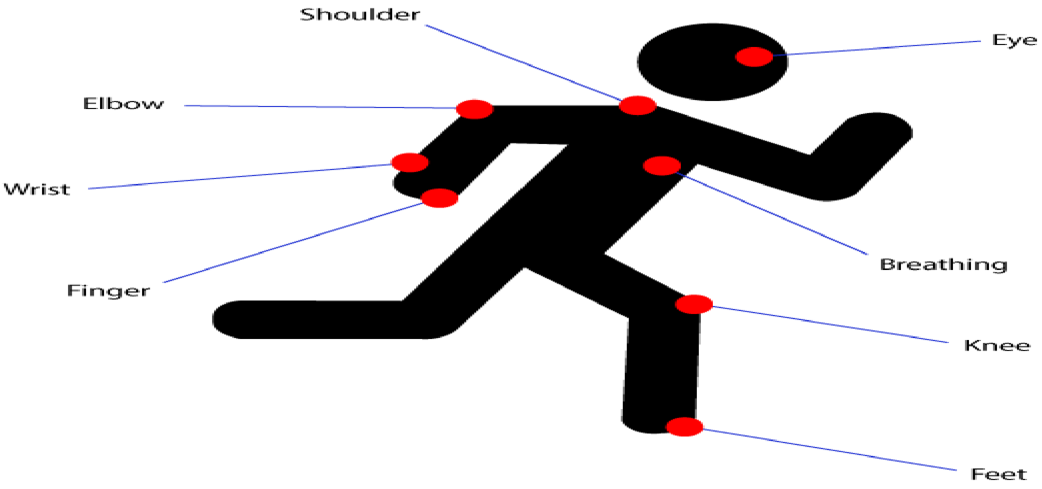
Vibration based power Requirements of wearable devices

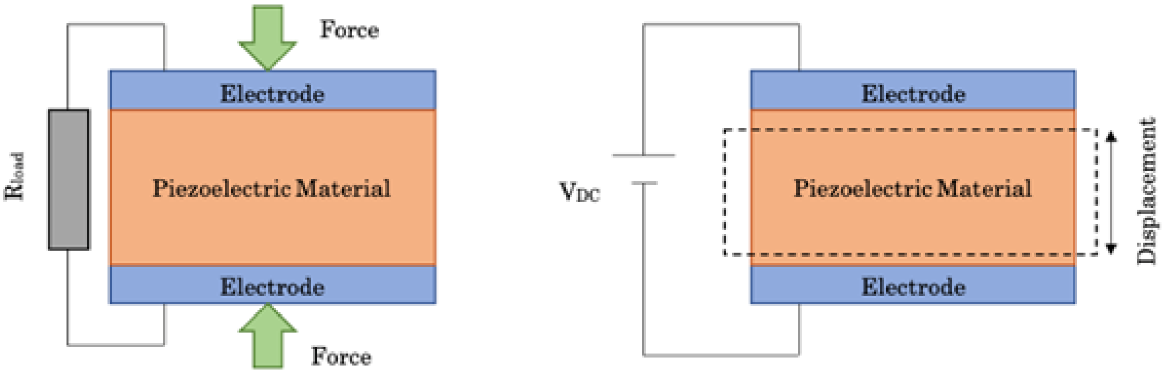
With the vast amount of wearable technology available, the demand for compact devices with smaller batteries, or no batteries at all, and longer charge duration has presented a challenge. Consumers of wearable technology want the convenience of a portable device without the need for frequent charging or bulky and expensive batteries. Producers of wearable technology are then tasked with creating devices that meet this demand. The use of piezoelectric components in wearable technology is a solution for this issue.

The use of piezoelectricity stands to reduce, or even eliminate, the need for frequent charging of devices and batteries. Consumers will no longer be burdened with having to be near an electrical outlet, which will in turn conserve electricity. As a result, wearable devices and more efficient batteries will have longer usable lives. This will also reduce the environmental hazards presented by the frequent disposal of batteries and electrical components into landfills.

Harvesting energy using piezoelectric ceramic involves the conversion of energy from vibrations that occur during walking, breathing, and moving on many parts of the body.



When stressed, piezoelectric components create an electrical current that can be immediately used or stored. The amount of energy produced is still relatively small and required body movements aren't often regular and predictable. Also, a large surface area is often necessary to harvest a sufficient amount of energy. This presents a challenge when thinking of the small size needed in wearable devices.



