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Thermoelectric Monitoring Systems in Iceland

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ABSTRACT

Reliable telemetry and surveillance systems are essential for the geothermal industry. An efficient power source for these systems would be the waste heat from the geothermal system for remote or hazardous locations where access to the electrical grid is limited. The authors have developed and patented a reliable thermoelectric generator that has been field tested at the Agricultural University of Iceland in Hveragerdi for more than two years. It can be easily attached to existing steam or hot water pipe systems. In field tests, the generator produced five watts of useable steady state power which was used to power a 3G web camera while trickle charging 12 volt batteries. Additional options for the additional power and enhanced robustness are being investigated. This paper presents the system and the experimental results.

1. INTRODUCTION

Geothermal locations can have problematic and unstable access to the regional electrical grid. Thermoelectric generators (TEGs) that use passive cooling could be a viable solution. A direct geothermal power source is usually dependable and constant throughout the day, unlike wind and solar energy sources. The surface of geothermal steam pipes could be a convenient power source in remote or physically problematic areas that would benefit from a reliable web accessible monitoring system. Traditional battery storage capacities decrease in colder temperatures. Colder ambient temperatures create greater temperature differences from the geothermal heat source, resulting in greater power production. A TEG that is cooled by ambient air would have no moving parts and therefore needs minimal maintenance.

The authors have designed and patented a TEG using a passive cooling system. It can maintain a steady state temperature difference (ΔT) of $76^{o}C$ across the surfaces of the thermoelectric modules (TEMs) using a low temperature steam pipe as a heat source and ambient air cooling (Dell et al., 2011; Dell et al., 2017; Dell et al., 2019). Natural convection and conduction are enhanced using metal fins mounted on a heat pipe. Each generator assembly features a mirrored pair of hot blocks mounted on a steam pipe (heat source). The TEMs are placed between the hot block and the finned heat pipe cold block which acts as a means of thermal transition to the ambient environment, which is the true heat sink.

TEGs were installed by the authors to a low temperature geothermal steam pipe (100° to 140°C) at the Agricultural University of Iceland at Olfus, Iceland (Dell et al, 2018). The ambient air temperatures can vary to more than 25° in the summer and -10°C in the winter. The ΔT can therefore easily range from 75° to 150°C. Since 2016 the TEGs have been located outdoors and are inside open-air wire mesh enclosures for security purposes. There is an indoor test bed in New York City at the Cooper Union with a controllable point of use steam generator that produces steam up to 160°C.

The authors' TEGs have powered microcontroller based, web accessible monitoring systems (Dell et al., 2012; Dell et al., 2014a; Dell et al., 2014b) as well as irrigation devices (Dell et al, 2015, and robots (Dell et al, 2016). Thermoelectric systems and photovoltaics are both essentially voltage sources. Microcontroller units, integrated circuits, battery arrays, etc., that were originally developed for low power photovoltaic systems can be seamlessly adapted to thermoelectric systems. New lower power telecommunications electronics were used by the authors to develop a completely off-grid 3G accessible security camera monitoring system, powered by a geothermal steam pipe (Mitchell et al, 2016; Dell et al, 2017b).

Iceland provided the ideal field conditions and ready access to steam pipe power sources needed for experimentation. This test bed was used to answer the question of a TEG system's thermoelectric reliability and robustness in an outdoor setting while providing constant power to webcams. The details of the experimentation and the results are described in this paper.

2. MATERIALS AND METHODS

The thermoelectric monitoring system consists of a Thermoelectric Generator (TEG), the test bed, and the electronic monitoring hardware. Each of these three interrelated parts are described in this section.

2.1 The Thermoelectric Generator (TEG)

The thermoelectric assembly has a mirrored pair of TEGs. It has a total a mass of 4.7 kilograms. The cold blocks are 3 kilograms. The total length is 52 centimeters and the width is 45 centimeters. The total height is 22 centimeters when installed on a horizontal 8-centimeter diameter pipe.

