatus Test Site configuration



First Field Test

A first pilot field test tested two geothermal-TEG units: a 5-layer 200 W apparatus and a single layer 240 W apparatus built by Hi-Z, Inc., out of San Diego. The 5-layer unit was the same device used in Stanford successful laboratory experiments. The TEG apparatus were both built with stainless steel to overcome the potential corrosion problem and reduce apparatus thermal expansion. Note that one of the key parameters that may limit the number of the TEG layers is the mechanical strength of the stainless-steel plates (SSP) that hold the TEG modules. For example, copper might be better in terms of heat conductivity but might not be better than stainless-steel in terms of mechanical strength. The structures and the flow channels inside the 5-layer TEG apparatus were similar to those of plate heater exchangers.

The 5-layer TEG apparatus could be fit in a small box and was delivered to the geothermal well pad located at Bottle Rock (Figure 6). The Hi-Z unit was contained in a steel support framework with a data collector sitting above (Figure 7). In order to connect the TEG units to the geothermal well head system, pipes, adapters, and manifolds were constructed to adapt the different pipe fittings between the TEG lab apparatus and the geothermal well (Figures 6 and 7).

Both devises were tested between July 27 and 29, 2019. It was not possible to control the inlet pressure and steam flow rate into the apparatus because no pressure control valve (PCV) was installed. The 5-layer TEG apparatus leaked due to the high pressure and high temperature. It was not possible to measure any power output. We learned a lot from this field test even though the output could not be obtained.

Figure 6: Bottle Rock Geothermal Field: Wellhead, Pipes, and Manifolds Adapted to Connect to the 200 W 5-Layer TEG Lab Apparatus, July 2019.

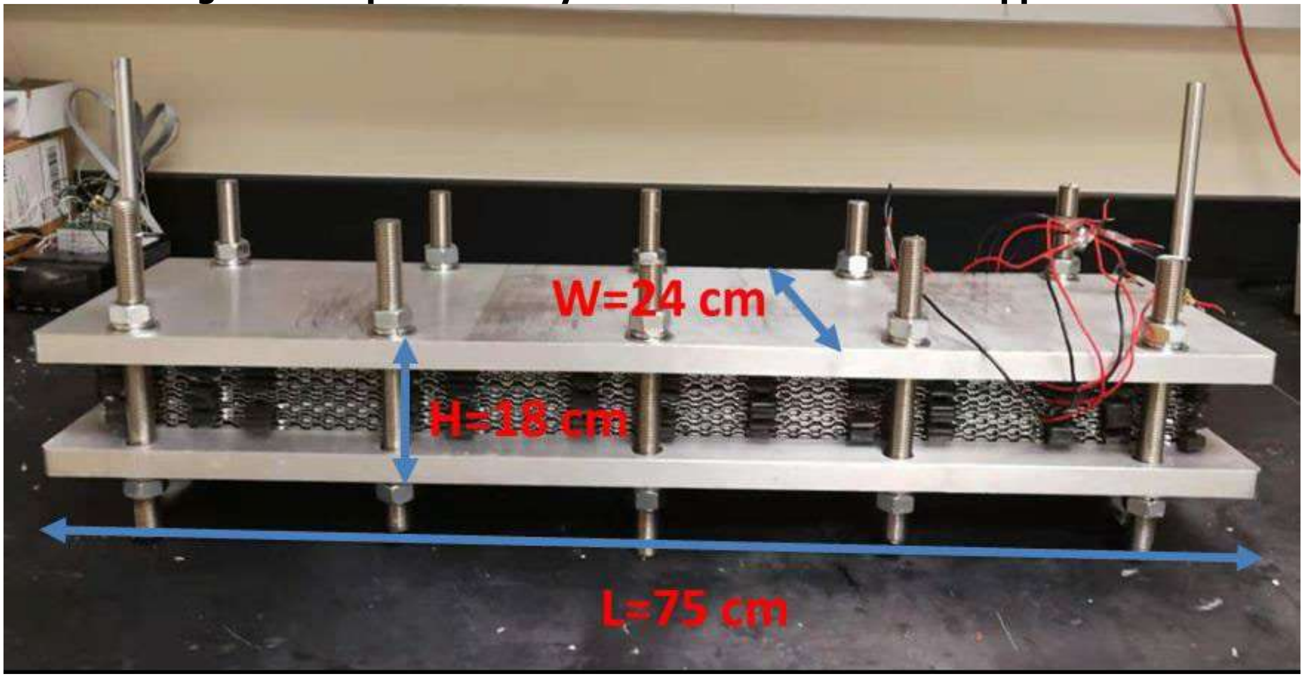
Figure 7: 240 W Geothermal-TEG Apparatus Deployed at Bottle Rock Geothermal Field, July 2019.

Left: internal view with (20) 12 W TEG modules over a steel fluid heat exchanger (gray). Right: Assembled TEG unit attached to the well head.

Second Field Test

Diagnosis of the leaking 5-layer TEG apparatus found Leakage was due to the sealing structure. That was redesigned and a new 6-layer-TEG apparatus was built (Figure 8) to withstand high pressure better, so long as pressures on the cold and hot sides of the TEG chips are approximately equal to each other. The heat exchange between the cold and hot sides of the TEG modules was enhanced by directing the hot and cold flow in countercurrent directions. A pressure control valve (PCV) was installed this time in order to control the inlet pressure and steam flow rate. With the PCV, we could test the TEG apparatus at different inlet pressures and determine the specific pressure if the TEG apparatus started to leak. The power output as a function of steam pressure or steam flow rate could be measured.

Figure 8: Improved 6-Layer Geothermal-TEG Field Apparatus



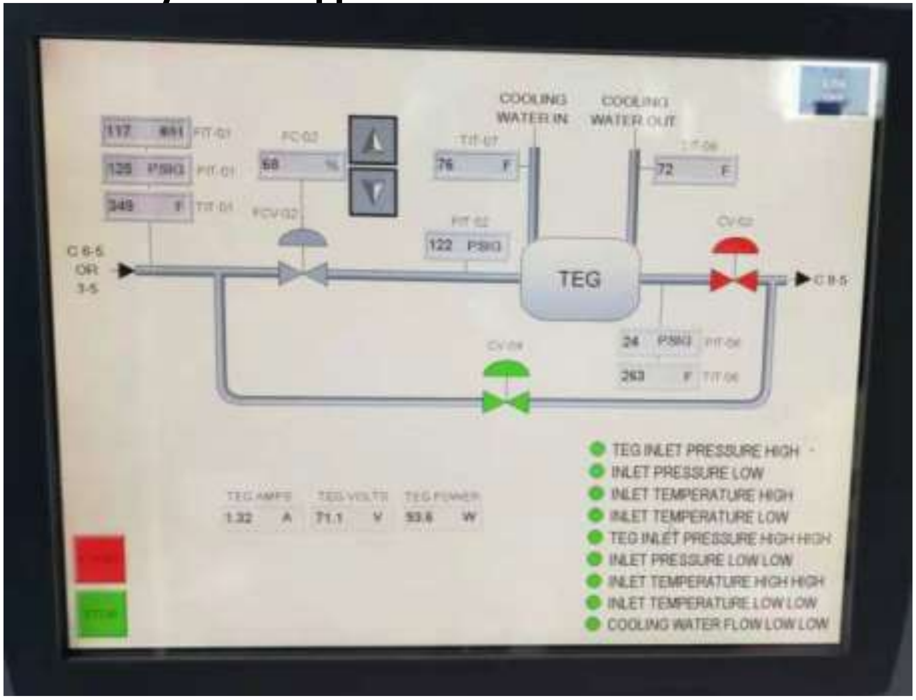
The schematic and the flow configurations were the same as for the first field test. The main difference in the second field test was that the pressure control valve (PCV) was installed. With the PCV, the power output as a function of steam pressure or steam flow rate could be measured.