Direct and inverse piezoelectric effects.

Two promising factors in surmounting these obstacles are the versatility of piezoelectric components and the fact that the efficiency of piezoelectric energy harvesting has increased, while the power requirements for current wearable devices have been reduced.

There are four different types of materials that can be used for piezoelectric energy harvesting: ceramics, single crystals, polymers, and composites. Of these, ceramic is the preferred material for this type of energy harvesting because of its low cost, effective piezoelectric properties and easy incorporation into energy harvesting devices.

Piezoelectric vibration energy harvesting is the preferred method for use with wearable devices since it is the most capable of producing the power level needed for small-scale devices.

There are two kinds of mechanical energy that can be scavenged from the human body. The first is related to continuous activity, such as breathing and heart beating; while the other is related to discontinuous movements, such as walking and joint movements. Of these, the process of walking produces the largest amount of power compared with other body motions. It has been recorded that a 68kg man is able to generate 67W when walking at a speed of two steps per second. The easiest way to harvest this energy is through piezoelectric shoe inserts.

Body joints are also attractive locations for harvesting energy due to their high motion amplitude, fast angular velocity, large impulse force, and high frequency of use in daily human activities. For example, the knee joint produces high biomechanical energy since it generates a larger torque in comparison to other human joints. Knee joint motions are often related to gait motion, where walking and running frequencies are normally in the range of 0.5-5 Hz.

Even for relatively minor activities such as eye blinking, piezoelectric transducers have effectively been used to convert motional energy into electricity. For example, a self-powered sensor was developed for both energy harvesting and health rehabilitation monitoring, which was based on polymeric piezoelectric nano/microfibers.

Furthermore, continuous energy can be harvested from the process of human breathing. There are two kinds of energy that can be collected in this case. The first relies on scavenging energy due to the intake and release of air, which can produce approximately 1 W of power. The other relies on chest expansion, which requires a tight band fixed around the chest of the user to generate around 0.83 W when breathing normally.

Wearable Piezoelectric Applications

Piezoelectric components can be used for wearable technologies and other new technologies. Their use presents vast possibilities across many industries. Human comfort, convenience, health and safety have the potential to be greatly improved with the availability and use of products containing piezoelectric components. Many of these capabilities and products are already emerging in today’s society.

These include:

- A piezoelectric pacemaker that is powered by the rhythm of a beating heart. This eliminates the need for invasive and dangerous surgery for battery replacement
- Footpath lighting powered by footsteps striking energy-absorbing tiles

- The ability to power monitoring and sensor devices in remote and dangerous places (bridges, pipelines, etc.). This eliminates the risk to humans that arises when batteries need charging or replacing
- A vehicle driver’s seat that uses piezoelectric sensors to monitor and sense driver’s heart rate and respiration. It uses vibration sensors to allow ventilation and massage features to be automatically activated in the seat when driver stress is detected
- Wearable devices that can be charged by walking, running or other physical activity

Some wearable sensors on the market today include fitness and activity wristbands and monitors that observe distance, respiration, heart rate, and even sleep patterns. Wireless blood pressure cuffs measure patient’s blood pressure through a phone app. Quartz watches have been around for a long time and employ the natural piezoelectric property of quartz to keep precise time. Monitors that detect and measure fetal heartbeats use piezoelectric components to convert the vibration into a readable signal.

The use of “smart” fabrics is also gaining popularity. The flexible fabrics are infused with piezoelectric materials that act as sensors to measure, monitor, and harvest energy. A single pressure-sensitive layer is sandwiched between two conductive layers. These sensors are currently being developed for use as shoe insoles, clothing, and wearable devices that measure information such as pressure, steps, energy expended, etc. The amount of energy created by the fabrics differs with factors such as the type of piezo material used and the movement of the user.

Design Challenges in Wearables with Piezoelectric Technology

There are challenges facing the design and implementation of piezoelectric technology within wearable devices.

Material Choice

Textiles that have a greater elasticity perform at a greater efficiency when harvesting piezoelectric energy. The greater elasticity of the material increases the stresses occurring in the garment and, consequently, increases the elongation of piezoelectric elements. In addition, the garment must be form fitting in order to increase the clothing pressure and increase the piezoelectricity efficiency by increasing the strain exerted on the harvester on the garment. However, with this increased tightness of the garment on the user, this subsequently restricts the user’s movements and their ability to harvest energy.