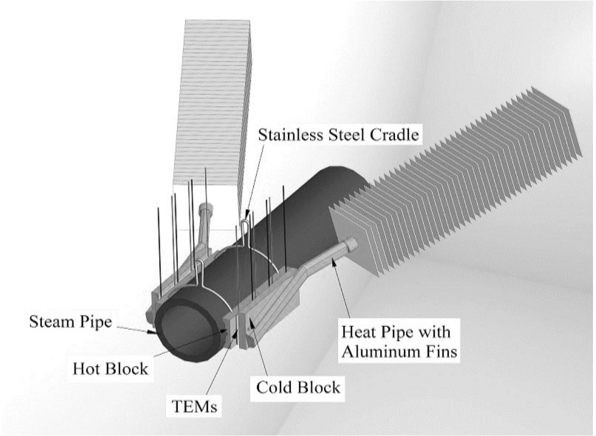

Figure 1: SolidWorks thermoelectric assembly schematic shown mounted on a steel pipe. Note there are two mirrored TEGS shown.

High temperature thermal greases are needed to increase thermal conductivity of the TEGs. Timtronics Red Ice high temperature thermal grease is applied at the thermal interfaces of the steam pipe with the hot blocks, the hot blocks with the TEMs, and the TEMs with the heat pipe cold blocks. This thermal grease also reduces any galvanic problems and can also act as a de facto electrical insulator for the TEMs due to its high electrical resistance.

Hot blocks transfer heat from the steam pipe to the TEMs that are usually wired in series. As shown in Figure 1, they also serve as transition surfaces from the various diameter pipes to the flat TEMs. The TEMs are held in position by the recessed milled channel in the flat side of the hot blocks, creating lateral rails on the edges (bottom of Figure 2). The pipe side of the hot block has milled parallel recessed grooves lengthwise as are also seen in the top of Figure 2. The grooves serve multiple functions, including exit ports for surplus thermal grease and allow for differences in pipe geometry. The grooves also reduce the potential of hot block warp from differing expansion and contraction rates between the hotter surface near the steam pipe and the cooler side near the TEMs interface. This prevents TEM damage and preserves the thermal grease interface. The hot blocks are made of machined steel to minimize possible galvanic reactions with the steel steam pipes. This also reduces any contraction and expansion rate differences that could possibly degrade the thermal grease interface between the steam pipe and the hot block.

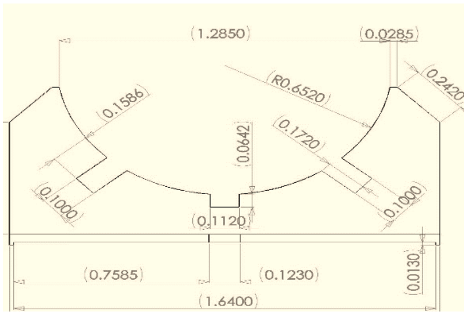

Figure 2: Hot block end view dimensioned drawing showing radius grooves and TEM flat surface recess.

A pair of hot blocks are held together by two work hardened stainless steel wire springs in a cradle configuration as shown below in Figure 3 (right). This cradle system serves as an alignment guide during the installation. Wire harnesses from the TEMs can be easily attached to the springs. This alignment also decreases the possibility of pipe warp due to the pipe temperature changes when the heat is harvested for the TEMs electric power production, because the hot blocks are located on exactly opposite sides of the pipe. Finally, the springs are installation gripping points for the TEGs. Traditional hose clamps are fastened around both ends of the hot blocks and the pipe. This provides the additional clamping pressure needed to maintain the thermal grease interfaces.

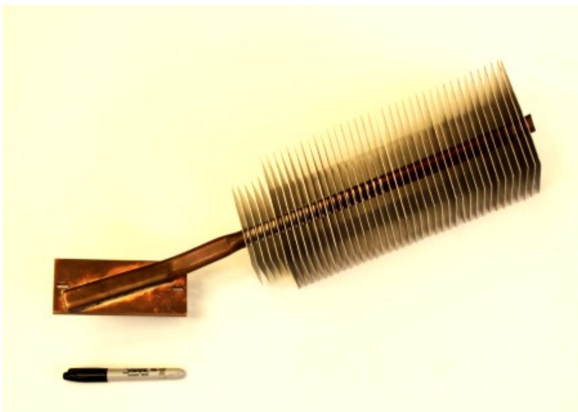

Figure 3: Right: Hot blocks cradle assembly. **Left: Heat pipe assembly, marker pen shown for scale.**

Using the cradle system shown in Figure 3 enables a TEG installation time of approximately thirty minutes. This system allows TEGs to be installed on the surface of existing functioning steam pipes that are rough sanded.