The new TEG apparatus was installed in the same fashion as the first field test. The Coleman 3–5 geothermal well had been shut in and had not been in production for several years. It took 5 hours to warm up the well and place it in stable production, at which time the tests were run to measure the power output at different steam pressures (or steam flow rate) and different pressures of cold water (or water flow rate). The field test began on September 27, 2019, and ended on September 29, 2019.

The new 6-layer TEG apparatus had no leak when the inlet steam pressure was less than 100 psi and leaked a little when fully open to the maximum pressure from the geothermal production well. The steam pressure at the inlet of the 6-layer TEG apparatus was about 122 psi, close to the wellhead pressure of 125 psi at the geothermal producer. The apparatus stopped leaking when the pressure of the cold water was increased to about 80 psi.

A data acquisition system was developed to record the values of pressure, temperature, and flow rate at both inlet and outlet on cold and hot sides of the TEG apparatus. A typical screen shot of the data acquisition system is shown in Figure 9. The new 6-layer TEG device could generate about 93.6 W per layer (about 500 W total) without any leak at the wellhead pressure of 125 psi and the temperature over 176 °C (349 °F). The pressure drop across the 6-layer TEG device was about 98 psi at a flow rate of around 120 pounds per hour.

Figure 9. View the Power Output and Other Parameters Measured Using the Modified 6-Layer TEG Apparatus at Bottle Rock Geothermal Field.



117
125 PSIG
349 F
68 %
76 F
72 F
122 PSIG
24 PSIG
263 F

TEG AMPS 1.32 A
TEG VOLTS 71.1 V
TEG POWER 53.6 W

- ● TEG INLET PRESSURE HIGH
- ● INLET PRESSURE LOW
- ● INLET TEMPERATURE HIGH
- ● INLET TEMPERATURE LOW
- ● TEG INLET PRESSURE HIGH HIGH
- ● INLET PRESSURE LOW LOW
- ● INLET TEMPERATURE HIGH HIGH
- ● INLET TEMPERATURE LOW LOW
- ● COOLING WATER FLOW LOW LOW

CHAPTER 3:
Project Results

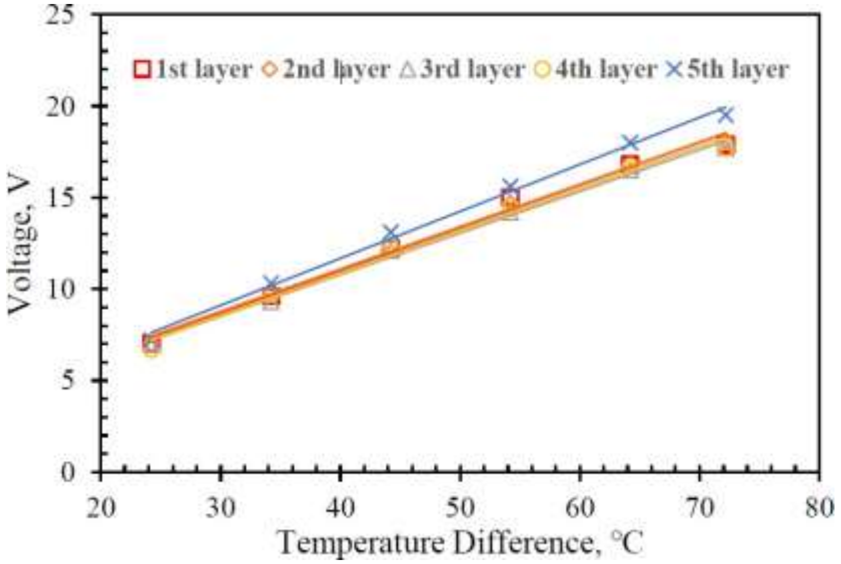
Phase 1 – Lab-Scale Experiments

Voltage and power output of the 5-layer TEG lab apparatus was measured at different temperatures and flow rates.

Effect of Temperature Difference

The voltages and power outputs of each layer of the 5-layer TEG apparatus measured at different temperatures and flow rates are shown in Figures 10 and 11. The voltage and power increase with temperature difference almost linearly, which is consistent with the observation reported by Chen, et al. (2017). Note that the water flow rate on the cold and hot sides were 103.9 and 205.7 L/hour respectively. The linear phenomenon is interesting and may be used to predict the power output at higher temperatures.

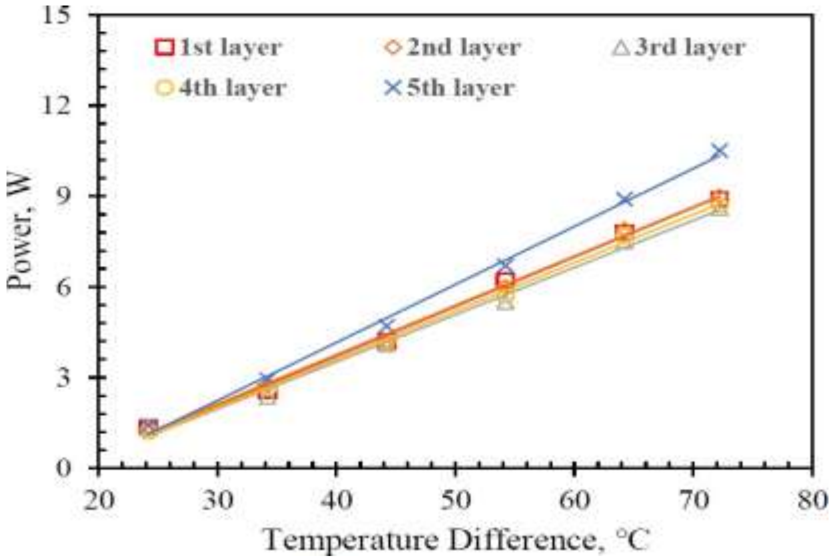
Figure 10: Voltage of Each Layer of the 5-Layer TEG Lab Apparatus at Different Temperature Difference



Water flow rates on the cold and hot sides were 103.9 and 205.7 L/hour respectively.

Another interesting observation is that the voltage and power of each layer of the 5-layer TEG apparatus are close to each other, especially layer one to layer four. This implies that the heat transfer rates on different layers are almost the same, which makes the delivering of the electricity to the load easier, more uniform, and more stable.

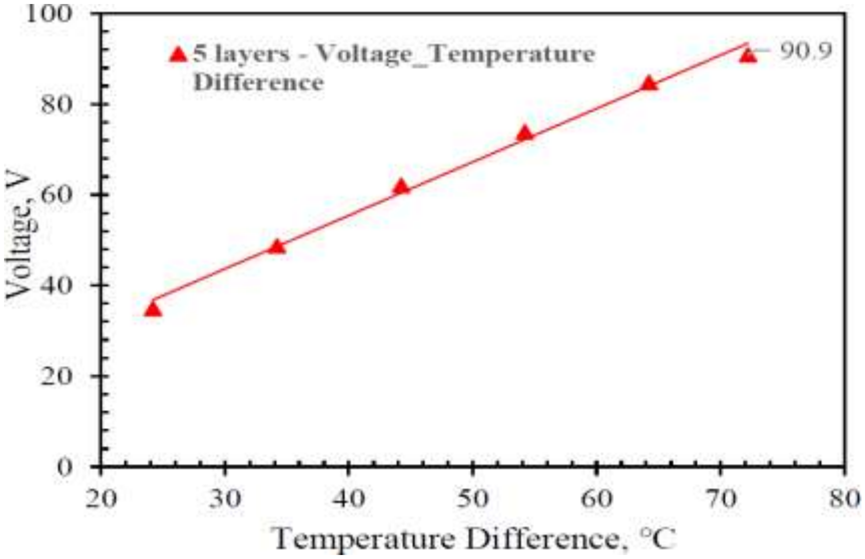
Figure 11: Power of Each Layer of the 5-Layer TEG Apparatus at Different Temperature Difference



Water flow rates on the cold and hot sides were 103.9 and 205.7 L/hour respectively.

