WHITE PAPER

Basics of Thermoelectric Energy Harvesting

sheetak

Advanced Thermoelectrics

The world's energy consumption grew exponentially in the last half-century with the advent of computers and the Internet. "Smart" buildings, vehicles and accessories are creating cities powered by the Internet of Things, further contributing to the need for electricity. Energy harvesters are the "green" and eco-friendly solution as we continue down this path.

Executive Summary

Put simply, energy harvesting converts energy from one form – kinetic, photonic, thermal, magnetic, etc. – into usable electricity. The specific needs of an application guides what type of energy harvester to use.

Energy harvesting is leading the charge in providing sustainable solutions for the rise in global power consumption and growing need for renewable energy sources. Energy harvesters can alleviate the stress from the world's reliance on fossil fuels, which is heavily impacting the environment in negative ways. Many countries around the world have already pledged to reduce carbon emissions in the coming decades, and a switch to renewable energy using energy harvesting technologies will aid in reaching that goal.

Energy harvesting devices, especially thermoelectric generators (TEGs), are also a step toward a battery-free future. Batteries contain many metals that can become hazardous waste and harm the environment. Energy harvesters can supplant the need for batteries by either recycling the waste energy being produced by a device or reclaiming energy from the ambient conditions and turning it into electricity.

Sheetak specializes in thermoelectrics, so the main considerations covered in this paper will be applicable to designing thermoelectric generators. But many of the criteria discussed will be applicable to other types of energy harvesting as well.

How TEGs Work

Thermoelectric generators are like mini hydroelectric dams. Just like a dam generates electricity by water flowing from one side to the other, TEGs generate electricity by heat flowing from one side of the device to the other. This is in large part due to heat often flowing through metal in the form of electrons, which is what electricity is composed of.

To keep the heat flowing, one side of the thermoelectric generator needs to be heated or cooled. This is called heat rejection and can be accomplished with anything from passive aluminum (fin heatsinks) to active water cooling. The Seebeck effect lets us take advantage of this to capture some of those thermal electrons and harness them for use elsewhere.

The Seebeck Effect

The Seebeck effect states that a temperature differential between two differing materials (N-negative and P-positive doped semiconductors) causes electrons to flow to the colder side. A difference in electron concentration creates a potential difference, or voltage.

The Seebeck effect is relatively weak on the scale of a single couple (a couple being a N/P junction as shown in Figure 1.01). But multiple couples aligned thermally in parallel and electrically in series multiplies the effect several times over (as shown in Figure 1.02). The smallest TEGs have 30 couples while the largest have in excess of 1,000. The more couples there are and

Figure 1.01

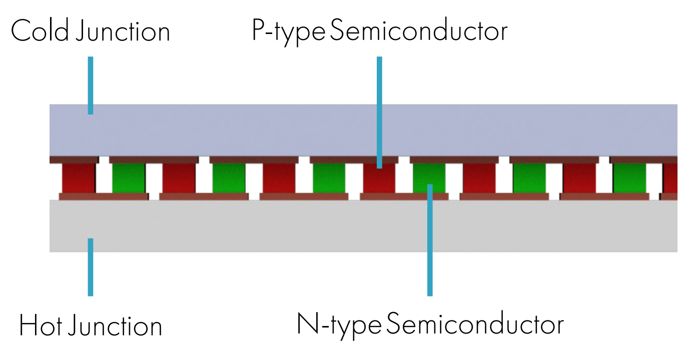
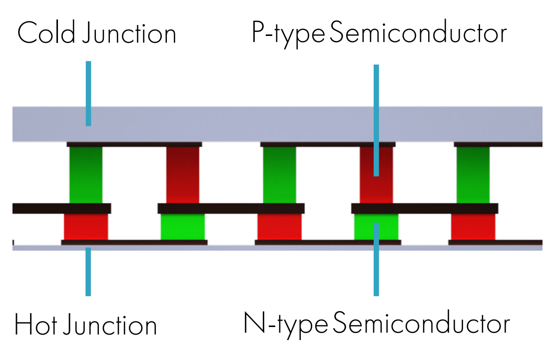


Figure 1.02



the larger the temperature difference between the two sides, the most electricity generated. Most TEGs are rated for upward of 150°C.