Durability

Energy harvesters are required to have high environmental durability and operational reliability. However, in the case of piezoelectric energy harvesters, the material properties may change during the manufacturing process, even if the piezoelectric effect is caused by intrinsic physical properties such as the crystal structure of the material. When a strain is repeatedly applied to a material, macroscopic cracks may occur resulting in a drop in the amount of power generated. Clarifying the mechanism behind the deterioration of materials that occurs during the conversion of kinetic energy into electric energy and taking countermeasures are challenges for piezoelectric technology.

Operating Frequency

It is a well-known issue with piezoelectric energy harvesters that they do not harvest energy efficiency at varying frequencies. These devices operate at a high frequency whereas humans have an ultra-low frequency of around 1Hz. As the operating bandwidth of piezoelectric energy harvesters is quite high, this significantly limits their utility within real world applications in wearable devices. In addition, the motion range of humans is usually much higher than the predetermined device size and so resonant devices cannot render the advantage of powerful magnification. The operating excitation frequency must fall in the resonant frequency range of harvester so as to obtain the best results. Most commonly, the frequency up conversion technique is used to overcome this hurdle. Mostly, mechanical plucking mechanism by using piezoelectric bimorph was used for frequency-up conversion to power low-powered electronics. However, these devices showed some drawbacks such as reduced longevity due to direct contact between bimorph and plectra and noise. To overcome such challenges, a prototype for piezoelectric knee-joint EH by replacing mechanical plucking by the non-contact magnetic plucking device to perform the frequency-up conversion and achieve a power output. In addition, piezoelectric vibrational EHs with a flexible 3D structure fabricated by a microfabrication process can cover low frequencies and achieve a large strain.

Future Considerations and Complications for Wearable Technology in General

Before portable and wearable self-powered system can move toward large-scale practical applications, there are still many problems that should be fully addressed soon. Most wearable and portable self-powered systems are based on flexible materials, which experience device performance degradation during long-term operation. Therefore, in the future, we should study additional material and structural designs to improve the stability of the system under long term work while ensuring the wearability of the device.

Currently, portable wearable self-powered electronic devices are mainly desktop laboratory devices, which only demonstrate a concept. Since there is no work to propose a standardized manufacturing process for portable and wearable self-powered electronic devices, it is impossible to achieve complete consistency with respect to the performance of two different devices. Therefore, in the future, we need to consider the issue of performance calibration between different devices, or we can develop standardized processes for portable wearable devices that can be mass produced.

Hybrid energy harvesting technology that integrates multiple transduction methods is most likely to act as a power source for future self-powered systems. However, the large differences in the frequency, amplitude, and waveform of electrical power converted through different transduction methods make it an unsolved problem to develop power management technologies suitable for different energy harvesting methods. Furthermore, an increasing number of functional modules are being integrated into self-powered systems. We need to rationally design power management circuits to improve the energy conversion efficiency and achieve energy distribution among various functional modules. In addition, a wireless module is needed to realize the transmission of information.

Human body as a heat source for power generation

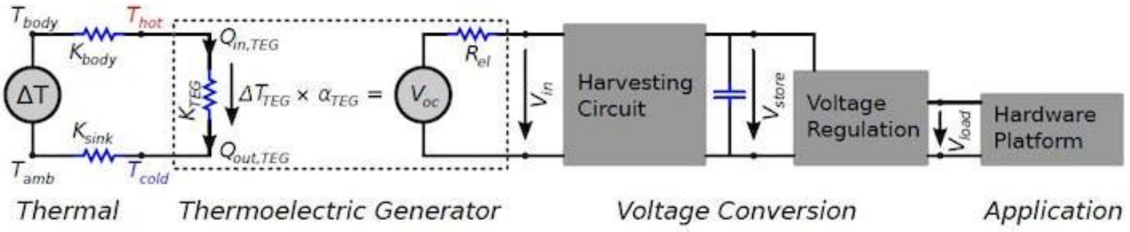
Body heat applied to a thermoelectric generator plus energy harvesting to produce power for a wearable device achieves both minimization of form factor and power consumption. nother consideration in powering wearable devices is the necessity to impose weight and size constraints, particularly if you initially choose a battery as the source of power. To limit size and weight you should use energy harvesting instead of the battery. The article points out that you can harvest energy from several environmental sources:

- Light, using photovoltaics
- Movement of the wearer
- Radio frequency energy (RF)
- Temperature differences using a thermoelectric generator (TEG)

An evaluation of these environmental sources reveals that photovoltaic or RF harvesters limit the application of zero-power wearables to environments where sufficient ambient light or RF emissions is provided to satisfy the energy budget. Movement-based harvesting systems require an active wearer and usually have unstable power generation characteristics. In contrast, the human body is a constant heat source and typically a temperature difference exists between body core and the environment.