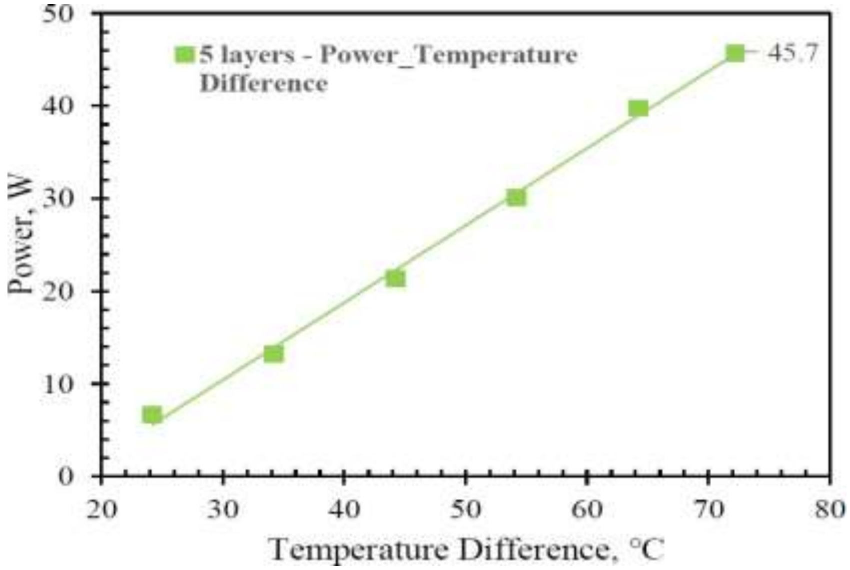
The voltages and the power outputs of the entire 5-layer TEG apparatus are shown in Figures 12 and 13, respectively. The water flow rates on the cold and hot sides were 654.55 and 1028.57 L/hour. The 5-layer TEG device could generate about 45.7 W electricity with a temperature difference of 72.2 °C between the cold and hot sides. The power of each module was about 0.51 W at this temperature difference.

Figure 12: Voltage of the 5-Layer TEG Apparatus at Different Temperature Difference



Water flow rates on the cold and hot sides were 654.55 and 1028.57 L/hour respectively.

Figure 13: Power of the 5-Layer TEG Apparatus at Different Temperature Difference



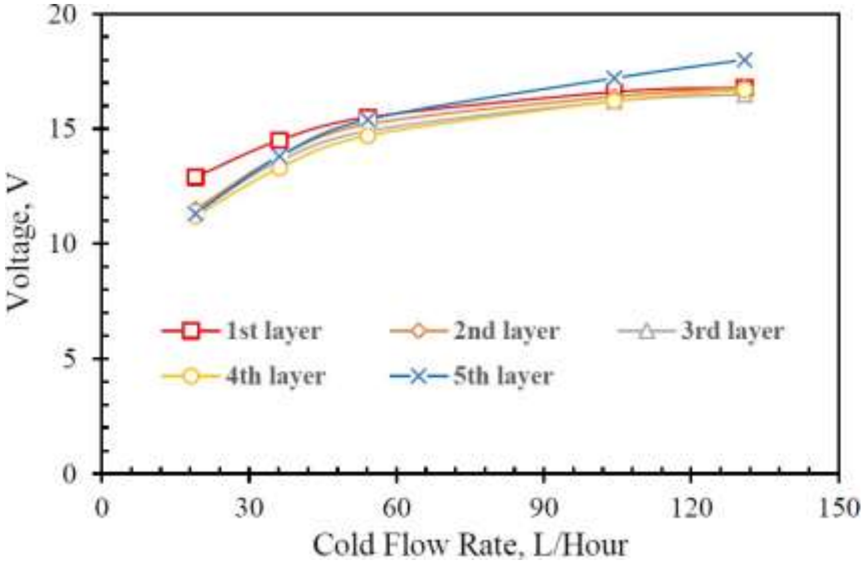
Water flow rate on the cold and hot sides were 654.55 and 1028.57 L/hour respectively.

Effect of Flow Rate

Voltage and Power Output at Different Flow Rates of Water on the Hot Side When Water Flow Rate on the Hot Side is Constant

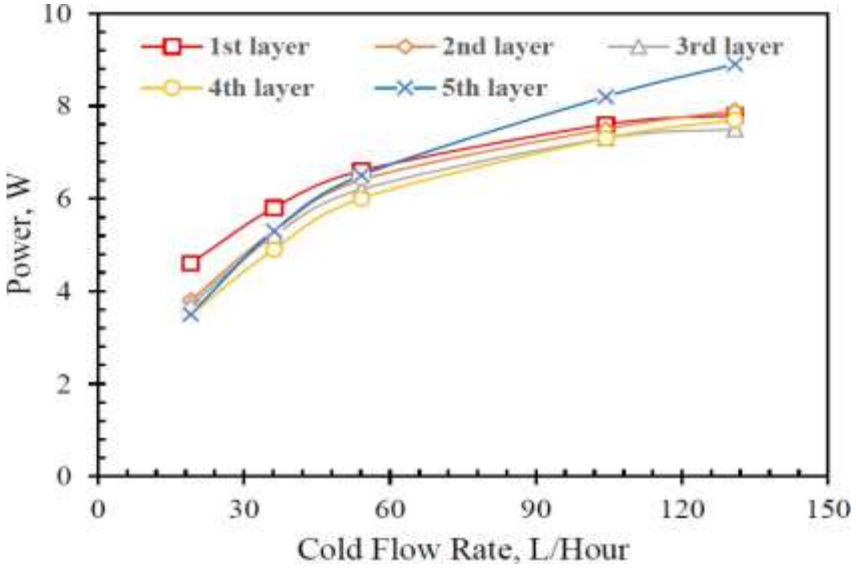
Using the 5-layer TEG apparatus, voltage and power output were measured at different flow rates of water on the cold side of the TEG apparatus when water flow rate on the hot side was constant. The data are plotted in Figures 14 and 15 respectively. The total water flow rate on the hot side was 666.67 L/h (133.33 L/h per layer) and was kept constant. The temperature difference between cold and hot sides was 64.2 °C and was kept constant.

Figure 14: Voltage of Each Layer of the 5-Layer TEG Lab Apparatus at Different Flow Rates on the Cold Side



Water flow rate on the hot side was 133.33 L/hour and temperature difference between cold and hot sides was 64.2 °C.