The TEMs thicknesses are tolerance lapped to 0.005 in. Each of the mirrored assemblies has three TEMs. There are six TEMs in each mirrored TEG assembly. There are 12TEMs, which are Laird ThermaTEC 14 PB23 Series, HT8modules. The TEMs are placed between the hot and cold blocks, and are fastened to the TEG with a pair of adjustable bolts inserted through the horizontal slots shown in Figure 3. Each cold block consists of a finned heat pipe that is soldered to a milled 1centimeter copper plate as seen in Figure 3 (left). The first four of the square fins measure 3 inches on each side to avoid contact with the steam pipe. The remainder are 4 inches on each side. The fins are heat shrunk into place. The cold blocks and heat pipe were tested in numerous configurations to verify the theoretical thermal efficiencies, fin size, material, and quantity in addition to the heat pipe (Dell et al., 2019).

The author's hot and cold block configurations create a significant ΔT across the TEMs. The ΔT induces a voltage (V) in the TEMs. The bulk material property that governs thermoelectric behavior is the Seebeck coefficient (α). In the case of the TEMs, α is a system property. The relationship between these three variables can be expressed as:

$$V = \alpha \Delta T \tag{1}$$

Each TEM is a voltage source (V_o) with an internal resistance (r_i) and a circuit load resistance (r_L). The maximum electric current (I_c) is developed from the open circuit voltage with only the TEM's internal resistance. It is measured by shorting the circuit (closing it with zero load resistance) and is given by Ohm's law: $I_c=(V_o)/r_i$. An electrical load placed across the module decreases the circuit current due to the additional series resistance. The loaded circuit current is $I_L=V_o/(r_i+r_L)$. Then, using Ohm's law, the voltage across the load is

$$V_L = \left(\frac{r_L}{r_i+r_L}\right) V_o \tag{2}$$

Power is the energy output over time, voltage is the potential energy per electric charge, and current is the electric charge flow over time. The load power available from an electric circuit is given by $P_L=V_L I_L$. From Equation (2), the power generated by a TEM can be expressed as

$$P_L = \left(\frac{r_L}{(r_i+r_L)^2}\right) V_o^2 \tag{3}$$

Solving $(dP_L)/(dr_L)=0$ yields $r_L=r_i$. The maximum power occurs when the load resistance equals the internal resistance, which is the classic case of impedance matching. It follows from Equation (3), the maximum achievable power is

$$P_{L,max} = \frac{V_o I_c}{4} \tag{4}$$

2.2 The Test Beds

The authors established two test beds for the thermoelectric generator and the electronic hardware. One test bed is in Iceland and the other at is at the Cooper Union for the Advancement of Science and Art in New York City.

2.2.1 The Test Bed in Iceland

The TEGs in Iceland have been operating outdoors since 2016 at the Agricultural University campus at Olfus, near Hveragerdi. They are powered by a geothermal steam pipe depicted in the left image of Figure 4 –and are housed in wire mesh enclosures for security purposes and to protect the generators from sheet rain runoff from the contiguous greenhouse roof (right image). The enclosures are directly above a geothermal steam pipe from a geothermal bore hole. The temperature ranges from 100°C to 140°C and the normal range is between 133°C and 139°C. The steel pipe steam line runs more than 500 meters from the borehole. It is mostly buried below grade and it is encased in Set ehf prefabricated extruded insulation. The temperature is slightly higher in the winter due to the higher volume of steam usage that increases the flow rate.

Initially, two mirrored generators were installed in the front enclosure (Figure 4 Right). A third generator – consisting of a half of the mirrored TEG assembly was installed in the second of the two enclosures. In 2019 a fourth generator was installed next to generator 3. The four generators are shown in Figure 5. TEG1 and TEG 2, mirrored generators, are shown in the top image. Generators TEG 3 and TEG 4 in the bottom image are identical and not mirrored, they are facing in opposing directions. TEG 3 was not removed to enable longer term reliability studies.

2.2.2 The Test Bed at The Cooper Union, NY

The authors also established a steam test bed at the Center for Innovation and Applied Technology at the Cooper Union for the Advancement of Science and Art. This test bed is depicted in Figure 6. It has an ESG Corporation SPEEDYLECTRIC Steam Boiler as a heat source and an array of 2 1/2 inch and 1 inch pipes in a single pipe configuration. The controllable steam source produces steady state working fluid temperatures between 100°C and 160°C. Ambient temperatures ranged from as low as 25°C to as high as 50°C when using small insulated enclosures. The operational TEG unit is mounted on a 2.5-inch nominal steam pipe since 2012 as shown in Figure 6. It has been running intermittently and is used for research purposes and student projects. It has the older thermal grease and the older Melcor thermoelectric modules. It has not been removed, refurbished, or changed in any way since its initial installation.

