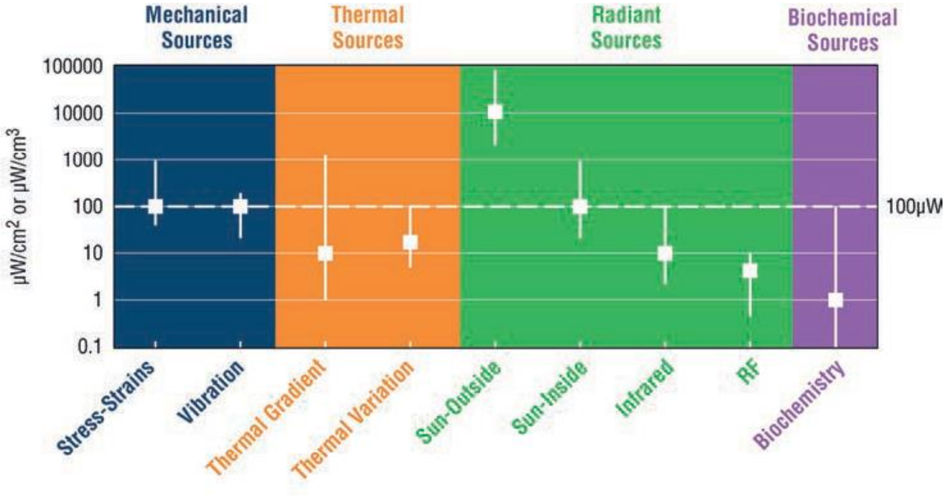

Figure 1: Harvestable energy sources and the amount of energy they generate

Wireless sensor nodes – no-battery zone

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The proliferation of ultralow-power wireless sensor nodes (WSN) for measurement and control, along with transducer technology advances, has made it possible to produce completely autonomous systems powered by local ambient energy instead of a battery. Powering a WSN from an ambient or "free" energy source is attractive because it can eliminate the need for batteries or wires. This is a clear benefit when battery replacement or servicing is inconvenient, labour-intensive and/or costly.

Wire elimination also makes it easy to expand monitoring and control systems on a large scale. Energy-harvesting wireless sensor systems simplify the installation and maintenance in diverse modes such as asset tracking, structural health monitoring (bridges, pipelines, railways, roads, etc.), agriculture and factory automation (process control, machine health monitoring, etc.), and others.

The best-known energy-harvesting collectors are large solar panels and wind generators, which have become major alternative energy sources for the power grid. But small embedded devices can also rely on energy-scavenging systems that capture milliwatts of power from light, vibration, thermal and even biological sources. The closer an energy-harvesting device is to supplying the overall demands of an embedded system, the closer the system is to operation without a battery.

Suitable sources for energy harvesting include:

- **Thermal energy** – waste energy byproduct from furnaces, heaters and friction sources;
- **Light energy** – captured from sunlight or room lighting;
- **Mechanical energy** – from vibration, mechanical stress and strain;

The closer an energy-harvesting device is to supplying the overall demands of an embedded system, the closer the system is to operation without a battery

- **Electromagnetic energy** – from inductors, coils and transformers;
- **Natural ambient energy** – from the environment such as wind, water flow and ocean currents;
- **The human body** – naturally-generated thermal energy or movement;
- **Other** – for example from chemical and biological sources.

The amount of energy that can be captured from these sources is shown in Figure 1 in the form of µW/cm^2 or µW/cm^3, depending on whether the harvester is two- or three-dimensional. The figure shows that outdoor sunlight produces the most harvestable energy per unit volume, with thermal energy, stress and indoor lighting close behind.

Wireless sensor solution

An energy-harvesting system requires an energy source and several electronic components, which include:

- An energy-conversion device (transducer) such as a piezoelectric element or solar panel that converts ambient energy into electrical form;
- An electronic interface device or converter, such as a low-voltage buck-boost converter, to capture energy from a low-voltage source and convert it into a regulated, usable voltage to power a load and/or charge a battery or a supercapacitor;
- Sensors, microcontrollers and a transceiver to read, record and transmit the data as part of the WSN.

It is very important that these devices have a low quiescent current to allow accumulation of the harvested energy to power the sensor network, or to monitor and control a device. It is also essential to understand how much average power is available from the harvestable energy source and how to make it power the device for successful implementation.