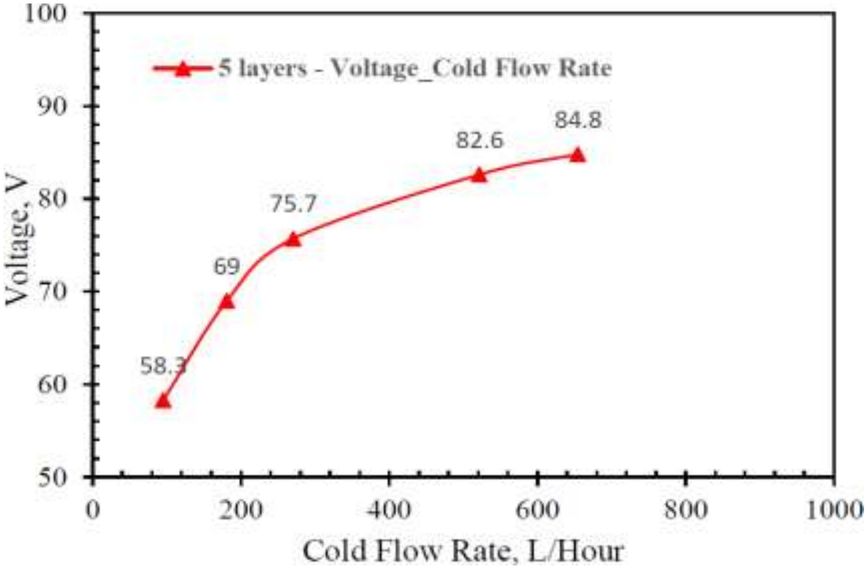
Figure 15: Power of Each Layer of the 5-Layer TEG Lab Apparatus at Different Flow Rates on the Cold Side



Water flow rate on the hot side was 133.33 L/hour and temperature difference between cold and hot sides was 64.2 °C.

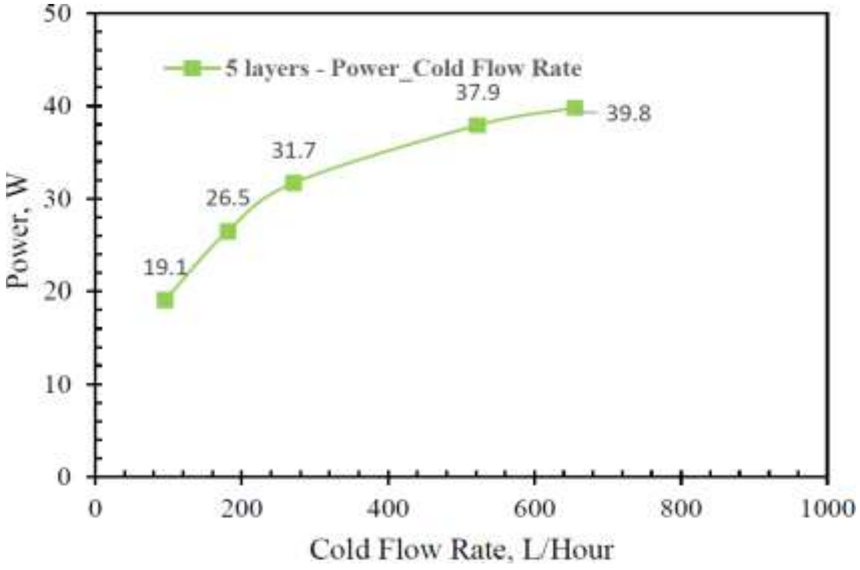
When water flow rate on the hot side was constant (666.67 L/hour) and the temperature difference between cold and hot sides was kept at 64.2 °C), the voltage and the power output of the entire 5-layer TEG apparatus at different rates on the cold side are shown in Figures 16 and 17, respectively. The 5-layer TEG device could generate about 39.8 W electricity at this temperature difference between cold and hot sides.

Figure 16: Voltage at Different Flow Rates of Water on the Cold Side of the 5-Layer TEG Apparatus When Water Flow Rate on the Hot Side is Constant.



Total water flow rate on the hot side was 666.67 L/hour and temperature difference between cold and hot sides was 64.2 °C.

Figure 17: Power Output at Different Flow Rates of Water on the Cold Side of the 5-Layer TEG Apparatus When Water Flow Rate on the Hot Side is Constant.



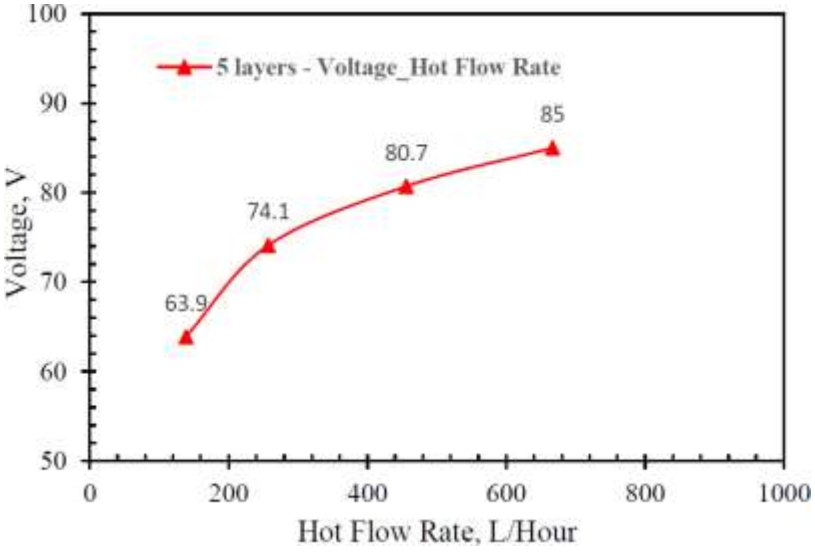
Total water flow rate on the hot side was 666.67 L/hour and temperature difference between cold and hot sides was 64.2 °C.

Figures 16 and 17 illustrate that voltage could reach as high as 84.8 V. Both the voltage and power output increase with the flow rate of water on the cold side. The effect of flow rate is very significant, which is reasonable. This is because the higher the flow rate, the faster the heat transfer between liquid and TEG modules.

Voltage and Power Output at Different Flow Rates of Water on the Hot Side When Water Flow Rate on the Cold Side is Constant

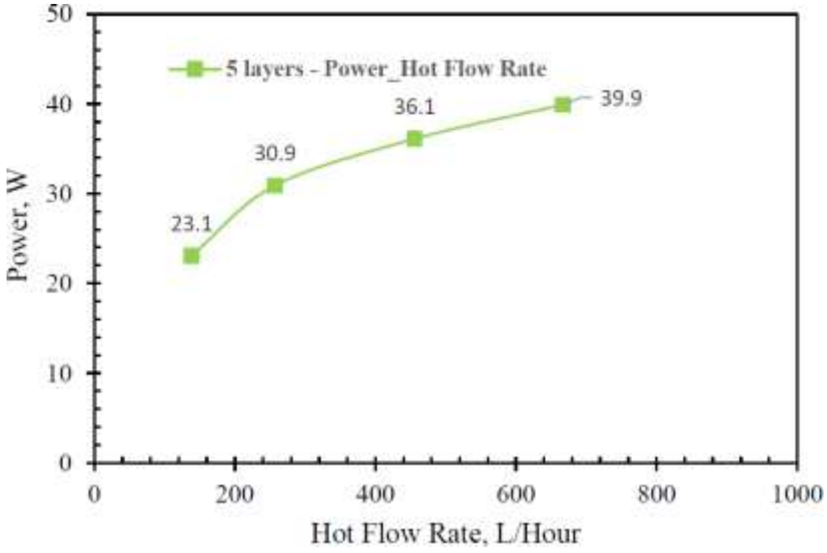
We also measured the voltage and power output at different flow rates of water on the hot side of the TEG apparatus when water flow rate on the cold side is constant. The data of each layer are plotted in Figures 15. The results demonstrate that both the voltage and power output increase with the flow rate of water on the hot side, which follows the same trend for the effect flow rate on the cold side. Note that the water flow rate on the cold side was 130.91 L/hour for each layer and was kept constant. The temperature difference between cold and hot sides was equal to 64.2 °C and was kept constant.