Even in a scenario where the wearer is stationary and situated in a dark room (e.g., during sleep), energy can be produced. Lower ambient temperatures, the presence of air convection, or increased activity of the wearer can drastically increase the amount of accumulated energy. Because the voltages produced by thermal harvesting are typically too low to power wearable electronics, you must include a high-efficiency dc-dc converter into a wearable system.

Thermoelectric energy conversion of human body heat represents a promising alternative as it is largely independent of external factors. The average power harvested per square centimeter is higher using the thermal harvester than an equally sized solar cell. However, the produced voltage is used to directly charge a supercapacitor as an energy buffer and the device is only operational if the ambient temperature is lower than 25°C to 27°C. In one application a Thermoelectric Generator (TEG) on a human forehead powered a 2-channel EEG system with a power consumption of 0.8mW. You can harvest up to 30 μWcm^{-2} before dc-dc conversion (Voltage Regulation in *Fig. 1*). A two-stage custom dc-dc converter design is used to convert the voltage produced by the TEG to 2.75V. Due to the large thermal harvester, the system has limited wearability. Previous systems relied on custom designed and fabricated components, including the TEG and dc-dc circuits, to optimize the output power for a very specific application scenario. Application-specific components are necessary to obtain the power output and physical size required for a wearable sensor application. Plus, state-of-the-art thermal harvesters may be too bulky and uncomfortable to achieve true wearability.



Wearable devices have been used to monitor a variety of health and environmental measures and are now becoming increasingly popular. The performance and efficiency of flexible devices, however, pale in comparison to rigid devices, which have been superior in their ability to convert body heat into usable energy.

Hybrid power devices are combinations of different power technologies. Hybrid power plants often contain a renewable energy component such as photovoltaic (PV) that is combined with wind power, thermoelectric power, solar thermal power, or a system like battery storage or solar thermal storage. Thermoelectric generators are semiconductor devices that have no moving parts and convert heat directly into electricity. When combined with thermal storage they can provide electricity round the clock at as low as $0.06 per kilowatt-hour and could achieve 16% efficiency.

PV cells convert the UV and visible regions of the solar spectrum while the thermoelectric modules use the infrared region to produce electrical energy. Thus, combining both these systems in a hybrid system provides enhanced performance. While PV panels convert up to 20% of solar energy into electricity, the solar thermal collectors capitalise on the untapped heat energy of the PV system, thereby increasing the energy production efficiency while occupying less space

Global energy demand is likely to increase by 48% in the next 20 years due to population explosion. Currently 80% of energy needs are met by fossil fuels, which emit greenhouse gases that lead to global warming and climate change. Their negative environmental impact is leading to development of renewable energy sources like solar, geothermal, and hydro.

Photovoltaics

A photovoltaic cell is made of semiconductor materials that absorb photons of the sunlight and generate a flow of electrons. Photons are elementary particles generated by Sun that carry solar radiation at a speed of 300,000km/s. When the photons strike a semiconductor material like silicon, they release the electrons from its atoms, leaving behind a vacant space called 'hole.' The stray electrons move around looking for a hole to fill.

Generally, a PV cell is made up of two types of silicon. The silicon wafer that is exposed to the Sun is doped with atoms of phosphorus, which has one more electron than silicon. The back side of the cell is made of silicon doped with atoms of boron, which has one less electron than silicon.

The sandwich thus constructed works like a battery. The layer that has surplus electrons becomes the negative terminal (n) and the other side that has a deficit of electrons acts as the positive terminal (p). An electric field is created between the two layers at the junction.

On excitation by photons electrons are swept to the n-side by the electric field at the junction, while the holes drift to the p-side. Both the sides are provided with metallic electrical contacts to collect electrons and holes. Electrons then flow in the external circuit in the form of electrical energy. Fig. 1 shows how a PV cell works.