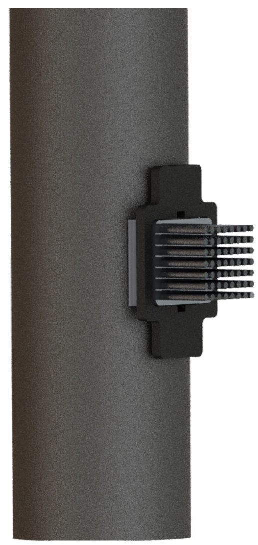
As discussed above, to generate electricity with TEGs, one side of the chip must be warmer (or cooler) than the other. This is called a temperature differential or ΔT. The process of generating a ΔT is called heat rejection, which can be accomplished in a number of ways depending on the application.

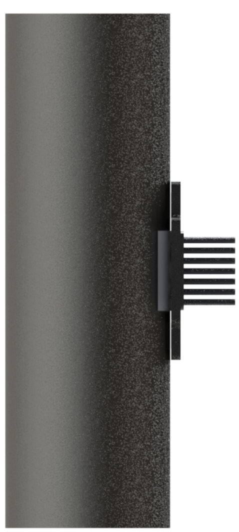
Active cooling is common when generating large amounts of electricity. This is often accomplished with water cooling or forced air. For generating smaller amounts of power (e.g. when powering wearables or remote devices), passive cooling with aluminum heat sinks is more common.

Selecting a TEG

When selecting specific TEGs for an application, the temperature range for the application must be known. The most commonly used material is bismuth telluride, which can operate up to 150°C, but there are plenty of other materials for higher temperature ranges.

The ZT listed on a TEG's datasheet will let designers know the level of performance to expect from a device. ZT is a unitless parameter expressed as a decimal number less than one that represents a TEG's Seebeck coefficient, electrical conductivity (ideally high) and thermal conductivity (ideally low).





Pictured above and to the left are examples of thermoelectric generators where the assembly is mounted to a pipe with hot liquid or hot gas passing through it, and the cold side of the TEG device is cooled via natural convection with a passive aluminum heat sink.

ZT is largely determined by material, but can also vary based on exact operating temperature and the thickness of the device. Thinner devices tend to have higher ZT, making them more efficient, but they also require more robust heat rejection systems.

Another consideration is power regulation, specifically voltage regulation. The power generated by an energy harvesting system will need regulation. A regulator with dynamic impedance matching provides ideal energy transfer. For high power applications, a regulator designed for residential solar systems should suffice. For low power thermoelectric energy harvesting applications, the devices shown in Table 1.01 are recommended.

Table 1.01

Part Number	***SPV-1050***	***AEM20940***	***LTC3108***
Manufacturer	STMicroelectronics	epeas	Analog Devices
Cold Start Voltage	0.55V	60mV**, 380mV	20mV
Min Input Voltage	75mV	50mV	20mV
Max Input Voltage	18V	3.5V	500mV
Number of Outputs	2	2	2
Output Voltage	1.8V, 3.3V	1.2V - 4.1V	2.35V - 5V
Max Output Current	200mA	80mA	7mA
Storage Management	Lithium Battery, Thin Film, Super-Capacitor	Battery, Super-Capacitor	Battery, Super-Capacitor
Configuration	Boost, Buck-Boost	Buck, Boost	Buck, Boost
Impedance Matching	MPPT*	MPPT*	MPPT*
Max Conversion Efficiency	88%	95%	60%

* MPPT (Maximum Power Point Tracking) is a dynamic impedance matching system that maximizes conversion efficiency even if your TEG's impedance shifts over time due to changing environmental factors like temperature, humidity, etc.

** 60mV is achievable with optional, external start up circuit.

Most energy harvesting methods are reliant on inconsistent or cyclic energy sources, and TEGs are no different. Solar panels only work during the day. Wind turbines only work when there's wind. Likewise, TEGs require a heat source, and not all applications can guarantee a perpetual source of heat.

In applications where a heat source may be lost temporarily, there must be some other way to store electricity. The energy storage method will need to be large enough to meet the application's needs between heat cycles. The larger the power requirements, the larger the required battery.