Figure 18: Voltage at Different Flow Rates of Water on the Hot Side of the 5-Layer TEG Apparatus When Water Flow Rate on the Cold Side is Constant.



Total water flow rate on the cold side was 654.55 L/hour and temperature difference between cold and hot sides was 64.2 °C.

Figure 19: Power Output at Different Flow Rates of Water on the Hot Side of the 5-Layer TEG Apparatus When Water Flow Rate on the Cold Side is Constant.



Total water flow rate on the cold side was 654.55 L/hour and temperature difference between cold and hot sides was 64.2 °C.

Because 90 TEG modules have been assembled in the 5-layer TEG lab apparatus, the power of each module was about 0.45W at a temperature difference between cold and hot sides of 64.2 °C.

Phase 2 – Design and Performance of Field-Scale TEG Apparatus

Design Parameters for 20 Kw Geothermal-TEG Apparatus

Based on the performance results of laboratory scale TEG apparatus, the following parameters for a 20-kW field scale device were4 developed:

Geothermal Flows Required for TEG-Geothermal Operation

TEG power efficiency improves as the temperature difference (ΔT) across the TEG module increases to a point. At the scale of this project, the TEG modules optimized at a ΔT ~ 200 °C. However, at the Bottle Rock Project geothermal field a ΔT of only 152 °C could be created across the TEG modules with a steam flow rate of 120 lb/hour. A 20 kW TEG-geothermal apparatus was scaled accordingly.

Number of Layers in Module

With a flow rate of 120 lb/hour steam and a temperature difference of 152 °C, approximately 200 layers of TEG modules would be needed to generate 20 kW, or approximately 5,000 TEG modules. The TEG modules considered are 40 x 40 mm, and 5,000 modules would cover a manageable 8 m^2.

Thickness and Type of Insulator Material

The thickness and type of thermoelectric materials are 0.75 mm. Bismuth telluride (BiTe) alloy was found to be the most efficient and widely commercially available TEG modules. To ruggedize for field use, the TEG modules should be framed in metal (e.g., aluminum) instead of ceramic.

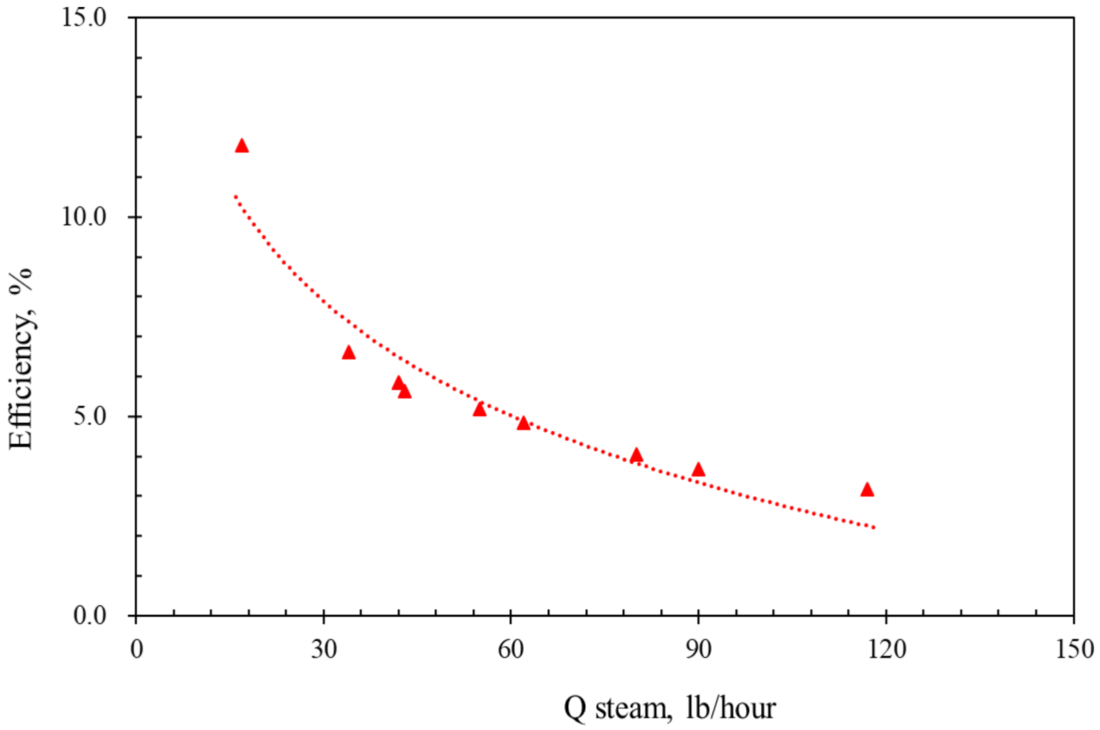
Best Type of Cooling System

A plate-and-frame heat exchanger using liquid water as the cooling media was the most efficient way to carry heat away from the cold-side of the TEG modules.

Expected Power Efficiency

The efficiencies of the TEG apparatus are affected by a lot of factors. According to the field test results conducted at the Bottle Rock geothermal facility in California, USA, the expected efficiency will range between 3 to 10% (Figure 20), depending on the temperature and the flow rate of geothermal fluid as well as other factors.

Figure 20: Geothermal-TEG Efficiency



Efficiencies of total six-layered (η) TEG apparatus at different flow rates on the hot side (water flow rate on the cold side was about 69.3 lb/hour and the temperature difference between cold and hot sides was 152 °C).

Geothermal-TEG Field Test

The 200 W geothermal-TEG built by Hi-Z was tested at Bottle Rock in July 2019. Electrical power was generated with the Hi-Z TEG apparatus using steam over a series of tests and multiple steam flows, cooling water flow rates, and cooling water temperatures. Power outputs, shown in Figure 21, ranged between 110-130 W with a steam temperature of 152–158 °C and a ΔT 110–117 °C. The predicted max power output of this TEG unit for field testing at the Bottle Rock facility was calculated to be 124 watts with a ΔT of 102 °C across module surfaces. The actual power output of the TEG during the field test was measured to be 140 watts with a ΔT of 104 °C across the module surfaces. This gives a shifted hot-side value of 154 °C as represented by the yellow vertical line in Figure 21. From these results it was determined that the TEG had performed nearly as expected. The slightly better performance was due to a somewhat hotter hot side than expected and in part due to a lower average temperature for the module.

Figure 21: Data Set 1 - Voltage Measured from Each Layer of the 6-Layer Geothermal-TEG Field Test as a Function of Steam Flow Rate.