It's all about the duty cycle

Many wireless sensor systems consume very low average power, making them prime candidates to be powered by energy-harvesting techniques. Sensor nodes can be used to monitor physical quantities that change slowly. Measurements can therefore be taken and transmitted infrequently, resulting in a low duty cycle of operation and a correspondingly low average power requirement.

For example, if a sensor system requires 3.3V at 30mA (100mW) whilst awake but is only active for 10ms out of every second, then the average power required is only 1mW, assuming the current in the sensor system is down to microamps in between transmit bursts. If the same wireless sensor only samples and transmits once a minute instead a second, the average power plummets to under 20µW. This difference is significant, because most forms of energy harvesting offer very little steady-state power – usually no more than a few milliwatts, and in some cases only microwatts. The less average power required by an application, the more likely it can be powered by harvested energy.

Energy-harvesting IC solutions

There are several energy-harvesting commercial products available already, including LTC3108 from Analog Devices. This is an integrated monolithic solution for operation from input voltages as low as 20mV, enabling it to power wireless sensors from a thermoelectric generator, or TEG (see side box on page 54), harvesting energy from temperature differentials as low as 2°C. Using a small (6mm × 6mm), off-the shelf step-up transformer and a handful of low-cost capacitors, it provides the regulated output voltages necessary for powering a WSN. The resulting design can support a 50mW load with a duty cycle of up to 3.7%.

The LTC3108 uses a step-up transformer and an internal depletion mode MOSFET to form a resonant oscillator capable of operating

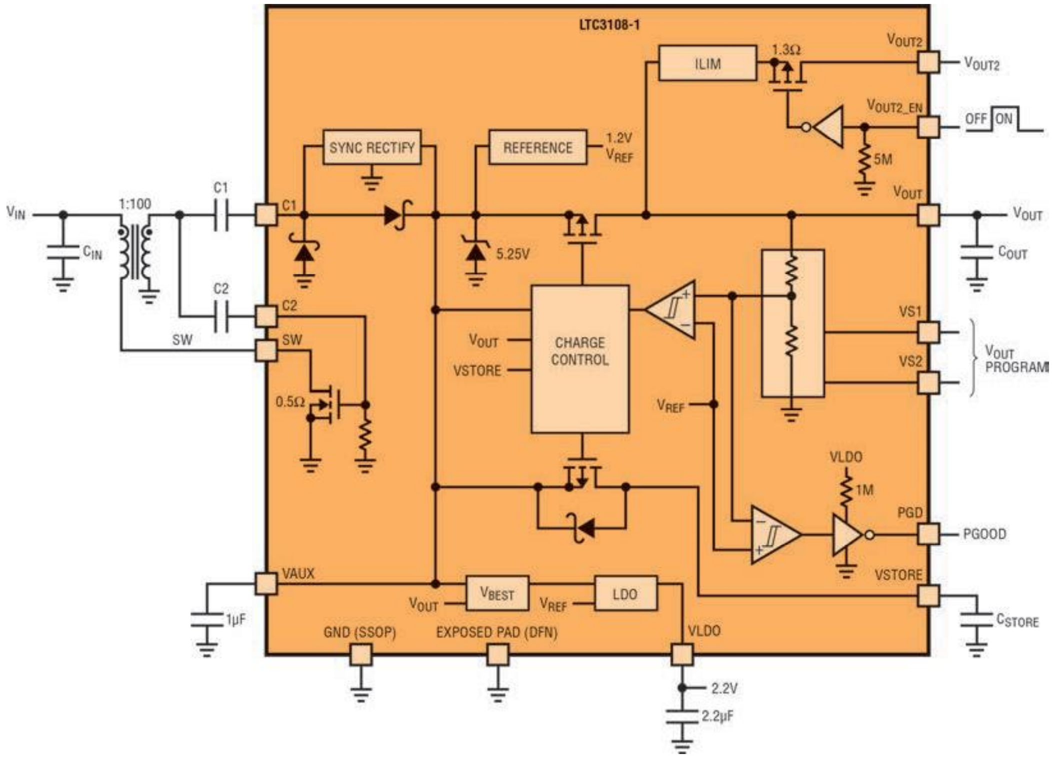
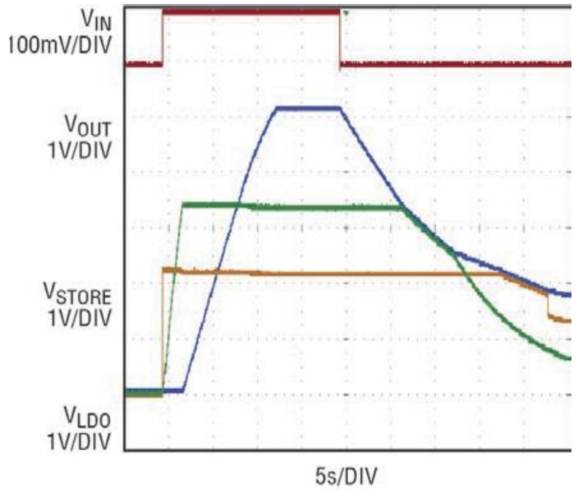