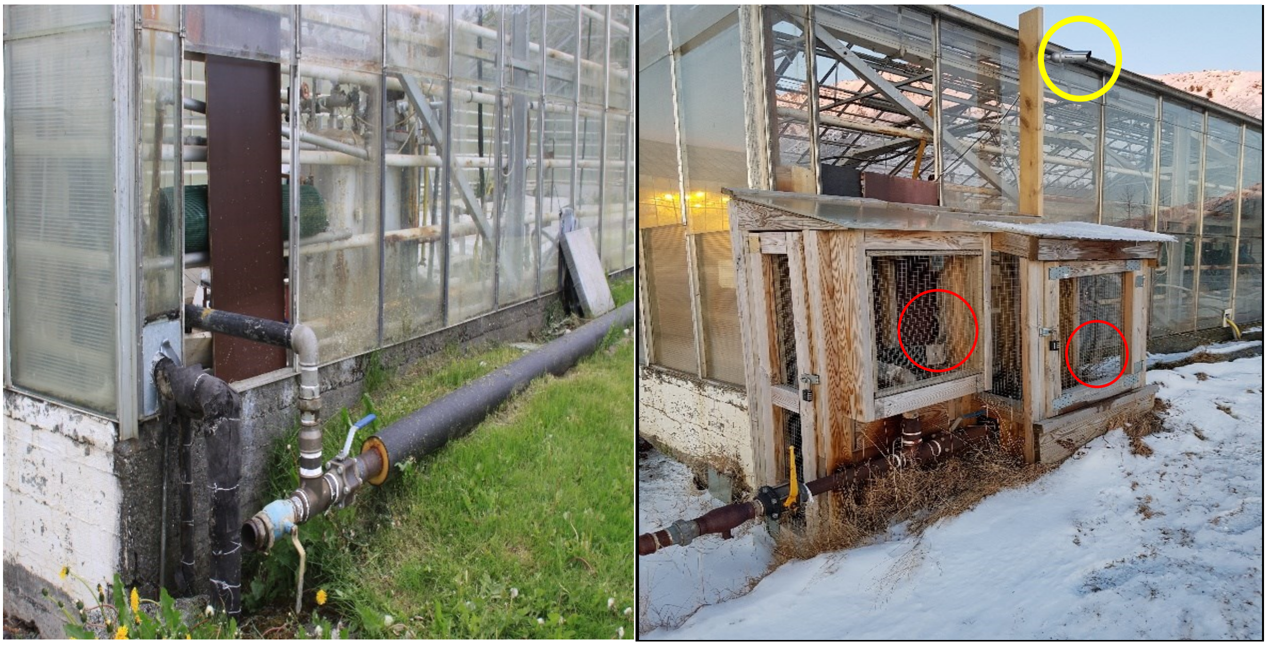

Figure 4: Left: Test bed geothermal steam pipe at the agricultural university of Iceland near Hveragerdi. Right: TEGs exterior housing are attached to the greenhouse. The video camera is visible at the end of the vertical beam circled in black, and the TEGs locations are circled in red.