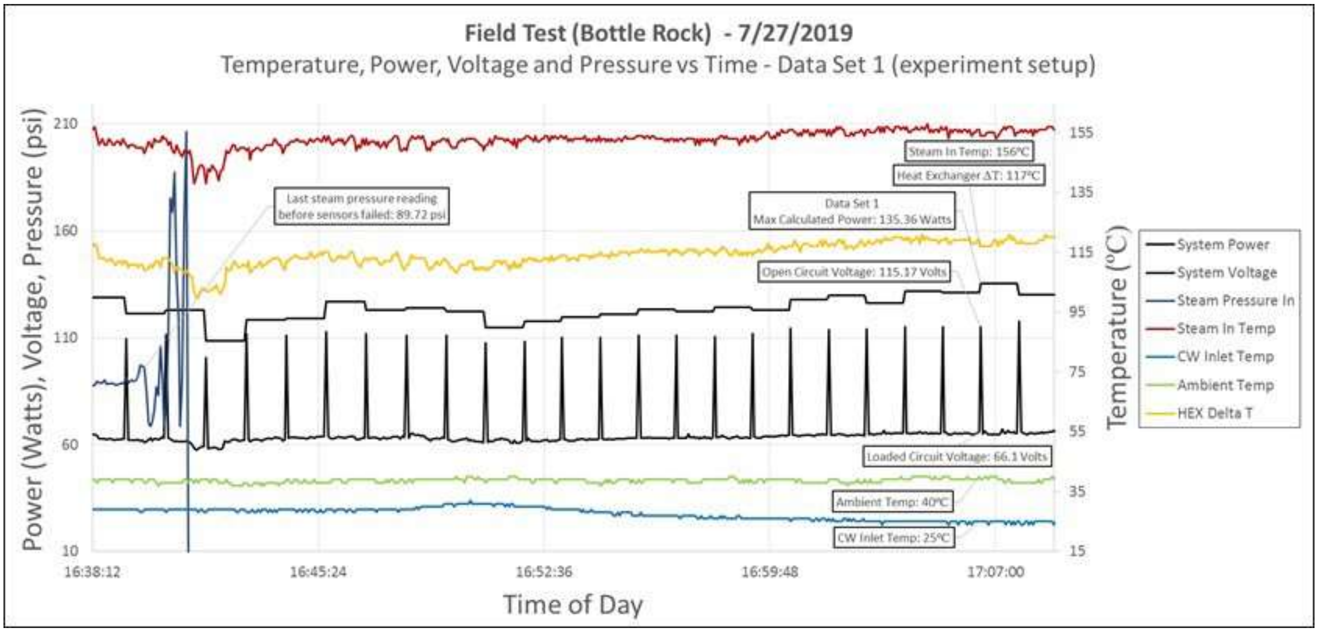


Figure 22: Data Set 2 - Voltage Measured from Each Layer of the 6-Layer Geothermal-TEG Field Test as a Function of Steam Flow Rate.

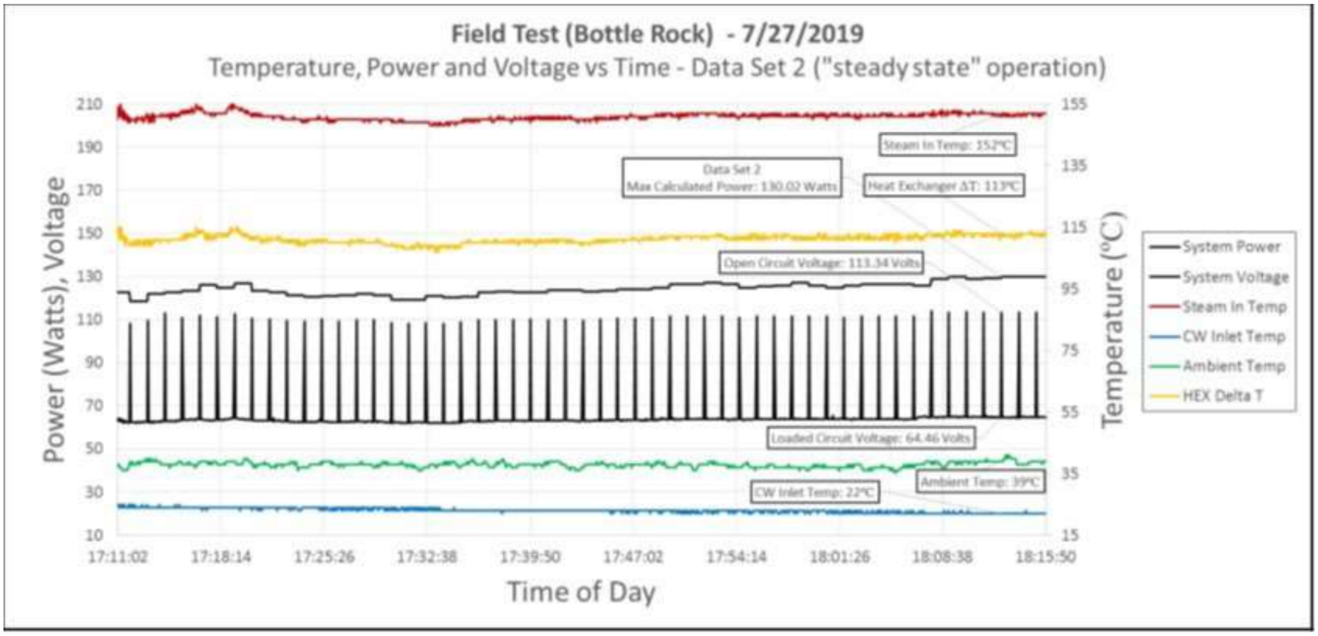
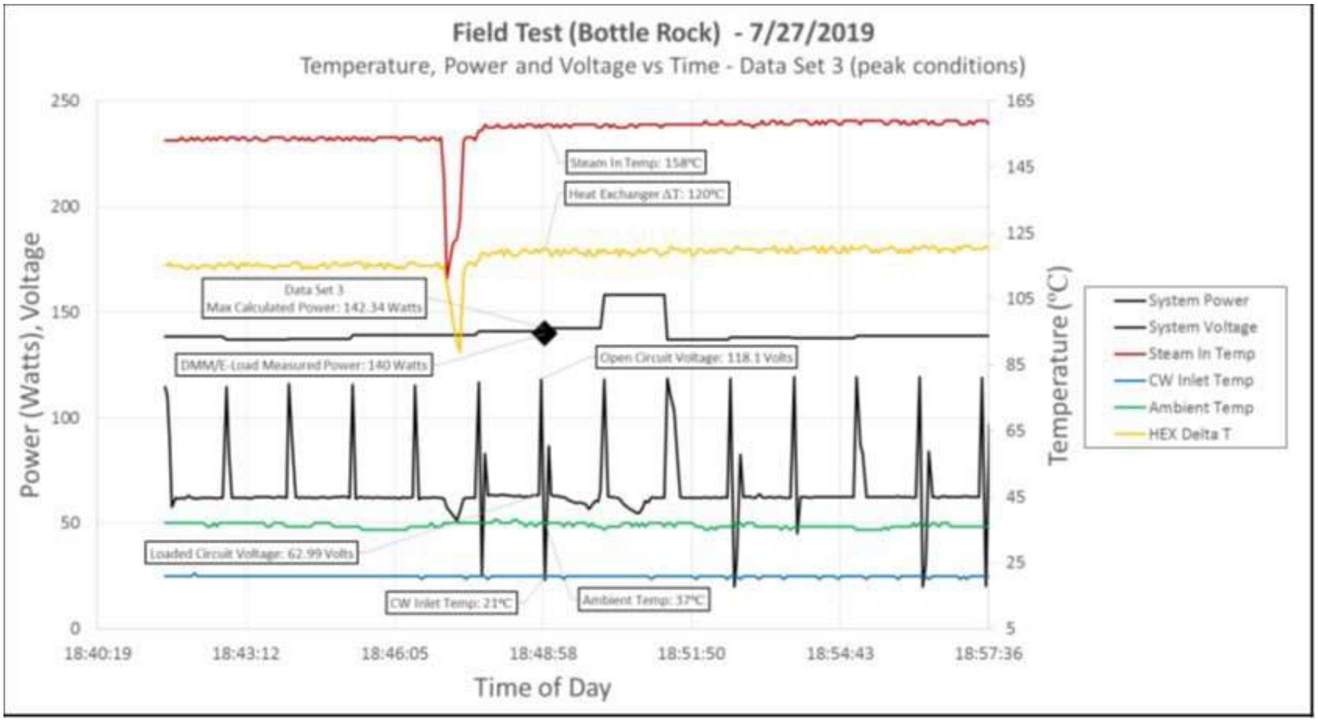
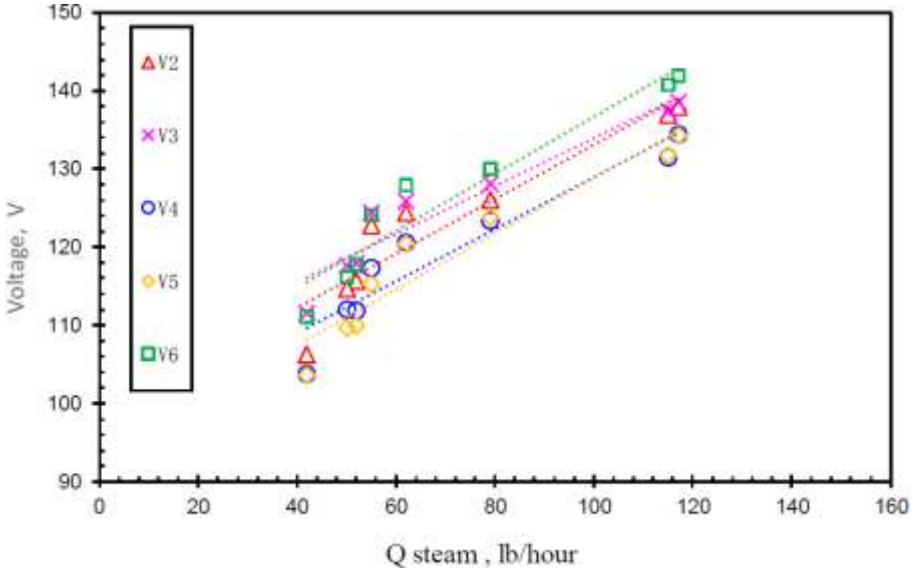