Figure 2: Block diagram of the LTC3108-1

Figure 3: Voltage sequencing during power-up and power-down



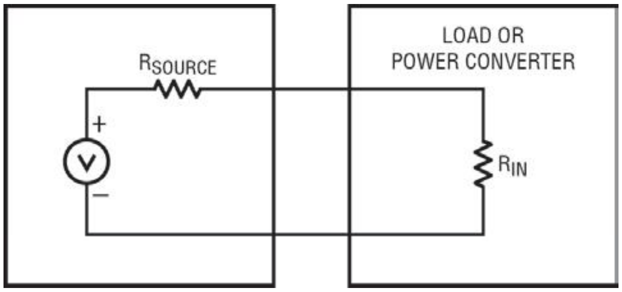


Figure 4: Simplified schematic of a voltage source driving a resistive load

from very low input voltages. With a transformer ratio of 1:50 or 1:100, the converter can start up with inputs as low as 20mV. The transformer's secondary winding feeds a charge pump and rectifier circuit, used to power the IC (via the V_{AUX} pin) and charge the output capacitors. The 2.2V LDO output is designed to be in regulation first, to power a low-power microprocessor. Then, the main output capacitor is charged to the voltage programmed by the V_{S1} and V_{S2} pins (2.35V, 3.3V, 4.1V or 5.0V) for powering sensors, analogue circuitry, RF transceivers or even charging a supercapacitor or secondary battery.

The V_{OUT} reservoir capacitor supplies the burst energy required during the low duty cycle load pulse when the wireless sensor is active and transmitting. A switched output (V_{OUT2}) is easily controlled by the host and also provides power to the circuits that don't have a shutdown or low-power sleep mode. A power-good output (P_{good}) is included to alert the host that the main output voltage is close to its regulated value.

Figure 2 shows a block diagram of the LTC3108-1, an alternative to LTC3108, which is identical except for different output voltages (2.5V, 3.0V, 3.7V or 4.5V).

Once V_{OUT} is charged and in regulation, harvested current is diverted to the V_{STORE} pin for charging a large storage capacitor or secondary battery. This storage element can be used to maintain regulation and power the system in the event that the energy-harvesting source is intermittent, or to provide additional peak power for transmission. The output voltage sequencing during power-up and power-down can be seen in Figure 3. A shunt regulator on the V_{AUX} pin prevents V_{STORE} from charging above 5.3V.

Load matching

For open energy sources such as TEG devices, the power electronics should extract the maximum possible output power. The equivalent circuit in Figure 4 shows that maximum power is extracted when the load matches the Thevenin equivalent source resistance of the TEG device.

Figure 5 shows the power delivered to the load as a function of load resistance. It can be seen in each curve that maximum power is delivered to the load when the load resistance matches the source resistance. Nevertheless, it is also important to note that when the source resistance is lower than the load resistance, the power delivered may not be the maximum possible but is still higher (1.9mW in this example) than a higher source resistance driving a matched load (0.8mW in this example). Therefore, choosing a TEG with lower output impedance leads to higher possible output power.

Choosing a TEG for power generation

Most thermoelectric module manufacturers do not provide data for output voltage- or output-power versus differential temperature, which is what a designer of a thermal energy harvester needs to know. Two parameters that are always provided are V_{MAX} and I_{MAX}, or the maximum operating voltage and current for a particular module (when driven in a heating/cooling application).