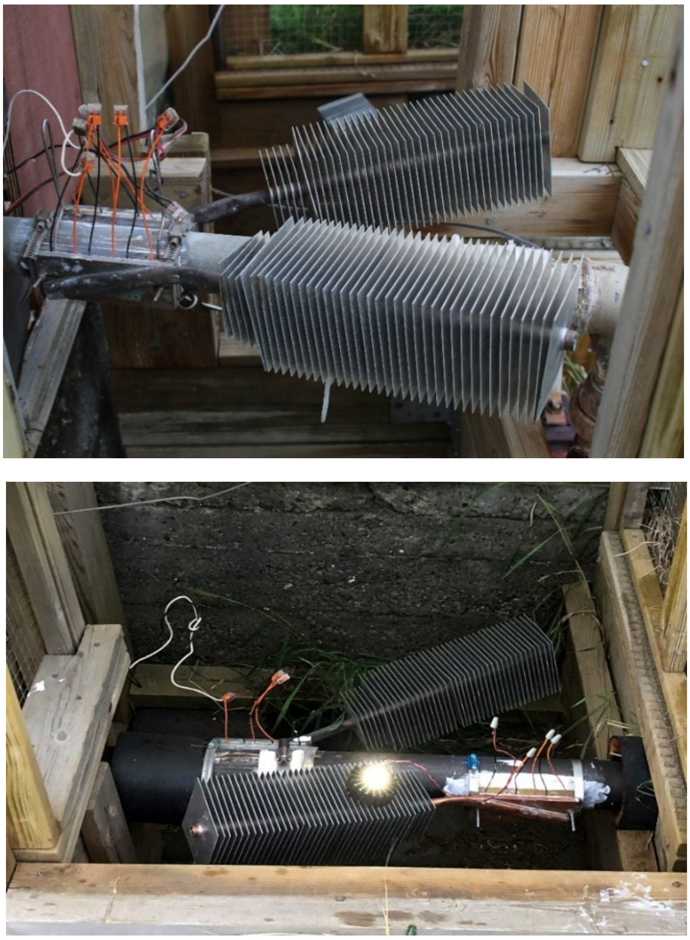

Figure 5: Top: Thermoelectric generators TEG1 and TEG2 as seen from the shed doorway entrance. Bottom: TEG 3 and TEG 4 as mounted.

The electrical measurements from both test beds were taken in a steady state condition using Fluke multimeters, namely the 867B graphical multimeter, the 287 Multimeter, and the 289 Multimeter w/ TrendCapture. Current measurements were also taken with a FW Bell mA-2000DC / True RMS AC Non-Contact Milliammeter. Fluke contact probes and Fluke infrared noncontact thermometers were used for temperature measurements. The thermal patterns were documented with a Mikron 7200 infrared thermal camera.