Figure 23: Data Set 3 - Voltage Measured from Each Layer of the 6-Layer Geothermal-TEG Field Test as a Function of Steam Flow Rate.



The 6-layer field scale geothermal-TEG was tested at Bottle Rock in September 2019. Figure 22 shows the voltage measured from each layer of the apparatus except for the first layer V1, which had failed and is not shown). According to the results, one layer with 24 chips could generate a voltage from 120 V to about 140 V at the pressure of 125 psi and temperature over 176 °C (349 °F). The most important feature is that the values of the voltage from each layer did not vary significantly, which follows the trend of the Phase 1 experimental results. Power of a single layer (Layer 6, with 24 chips) could generate about 93.6 W and each chip could generate about 3.9 W. The power increased with the steam flow rate. This also follows the trend of the Phase 1 laboratory results.

Figure 24: Voltage Measured from Each Layer of the 6-Layer Geothermal-TEG Field Test as a Function of Steam Flow Rate.



The values of the voltage from each layer did not vary significantly. Since power is directly proportional to the voltage, the total maximum power potential for the 6-layer TEG apparatus was estimated to reach ~560 W at a steam flow rate of 120 lb L/hour. It was thus estimated that a device with a physical volume of 50 m^2 could generate about 1 MW of electric power.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Recognition of Business Case

This project sought to apply an innovative thermal power-generator (TEG) to a geothermal resource to make renewable geothermal electricity more competitive in the marketplace by adding flexibility, allowing remote and off-grid operation and improving operating cost. This pilot-scale project proved both the feasibility of using TEG materials to produce electricity from a geothermal resource and the feasibility of deploying this technology in an operating field. Geothermal resources have not been used to supply TEG technology with heat, and it remains to be shown that TEG technologies can be deployed at a field scale. On the other hand, the geothermal industry is conservative, risk-adverse, firmly rooted in the past, and as such have not yet attempted to use new technologies such as TEG.

Operational Need

Geothermal TEGs have the potential to produce geothermal electricity without all the infrastructure – turbines, steam piping, etc. – thus making small scale production and geothermally-source micro power grids both practicable and affordable. Small (<5 MW) geothermal projects could provide consumers with the same distributed power flexibility provided by solar and wind production with the additional benefit of being a more reliable base load source of electricity. TEG technologies can also allow geothermal heat to provide balancing and grid support as well as using the earth's heat for storage. TEG is direct generation that makes geothermal more like solar but available and dispatchable at any time of day.

Publications and Presentation of Results at Professional Meetings

The results, analyses, findings, and conclusions have been presented in three geothermal industry meetings and two peer-reviewed publications. The publications and presentation were well received, and inquiries have been received from electrical technology enthusiasts in the US and Canada. The presentations and publications are listed below.

Presentations

K. Li, G. Garrison, M. Moore, Y. Zhu, C. Liu, R. Horne, and S. Petty. 2019. Experimental Study on the Effects of Flow Rate and Temperature on Thermoelectric Power Generation, in: 44th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 2019.

K. Li, G. Garrison, M. Moore, Y. Zhu, C. Liu, R. Horne, and S. Petty. 2019. Design and Laboratory Study of a Five layer Thermoelectric Power Generator. GRC Transactions, Vol. 43, 2019.

K. Li, G. Garrison3 M. Moore, Y. Zhu, C. Liu, J. Hepper, L. Bandt, R. Horne, and S. Petty. 2020. Field Test of Thermoelectric Generators at Bottle Rock Geothermal Power Plant. GRC Transactions, Vol. 44, 2020.

Publications

K. Li, G. Garrison, M. Moore, Y. Zhu, C. Liu, R. Horne, and S. Petty. 2020 An expandable thermoelectric power generator and the experimental studies on power output. International Journal of Heat and Mass Transfer, Vol. 160, 120205.

K. Li, G. Garrison, Y. Zhu, M. Moore, C. Liu, J. Hepper, L. Bandt, R. Horne, and S. Petty. 2021. Thermoelectric power generator: Field test at Bottle Rock geothermal power plant. Journal of Power Sources. Vol. 485, 2021, 229266.

CHAPTER 5: Conclusions/Recommendations

Discussion

As a consensus of the data from modeling and experiments, the achievable values of the TEG conversion efficiency from thermal to electric energies are usually more than 10% for high-temperature, 5% for middle-temperature, and 1% for low-temperature applications (Chen et al., 2010).

There are many factors affecting the conversion efficiency of TEG. These include the maximum temperature on the hot side of TEG, the temperature difference between cold and hot sides of TEG, the water flow rates on both cold and hot sides, the heat transfer rates between fluids and TEG surfaces, and the pressure of the fluids (both cold and hot water). In general, the efficiency from thermal energy to electricity of a TEG system increases with the values of the above parameters (Hsu et al., 2010).

There are some other factors to influence the TEG efficiency such as the way to connect single TEG modules (series or parallel connections), number of layers of TEG modules, and flow directions of cold and hot fluids. The effects of different factors on the TEG efficiency are complex. It is worth to point out that the conversion efficiency of one TEG chip is much higher than that of a TEG system composed of many TEG modules when the temperature difference, the flow rate, and other parameters are the same. It is well-known that the low efficiency of a TEG system is currently one of the main concerns to utilize TEG technologies at a large scale.