A good rule of thumb when selecting a thermoelectric module for power-generation purposes is to choose a module with highest product of $V_{MAX} \bullet I_{MAX}$ for a given size. This generally provides the highest TEG output voltage and the lowest source resistance. One caveat to this rule is that the heat sink must be sized according to the size of the TEG; larger TEGs require larger heat sinks for optimal performance.

Note that, if given, the electrical resistance is specified as an AC resistance because it can't be measured in the conventional manner using DC current, since DC current generates a Seebeck voltage that yields erroneous resistance readings.

Thermal considerations

The size of the TEG required for a given application depends on the minimum ΔT available and the maximum average power required by the load, as well as the thermal resistance of the heat sink being used to maintain one side of the TEG at ambient temperature.

When placing a TEG between two surfaces at different temperatures, the "open circuit" temperature differential – before the TEG is added – is higher than the temperature differential across the TEG when in place. This is because the TEG itself has a fairly low thermal resistance between its plates (typically 1-10°C/W).

For example, consider a situation where a large piece of machinery is running with a surface temperature of 35°C and surrounding ambient temperature of 25°C. When a TEG is attached to it, a heat sink must be added to the cool (ambient) side of the TEG, otherwise the entire TEG would heat up to nearly 35°C, erasing any temperature differential. Keep in mind that it is the temperature difference across the TEG that produces electrical output power.

In this example, the thermal resistance of the heat sink and the TEG dictate what portion of the total ΔT exists across the TEG. A simple thermal model of the system is shown in Figure 6. Assuming that the thermal resistance of the heat source (R_S) is negligible, the thermal resistance of the TEG (R_{TEG}) is 2°C/W, and the thermal resistance of the heat sink is 8°C/W, the resulting ΔT across the TEG is only 2°C. The low output voltage from a TEG with just a few degrees across it highlights the importance of the LTC3108's capability to operate from ultralow input voltages.

Note that large TEGs usually have a lower thermal resistance than smaller ones due to the increased surface area. Therefore, in applications where a relatively small heat sink is used on one side of the TEG, a larger TEG may have less ΔT across it than a smaller one, and hence may not necessarily provide more output power. In any case, using a heat sink with the lowest possible thermal resistance maximises the electrical output by maximising the temperature drop across the TEG.

Wireless sensor load application

A typical wireless sensor application powered by a TEG is shown in Figure 7. In this example a temperature differential of at least 2°C is available across the TEG, so a 1:50 transformer ratio was chosen for the highest output power. This turns-ratio is recommended for temperature differences in the range of 2-10°C.

Using the TEG shown (a 40mm square device with a resistance of 1.25Ω), this circuit can start-up and charge the V_{OUT} capacitor from temperature differentials as low as 2°C. Note that there is a bulk decoupling capacitor across the input terminals of the converter. Providing good decoupling of the voltage from the TEG minimises input ripple, improving output power capability and allowing start-up at the lowest possible temperature difference.

In the example of Figure 7, the 2.2V LDO output powers the microprocessor, whilst V_{OUT} has been programmed to 3.3V, using the V_{S1} and V_{S2} pins, for powering the RF transmitter. The switched V_{OUT} (V_{OUT2}) is controlled by the microprocessor to power 3.3V sensors only when needed. The P_{GOOD} output lets the microprocessor know when V_{OUT} has reached 93% of its regulated value.

To maintain operation in the absence of an input voltage, a 0.1F storage capacitor is charged in the background from the V_{STORE} pin. This capacitor can charge up to the 5.25V clamp voltage of the V_{AUX} shunt regulator. If the input voltage source is lost, energy is automatically supplied by the storage capacitor to power the IC and maintain regulation of V_{LDO} and V_{OUT}.

In this example, the C_{OUT} reservoir capacitor has been sized to support a total load pulse of 15mA for 10ms, allowing for a 0.33V drop in V_{OUT} during the load pulse, per the equation below:

$$C_{OUT}(\mu F) = \frac{I_{PULSE}(mA) \bullet t_{PULSE}(ms)}{dV_{OUT}}$$

Note that I_{PULSE} includes loads on V_{LDO} and V_{OUT2} as well as V_{OUT}, but not any available charging current since it may be very small compared to the load. Given these requirements, C_{OUT} must be at least 454μF, so a 470μF capacitor was selected.