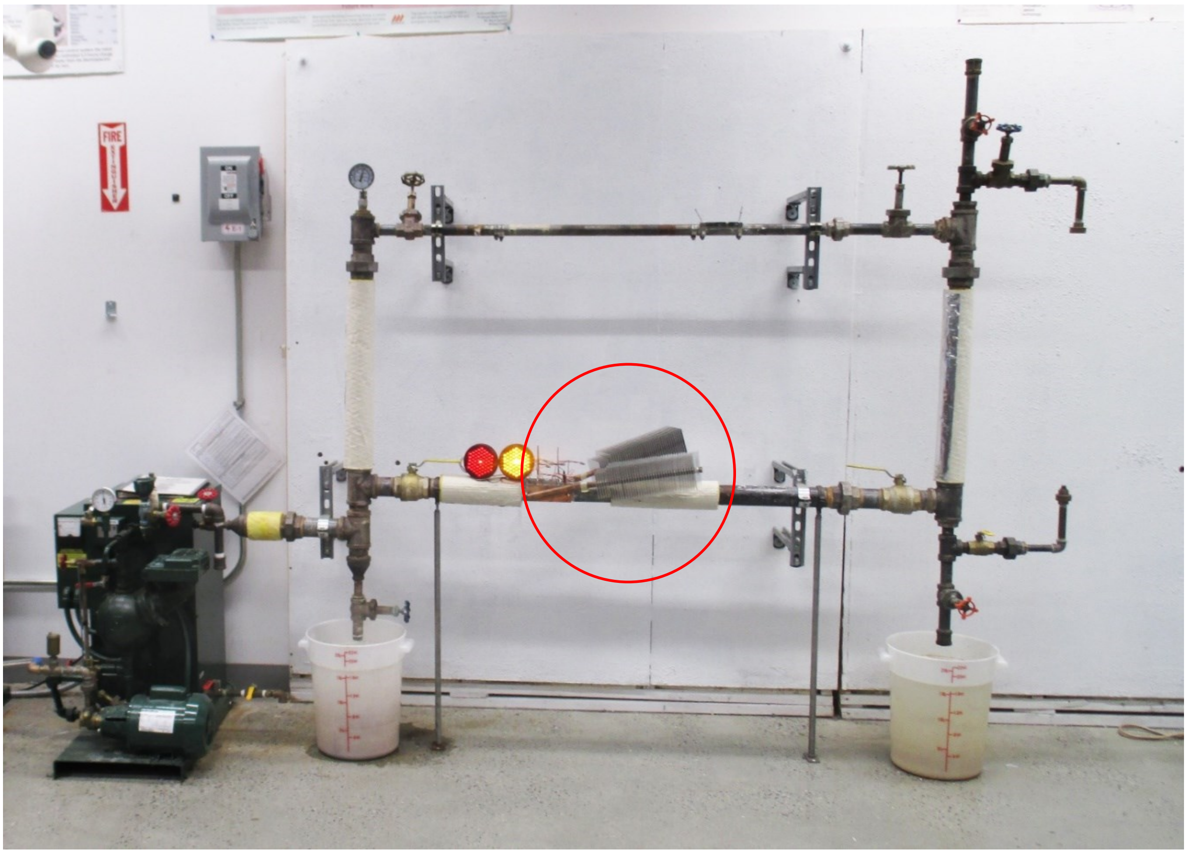

Figure 6: Steam test bed at The Cooper Union in New York City shown powering two LED light sources. The TEG is circled in red

2.3 The Electronic Monitoring Hardware

The basic wiring schematics for the TEGs and the electronic monitoring hardware is shown in Figure 7. The two generators are wired in series. In 2017 a third TEG was added, also wired in series. They are connected to a Phocos, Ulm, Germany, CA14-2.2. Solar Charge Controller. The charge controller is then connected to a BIGBAT 12 V, 3.2 Ah deep cycle lead-acid battery. This provides voltage stability, enables higher optional peak power draws. The system produces enough power to trickle charge the battery, even during the peak power draws. Additional batteries can easily be added for additional peak power. The battery also eliminates the electronic noise that can impede router and camera performance. Advances in mobile and handheld electronics continually offer lower power options. A Sierra Wireless, Richmond, Canada, AirLink RV50 Industrial LTE Gateway router draws approximately 1 W in standby mode with a low voltage disconnect. The authors established a dedicated cabinet to house the charge controller, the battery, and the router. It is placed inside the semi-heated contiguous greenhouse, again for security purposes, as is the antenna.

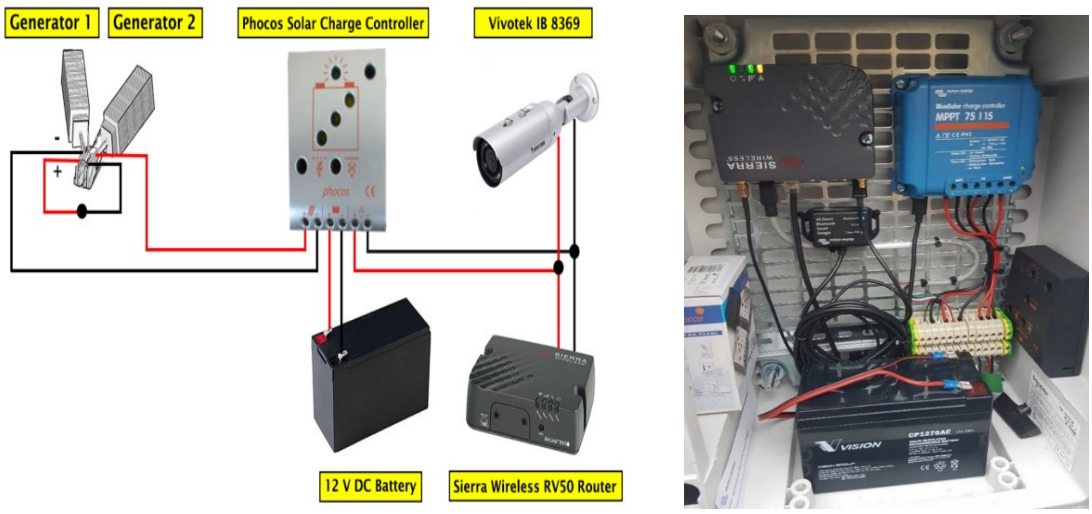

Figure 7: Left: Basic initial wiring schematic. Right: The complete 3G system in its dedicated cabinet, located inside the attached green house.

The RV50 and the Vivotek IB8369 IP-Camera are wired in parallel. The camera is shown in Figure 7 has a 2 Megapixel image sensor, a fixed 3.6mm lens, and a 0.72 kg 74 × 211 × 77 mm mountable housing. It has low-light capabilities up to 20 m and infrared LEDs.

The camera is connected to the internet by using the SIM card from a regular 3G Vodaphone mobile broadband USB stick. It has been working with its own dedicated web address since 2017.