For industrial applications with heavy loads, a pre-made battery bank with its own Battery Management System may be considered. For lighter loads, many of the energy harvesting chips recommended above in Table 1.01 have secondary power source management systems integrated already.

The two most popular choices for secondary power sources are lithium-based batteries and super capacitors. Table 1.02 below compares the pros and cons of those two options.

Table 1.02

Super Caps	*Lithium Batteries*
Charge fast	Charge slow
Naturally lose charge within a day or two, even without a load	Can hold a charge for months
Virtually unlimited number of charge cycles	Up to 2,000 charge cycles (typically 300-500)
10-20 year lifespan	Needs to be replaced every five years (typically every 2-3 years)
High power density, which is good for strong but short bursts of power	High energy density, which is good for long, sustained operation

There are newer secondary battery chemistries being released that combine the best features of both secondary batteries and the super capacitors, but they aren't as widely available yet. A prime example would be I-TEN's micro batteries

Why Use TEGs

Thermoelectric generators are solid-state devices, meaning they have no moving parts. That makes them highly reliable and completely maintenance-free. They're also made from common, low-cost materials.

TEGs can utilize waste heat, which allows the recovery and recycling of energy that's already been benefitted from before. Along a similar vein, TEGs can be installed anywhere something is being heated or cooled. That includes industrial machinery, engines, roofs/attics and more, making TEGs extremely versatile.

These devices are silent and take up very little space while still being scaleable. TEGs can fit into areas where other types of energy harvesters simply can't be placed. Additionally, thermoelectric energy harvesters boast a wide temperature range, further showcasing versatility.

TEGs reach up to 15% efficiency and produce in the milliwatt to kilowatt range. Thermoelectric energy harvesting chips can replace or supplement batteries in small devices but also be used to recover waste-heat from industrial applications, often in the kilowatt range. This technology is even beginning to replace batteries in some smart watches and other wearable devices.

There are a couple of considerations when using TEGs, though. The first is that a heat rejection method is a requirement for the device to function. The other is that the number of chips and the number of couples needed to service the application at hand may vary. Some integrations of a TEG may require multiple chips to harvest a sufficient amount of power.

Applications

Smart Buildings
Ambient IoT
Sensor Arrays

Wearables
Consumer Electronics

Medical Devices

Industrial
Waste-Heat Recovery

Automotive

Thermoelectric generators can also be used in remote devices (where battery replacement is difficult or impossible), commercial and domestic appliances, nuclear batteries and much more.

Other Energy Harvesters

Photovoltaic

Also known as solar power, photovoltaic energy harvesting converts light into electricity. Because this technology is so scalable, solar panels can be found anywhere from solar farms to wrist watches.

Large panels (like those on solar farms) designed to supply electricity for the grid have around 20% efficiency and are capable of harnessing the full spectrum light produced by the sun, including wavelengths, which are beyond the visible spectrum. Smaller panels, intended for indoor use to power objects like calculators, tend to have [24]% efficiency and are often optimized to use the visual spectrum produced by artificial light sources like LEDs and fluorescent lights.

Residential systems typically generate 200-400W/m^2 during peak daylight hours. Smaller devices (like lawn lights or calculators) are often closer to 10-15mW/cm^2 when placed under ideal conditions.

Pros	***Cons***
Wide range of applications	Only works with light
Scaleable to needs of application	Can take up large amounts of land
Natural light is renewable and clean	Current panels are rigid and heavy
One of the most mature EH technologies	
Long lifespan (residential panels typically rated for 30+ years)	

Potential applications include general power generation for the grid, supplementing/supplying power for reidential and commercial buildings, wearable devices and remote systems.

Piezoelectric

Piezoelectric energy harvesting converts vibrations or mechanical stress into electricity through the piezoelectric effect. This kind of energy harvesting can be used as vibration sensors for early failure detection on industrial equipment, on buoys for early warning systems for large waves, to power IoT devices or on smart roads to harvest waste energy from passing cars. It's worth noting that the efficiency of this method is inversely proportional to the excitation frequency, meaning that the lower the frequency of your source, the more efficient your energy harvesting system will be.