With the TEG shown, operating at a ΔT of 5°C, the average charge current available from the LTC3108 at 3.3V is about 560μA. With this information, we can calculate how long it takes

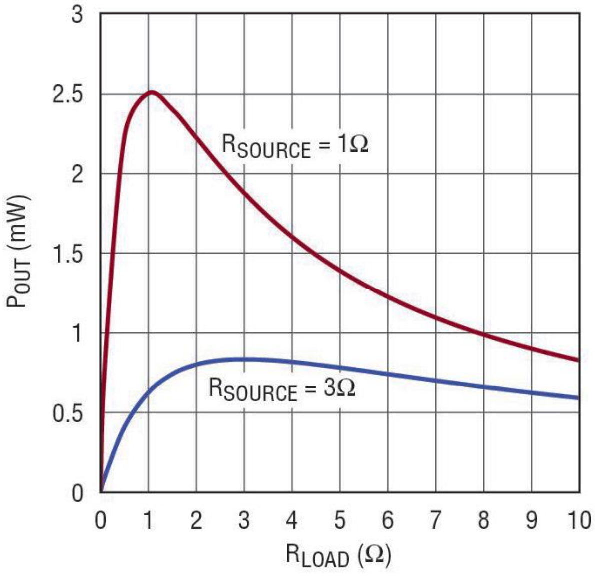


Figure 5: Output power from a source as a function of load resistance

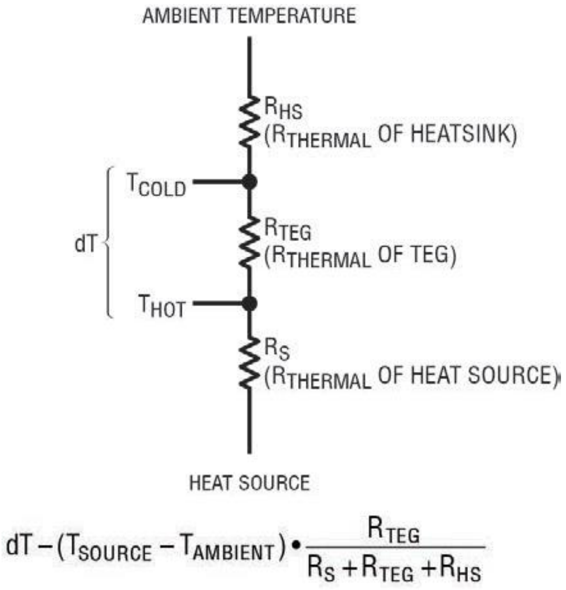


Figure 6: Thermal resistance model of a TEG and heat sink

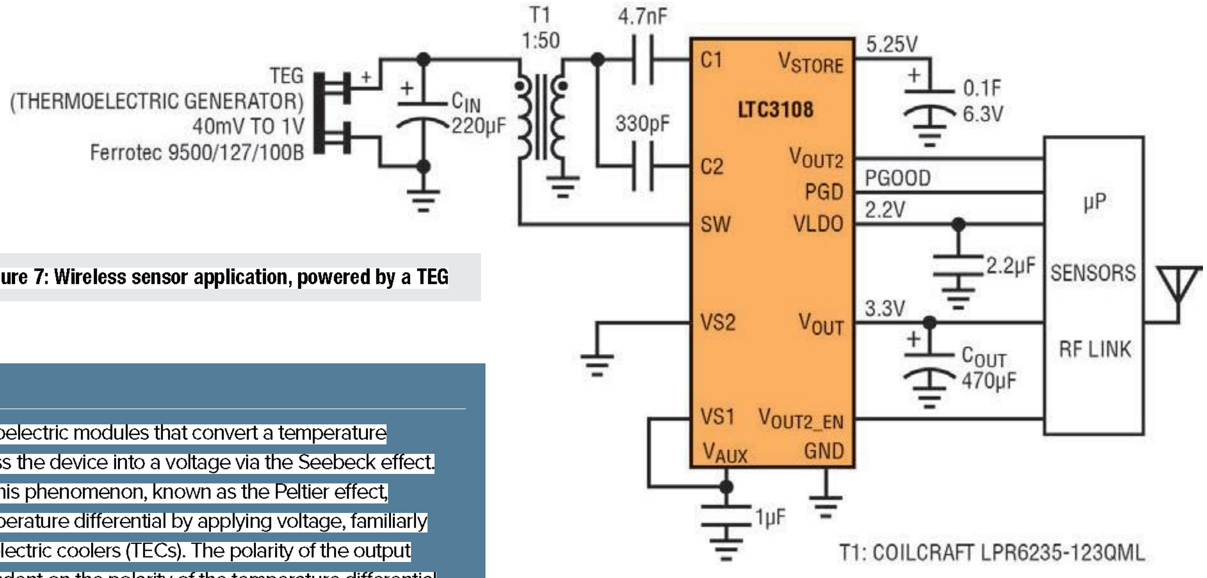


Figure 7: Wireless sensor application, powered by a TEG

to charge the V_{OUT} reservoir cap the first time, and how frequently the circuit can transmit a pulse. Assuming the load on V_{LDO} and V_{OUT} during the charging phase is very small (relative to 560µA), the initial charge time for V_{OUT} is:

$$t_{CHARGE} = \frac{470\mu F \bullet 3.3V}{560\mu A} = 2.77 \text{ seconds}$$

Assuming the load current between transmit pulses is very small, a simple way to estimate the maximum transmit rate allowed is to divide the average output power available from the LTC3108, in this case 3.3V • 560µA = 1.85mW, by the power required during a pulse, in this case 3.3V • 15mA = 49.5mW. The maximum duty cycle that the harvester can support is thus 1.85mW/49.5mW = 0.037, or 3.7%. Therefore, the maximum transmit burst rate is 0.01/0.037 = 0.27 seconds or about 3.7Hz.

Keep in mind that if the average load current (as determined by the transmit rate) is the highest the harvester can support, there will be no harvested energy left over to charge the storage capacitor (if storage capability is desired). Therefore, in this example the transmit rate is set to 2Hz, leaving almost half the available energy to charge the storage capacitor. Hence, the storage time provided by the C_{STORE} capacitor is calculated using the following equation:

$$t_{STORE} = \frac{0.1F \bullet (5.25V - 3.3V)}{6\mu A + 15mA \bullet \frac{0.01}{0.5}} = 637 \text{ seconds}$$

This calculation includes the 6µA quiescent current required by the LTC3108, and assumes that the loading between transmit pulses is extremely small. In this case, once the storage capacitor reaches full charge, it can support the load for 637 seconds at a transmit rate of 2Hz, or a total of 1274 transmit bursts.