3. RESULTS AND DISCUSSION

In 2012, thermoelectric steady state power readings were taken at the Cooper Union test bed with a steady state steam temperature of 160°C and an ambient air temperature of 30°C. The mirrored pair of TEGs had six TEMs. It produced an open circuit voltage of 21.29 V and a closed (short) circuit current of 1.139 A in steady state... This maximum available power was 6.09 W with a ΔT of 130°C. The average effective Seebeck coefficient for each TEM was 0.0274 V/°C.

In 2019, new electric power steady state readings were taken using the originally installed TEG, without any maintenance or updates made to the assembly. The steady state steam temperature was 153°C and the ambient air temperature was 28°C, producing a ΔT of 125°C. The 6 TEMs on the generator now produced 19.32 V open circuit and 0.96 A closed (short) circuit. The maximum available power was 4.64 W with a ΔT of 125°C. The average effective Seebeck coefficient for each TEM was 0.0258V/°C. Using this Seebeck coefficient the predicted voltage for 6 TEMs would be 20.124 V open circuit. When compared with 2012's reading of 21.39V, there is a decrease in steady state open circuit voltage of 6%

The closed-circuit amperage dropped to 1.07 A. When compared with 2012's 1.139A, there is a decrease in steady state closed (short) circuit current of 10%. Using these figures, the comparative 2019 steady state power production is 5.38 W. This is 12% less than the 2012 results. The system's annual average performance degradation was 0.58% per year over the seven-year test period.

This is possibly due to the degradation of the thermal grease and the expected degradation of the thermoelectric modules. Laird Thermal Solutions suggests replacement after 40,000 hours (4.6 years continual operation) (Laird Thermal Systems, 2019).

In Iceland in 2018, the older lower amperage Melcor TEMs which were used previously at another location were replaced with higher efficiency and higher amperage Laird ThermaTEC 14 PB23 Series, HT8 modules. At the same time the thermal grease was upgraded to Timtronics Red Ice high temperature thermal grease. In March of 2019, with a ΔT of 140°C, the open circuit voltage and short circuit current for the three TEGs wired in series and operating in steady-state was 31.6 V and 1.35 A. The steady state power production capacity was approximately 10.7 W. These results are compared to the results from June of 2017 in Table 1.

Table 1: Agricultural University of Iceland 2017 and 2019 TEG output.

		June 2017	March 2019
Temp (°C)	Steam Pipe	134.4	137
	Ambient Air	9.83	1
	ΔT	124.6	136
Power (W)	TEG 1	1.74	3.67
	TEG 2	1.99	3.59
	TEG 3	2.25	3.43
	Series	5.98	10.7

The original thermal grease used in Iceland was not the same as the thermal grease for the Cooper Union TEG system. The original Iceland thermal grease was observed to have dried out when disassembled. As these upgrades were performed simultaneously, the specific breakdown of the two variables (the modules and the thermal grease) cannot be specifically differentiated.

Figure 8: Iceland, March 2019 daily energy draw. The lower number of the last day was caused by the mid-morning collection of the data.

Continued use of the 3G system shows an average energy draw of approximately 60 - 70Wh per day as shown in Figure 8. When calculated over 24 hours, the average constant power draw is 2.07W, which is less than 30% of the system's total power generation capacity.

Although rather bulky and relatively inefficient when compared to newer webcams, the Vivotek IB8369 IP-Camera has shown extreme reliability survivability in Iceland's climate extremes. An identical camera installed has been working without interruption since early 2015 in a nearby installation in Selfoss.

As shown in Figure 9, the camera has provided constant monitoring year-round, even during a power failure (Ćirić, 2018) for the authors' geothermal intensive bottom heat agricultural system test bed at the Agricultural University of Iceland. The 3G system operates completely off the grid without interruption and it is accessible from any international, internet enabled web browser.