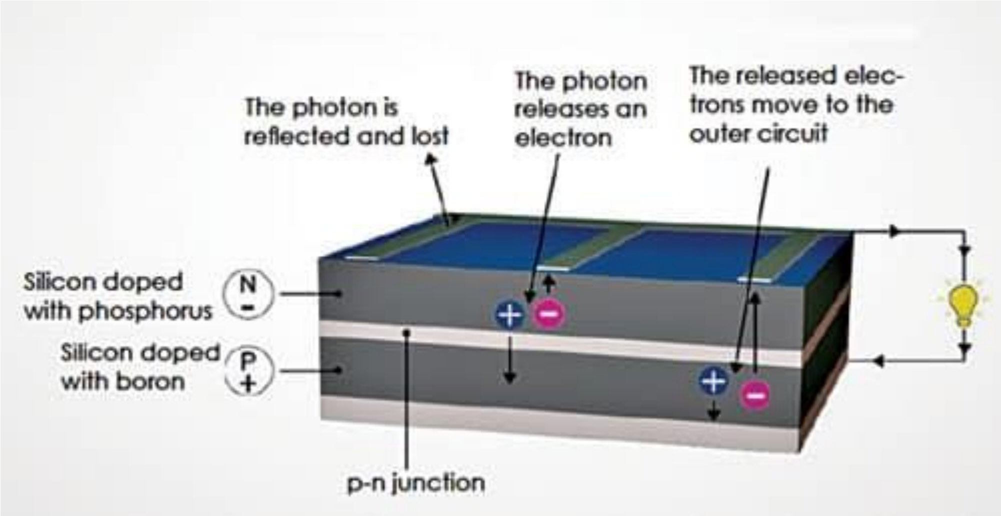


Fig. 1: **Working of a PV cell**

Thermoelectricity, as the name suggests, stands for the conversion of thermal energy (temperature difference) into electricity. It encompasses mainly two phenomena: the Seebeck effect and Peltier effect.

Seebeck effect is the phenomenon that a potential difference will appear between the two ends of a metal or semiconductor wire when they are kept at different temperatures. The potential difference is proportional to the temperature difference and the material's property known as Seebeck coefficient.

All materials are made of atoms, and atoms contain positively charged nucleus with negatively charged electrons moving around them. The electrons that are closer to the nucleus are bound more strongly, whereas the outer ones are loosely bound. When the temperature is uniform, the distribution of negative electrons is uniform and neutralises positive ions everywhere in the material, as shown in Fig. 2.

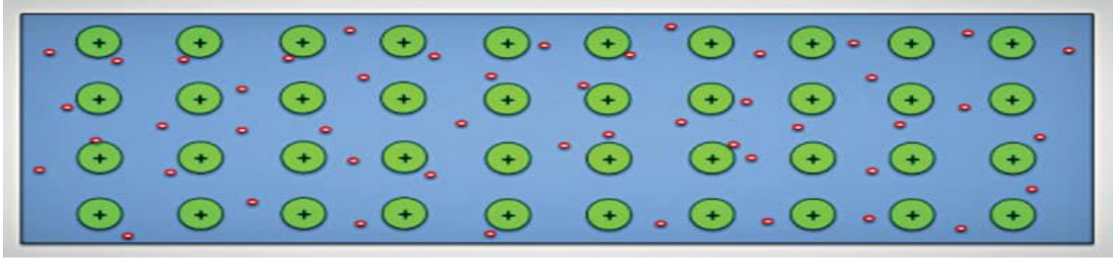


Fig. 2: Uniform distribution of neutral atoms

But when one end of the wire is heated and the other end is kept cool, electrons at the hot end gain more energy and higher speed than those at the cool end, which is indicated by the longer arrows in Fig. 3. So, at any instant more electrons move to the cold end than those moving back. So, the hot end becomes positively charged and the cold end becomes negatively charged, and current flows through the external conductor of a thermoelectric generator (TEG).