For applications where higher temperature differentials (i.e. higher input voltages) are available, a lower turns ratio transformer, such as 1:50 or 1:20, can be used to provide higher output current capability. If the minimum input voltage is at least 50mV under load, then a 1:50 ratio is recommended. If the minimum input voltage is at least 150mV, then a 1:20 ratio is recommended.

TEG Basics

TEGs are thermoelectric modules that convert a temperature differential across the device into a voltage via the Seebeck effect. The reverse of this phenomenon, known as the Peltier effect, produces a temperature differential by applying voltage, familiarly used in thermoelectric coolers (TECs). The polarity of the output voltage is dependent on the polarity of the temperature differential across the TEG. Reversing the hot and cold sides of the TEG changes the output voltage polarity.

TEGs are made up of pairs or couples of N-doped and P-doped semiconductor pellets, connected electrically in series and sandwiched between two thermally-conductive ceramic plates. The most commonly-used semiconductor material is bismuth-telluride (Bi_2Te_3). See the figure below for the TEG's mechanical construction.

Some manufacturers differentiate between a TEG and a TEC. When sold as a TEG, it generally means the solder used to assemble the couples within the module has a higher melting point, allowing operation at higher temperatures and temperature differentials, and therefore higher output power than a standard TEC (which is usually limited to a maximum of 125°C). Most low-power harvesting applications do not see high temperatures or high temperature differentials.

TEGs come in a wide variety of sizes and electrical specifications. The most common modules are square, ranging in size from about 10mm to 50mm per side and are usually 2-5mm thick.

Several variables control how much voltage a TEG will produce for a given temperature difference (proportional to the Seebeck coefficient). Their output voltage is in the range of 10-50mV/°C of differential temperature (depending on the number of couples), with a source resistance in the range of 0.5-5Ω. In general, the more couples a TEG has in series, the higher its output voltage for a given temperature difference. However, increasing the number of couples also increases the series resistance of the TEG, resulting in a larger voltage drop when loaded. Manufacturers can compensate for this by adjusting the size and design of the individual pellets to preserve a low resistance whilst still providing a higher output voltage.