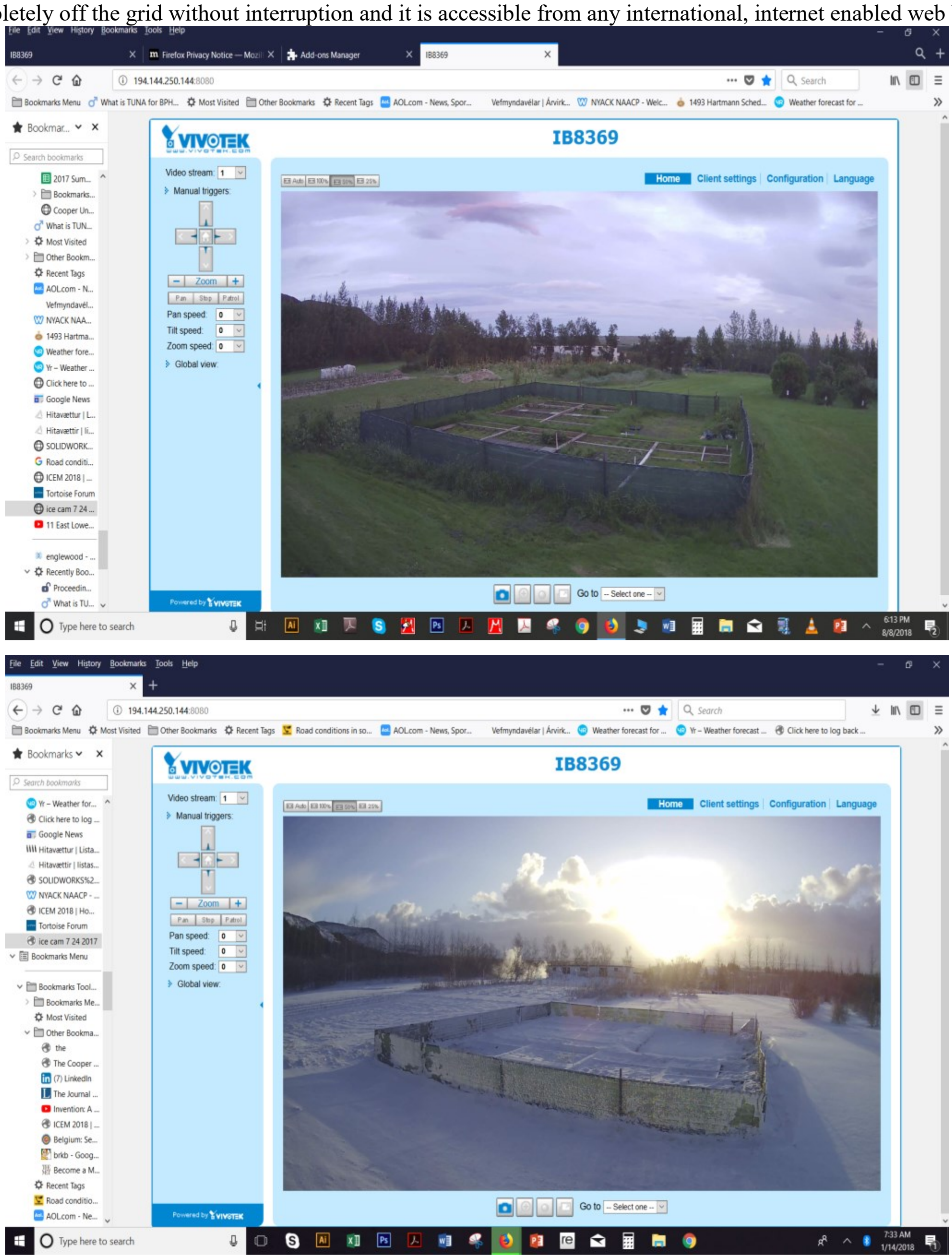

Figure 9: Top: Webcam screenshot taken on August 8, 2018 during an extensive power failure. Bottom: A winter screen shot from February November 14, 2018.

4. CONCLUSIONS

The authors' TEG system is a reliable alternative for powering webcams using standard 3G technology. Future work will harvest the unused surplus power for temperature data collection, and lower powered webcams will be incorporated when they can demonstrate the robustness needed for harsh weather conditions that commonly occur is locations like Iceland. The system is adaptable to other locations and tasks where the availability of the electrical grid is problematic and in other scenarios where point of use functionalities are advantageous.

The thermoelectric generator has proved its reliability in Iceland. Web cameras and other monitoring equipment can exist as stand-alone units using only the heat from the surface of a steam pipe as its sole power source. The system's robustness and longevity has been proven. Additional research is continuing and new advances in low power monitoring systems that are constantly being developed for low power photovoltaic systems can be seamlessly incorporated. Super capacitors now offer additional opportunities for expanded functionalities. Other options can be developed using this highly efficient and robust power generation platform.

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