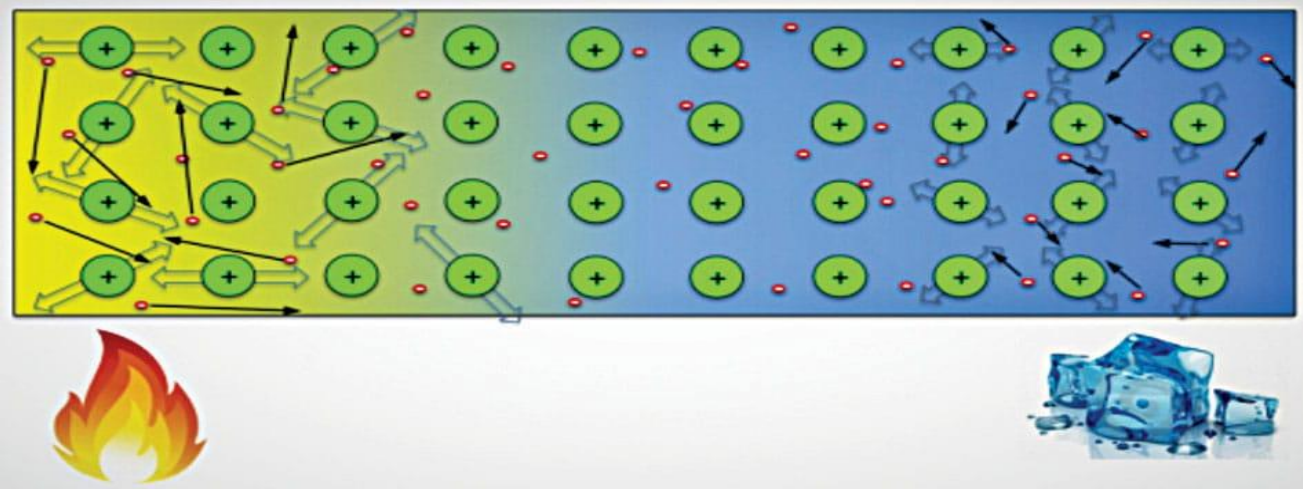


Fig. 3: Generation of potential difference due to heating in TEG

A single thermoelectric device is constructed from two solid-state devices that are usually made from bismuth telluride (Bi2Te3), as shown in Fig. 4. One of these pellets of semiconductor is doped with acceptor impurity to create a p-type component to have more positive charged carriers or holes, thus providing a positive Seebeck coefficient. The other is doped with donor impurity to produce an n-type component to have more negative charged carriers, thus providing a negative type of Seebeck coefficient. The two semiconductor components are then physically connected serially on one side, usually with a copper strip, and mounted between two ceramic outer plates that provide electric isolation and structural integrity.

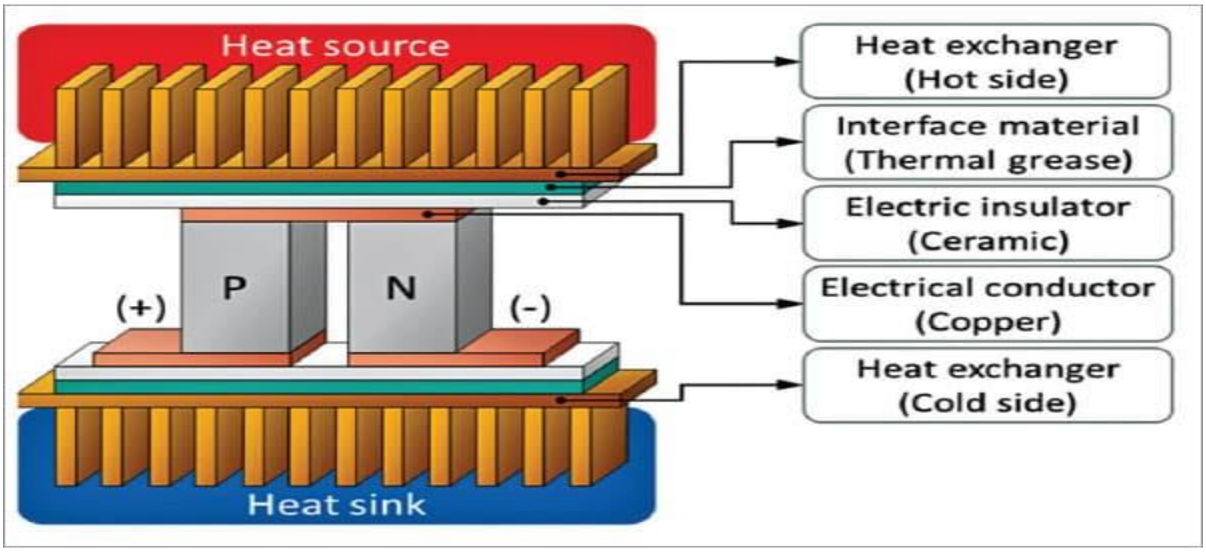


Fig. 4: Thermoelectric generator (TEG)

The Seebeck effect is a direct energy conversion of heat into a voltage potential. It occurs due to the movement of charge carriers within the semiconductor. Charge carriers diffuse away from the hot side of the semiconductor. This diffusion leads to a build-up of charge carriers at one end. This build-up of charge creates a voltage potential that is directly proportional to the temperature difference across the semiconductor.