The efficiency from thermal energy to electricity by the TEG apparatus measured in this study ranged from about 0.4 to 1.2% when the temperature difference between cold and hot sides of TEG ranged from about 25 to 70 °C, which seems reasonable. We have compared our experimental data with the results reported in the literature in order to further clarify this issue. Actually, the conversion efficiency data observed in this paper are in the range of about 1% for the low-temperature applications reported by Chen et al. (2009). For another example, the efficiency data measured in this study was also in the range reported by Hsu et al. (about 0.3%) under the similar low temperature conditions (the temperature difference was 30 °C) (Hsu et al., 2010).

As mentioned previously, we could add many layers of TEG modules and assemble them together to obtain great power output. What is the limitation of the number of the TEG layers? One of the key parameters that limits the number of the TEG layers is the mechanical strength of the stainless steel plates (SSP) that hold the TEG modules. Materials other than stainless steel could be used for manufacturing the plates that hold the TEG modules. We have to consider a balance between the mechanical strength and the heat transfer rate that both are affected by the thickness of the SSP. More layers of TEG modules could be assembled if thicker SSP were used but the heat transfer rates will be smaller. Low heat transfer rates will reduce the power output and efficiency of the TEG apparatus. We will further investigate on how many layers it can be expanded to in the future.

Laboratory-Scale TEG Apparatus

A 5-layer TEG device was designed and built in this study. The effects of flow rate, temperature, and temperature difference between hot and cold sides on the voltage, power output, and efficiency have been investigated experimentally. According to our experimental results, the following conclusions may be obtained:

(1) The 5-layer TEG device could generate about 45.7 W electricity with a temperature difference of 72.2 °C between cold and hot sides. The power of each TEG module was about 0.51 W at this temperature difference.

(2) The voltage, power output, and efficiency of each layer are almost identical, which makes delivering the electricity to the load more convenient, more uniform, and more stable.

(3) The voltage and power increase with temperature difference almost linearly.

(4) The voltage and power also increase with the water flow rates on both cold and hot sides, but not linearly.

(5) The efficiency increases with the water flow rate on the cold side but decreases very slightly with the increase in water flow rate on the hot side.

Field-Scale TEG Apparatus

According to our field test results, the following conclusions may be drawn:

(1) At a steam flow rate of 120 lb/hour, one layer (Layer 6 with 24 chips) could generate about 93.6 W, and each chip could generate around 3.9 W electricity with a temperature difference of 152 °C between the cold and hot fluid manifolds.

(2) The voltage and power output of each layer is almost the same, which makes the delivering of the electricity to the load easier, more uniform, and more stable.

(3) The effects of flow rate on the voltage and power output have been tested at the Bottle Rock geothermal facility in California, USA. The voltage and power also increase with the water flow rate on both cold and hot sides, but not linearly.

(4) The second field test of the 6-layer TEG apparatus conducted at Bottle Rock was successful and the results had a trend similar to the data measured in the laboratory.

(5) 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

The volumetric power density of this TEG-geothermal device was in a range comparable with commercially available power conversion systems. However, the efficiencies of the TEG apparatus were relatively low. The main reason for the low efficiency might be because the thermoelectric material used to make the TEG chips was bismuth telluride. Different thermoelectric material with greater values of figure-of-merit ZT might be used, which might have higher efficiency. However, the cost would be higher and at present such materials are not commercially available.

Cost Analysis

According to the analysis of the results of the second field test, it was estimated that the cost of per kW would be around \$13,900. The total cost of the 20 kW TEG would be around \$280,000, using the TEG chips deployed in the 6-layer test device, and the volume of a 20 kW TEG device would be around 1 m^3. These costs are very attractive compared with solar photovoltaic (PV) panels. The average cost of installing solar panels is \$3.05 per watt (\$3050 per kW), according to solar comparison-shopping marketplace EnergySage (TheStreet, 2019). 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., 2014). 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. 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 fluid.

CHAPTER 6: Benefits to Ratepayers

Growth of the geothermal industry has been held back by the need for large and costly power plants and large-scale infrastructure to produce geothermal electricity on an economic scale. Typically, a geothermal project cannot produce electricity economically at a scale less than 5 MW and there is a very large economy of scale for projects above 30 MW in size. TEG technologies, however, have the potential to produce geothermal electricity without all the infrastructure – turbines, steam piping, etc. – thus making small scale production and geothermally-source micro power grids both practicable and affordable. Small (<5 MW) geothermal projects could provide consumers with the same distributed power flexibility provided by solar and wind production with the additional benefit of being a more reliable base load source of electricity. TEG technologies can also allow geothermal heat to provide balancing and grid support as well as using the earth's heat for storage. TEG is direct generation that makes geothermal more like solar but available and dispatchable at any time of day. Research is on-going in the development of various TEG materials and metal interconnects. For this project, the scale up from the watt-level in the lab to use in a geothermal reservoir has the capacity to produce 10 kW to 100 kW and 500 kW in easily replicated steps. The project team could not find any other group studying or publishing work on deploying TEGs as power generators at geothermal resources in the US or international development groups.

This project will directly expand the production of electricity from renewable resources in the State of California by demonstrating the applicability of TEG technology. Geothermal-TEG will expand use of low temperature and stranded geothermal resources in the state which have not traditionally been used to produce electricity. TEG generating from geothermal can supply peaking power and balancing of intermittent renewable resources like wind and solar at much lower cost than batteries without relying on power supplied by the grid. Because TEG allows direct electrical generation from the heat of the earth, there is no safety risk from large rotating equipment and lower risk of accidental discharge of geothermal fluids.

California has a very large potential for geothermal resource development, with over 2000 MW currently supplied to the state grid. However, smaller resources in remote areas without grid connectivity may not be developable due to scale and lack of support for development. Use of TEG technology can enable development of these resources to supply small communities or off grid uses such as providing direct heat with small scale power. Because this technology can operate unattended, it can provide power to follow local demand, reducing reliance on balancing for areas at the end of long transmission lines. It has been estimated that the potential power that could be generated in California from small geothermal resources that have been ignored by larger power producers could be on the scale of up to 2 GW. These tend to be resource that are too far from power markets or adequate transmission to be economically attractive for utility scale power production. The reduced infrastructure need and maintenance requirements of geothermal-TEG technology could make developing these orphaned resources more attractive, especially for nearby off takers.

A premise of the project is the offset costs associated with adding renewable power to an existing facility. The other component of this work is that the techniques developed at this field can be used at other underperforming geothermal resources to create lower cost power. Prior to stopping power production, Bottle Rock Power plant at The Geysers emits approximately 183 g/kWh of CO_2. This compares with a natural gas power plant which emits more on the order of ~450 g/kWh. Use of TEG technology should compare favorably with battery storage costs while allowing completely dispatchable power at any time of day. TEG can also provide power on demand for off grid use or for grid support. For projects providing combined heat and power, TEG technology can use heat directly to generate power on demand while also providing heat for direct use such as heating, cooling, green-housing, food or wood drying, brewing or distillation. Costs will be significantly reduced due to the low operating cost which are similar to solar.

GLOSSARY OR LIST OF ACRONYMS

Term	Definition
CO_2	carbon dioxide
ΔT	“delta T”, temperature difference
m^3	cubic meter
°C	degrees Celsius
°F	degrees Fahrenheit
Q	flow rate
kW	kilowatt
LCOE	levelized cost of electricity
L/h	liters per hour
MW	megawatt
m	meter
psi	pounds per square inch
m2	square meter
TEG	thermoelectric generator
V	volt
W	watt

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