For context, an appropriately designed system can generate:

- 10mW from arm motion
- 100mW from breathing
- 1W from walking
- 2.3W-28.7W on a one mile stretch of road (or 72,800kWh-907,873kWh per year)

Pros	***Cons***
High power density	Limited by natural limitations of piezo-electric materials
Scaleable	Intermittent power generation
High output voltage	
Wide frequency range	

Electromagnetic and Radio Frequency

Electromagnetic and Radio Frequency (RF) energy harvesting converts moving electromagnetic fields/radio waves into usable energy through Faraday's law of induction. Some systems will harvest RF, while others rely on permanent magnets and a vibration source. Both methods are best paired with extremely low power devices or to supplement and extend the life of existing batteries. Systems that harvest radio waves are most applicable in (sub)urban areas where radio waves are more plentiful or in applications where you can supply it with a dedicated source of EMF. Vibrational systems can be used anywhere you have vibrations and in some cases may be interchangeable with PEH systems.

A single vibrational system riding on a train can produce 10-15mW continuously while an RF system harvesting ambient radio waves (868MHz) can produce 7.6uW.

Electromagnetic and Radio Frequency (cont.)

Pros	*Cons*
Can generate either AC or DC power	Is dependent on proximity to source
Enables wireless power transmission	May require dedicated EMF source

Environmental/Wind/Tidal/Ocean

Wind and tidal energy harvesting converts wind and ocean currents into electricity. While these can be executed on a small scale to power individual devices or supplement the energy consumption of a home, there is a large push to use them to mass produce clean electricity and bolster the electric grid.

An individual wind turbine rated for 3MW can produce enough electricity (16,400 kWh/turbine/day) to sustain 100s of homes (29 kWh/home/day). A single tidal power station rated for 254 MW would produce enough electricity to supply a city of 500,000 people.

Wind turbines are frequently rated for 25+ years. Tidal harvesters can have lifespans exceeding those of nuclear power plants.

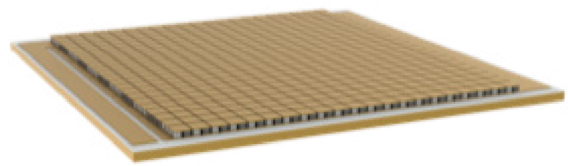
Despite the apparent lack of versatility in these energy harvesting methods, they have been used for powering remote devices such as traffic warning signs as well as for pumping water on farms. Tidal harvesters have even been used to directly protect the environment by preventing damage from storms and helping to slow down beach erosion.

Pros	*Cons*
Harnesses natural sources of energy	Requires large amounts of land
Has long lifespan	Can harm wildlife
Produces massive amounts of power	Intermittent power generation
	More expensive than other options
	Noisy
	Can be geographically limited

Our TEGs

CENTUM® EH is Sheetak's patented line of energy harvesters that delivers industry-leading output power in a compact form factor. The device can operate at temperatures up to 300°C.

We've leveraged automated, high-accuracy maufacturing processes (all done in the United States) and high-temperature materials to create battery-free energy solutions.



Standard Available Models

	Dimensions (mm)	T_h	*ΔT (°C)*	V_{OC} *(Volts)*	V_{ML} *(Volts)*	P_{ML} *(Watts)*	R_{AC} *(Ω)*
CENTUM EH-1029	40x40x2.3	27	10	4.3	2.2	0.14	34
			50	21.6	10.8	3.4	
			100	43.2	21.6	13.7	
CENTUM EH-646	30x30x2.3	27	10	2.7	1.4	0.09	21
			50	13.6	6.8	2.2	
			100	27.1	13.6	8.6	
CENTUM EH-336	20x20x2.3	27	10	1.4	0.7	0.03	17
			50	7.1	3.6	0.72	
			100	14.1	7.1	2.9	

About Sheetak

Sheetak is a disruptor in the thermoelectrics space, developing cutting-edge thermal management and energy harvesting chips for a broad set of market applications. With more than 25 granted patents in thermoelectrics and related technologies, Sheetak is setting new industry standards.

Located in Austin, TX, Sheetak delivers optimal material compositions, fabrication methods, quantum thermoelectric device designs, circuit designs, architecture and volume manufacturing.

We're pushing the edges of thermoelectric performance, so you can push the boundaries of the modern world.

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