The power generated in a TEG is single-phase DC that equals I2RL, where I is the current and RL is the load resistance. The output voltage and output power are increased either by increasing the temperature difference between the hot and cold ends or by connecting several TEGs in series, as shown in Fig. 5.

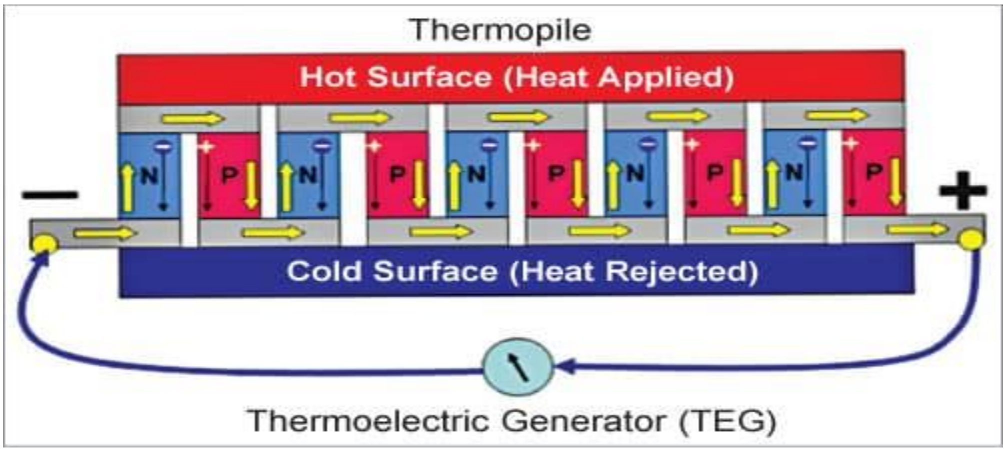


Fig. 5: Series-connected thermoelectric generator

The current flows as long as heat is applied to the hot junction. The process is reversible. If the hot and cold junctions are interchanged, the valence electrons flow in opposite direction and direction of the current changes. The thermoelectric effect allows converting waste heat into electric power.

By combining thermoelectric and PV effects, higher solar electricity conversion efficiency is possible. PV absorbs about 58% of solar energy between 200nm and 800nm wavelengths. The rest of the solar energy from 800nm to 2500nm cannot be converted to electricity by PV. But this spectrum of solar radiation can generate electricity through thermoelectric effect by heating TEG.

Thermoelectric figure-of-merit

The performance of thermoelectric materials is defined by unitless figure-of-merit as given below:

$ZT=\sigma S^2T/k$

where ZT is the thermoelectric figure-of-merit while σ, S, k, and T are electrical conductivity, the Seebeck coefficient, the thermal conductivity, and the absolute temperature, respectively.

The Seebeck coefficient of a material is the induced thermoelectric voltage per Kelvin generated in response to a temperature difference across the material, as induced by the Seebeck effect. It is often given in microvolts per Kelvin. The Seebeck coefficient depends on factors like temperature, work functions of the two TE materials, electron densities of the two components, and scattering mechanism with each solid. Performance of a TEG is determined by the Seebeck coefficient of the pair of materials forming the TEG.

Peltier Effect

In a circuit, when DC current flows through two dissimilar material, say copper and bismuth, the junction where the current passes from copper to bismuth would be hot and the junction where current passes from bismuth to copper would be cold. This effect, known as Peltier effect, is used to build devices like Peltier heater, solid-state refrigerator, and heat pump.

A good thermoelectric material should have following qualities:

1. Its Seebeck coefficient should be as high as possible. It is important to maximise energy conversion. The open circuit voltage generated by a TEG is proportional to the Seebeck coefficient and temperature difference across the TEG. Hence high Seebeck coefficient leads to a high voltage.
2. To minimise thermal loss through the thermoelectric material and to have large temperature difference across the TEG, thermal conductivity of the TE material should be as low as possible.
3. Its electrical conductivity should be as high as possible for reducing internal Joule heating losses of the thermoelectric elements.

A TEG’s efficiency depends very much on the operating temperature difference between the junctions. The bigger the temperature difference, the more efficient the TEG.

There are **three main types of thermoelectric materials** used in thermoelectric generators:

1. **Bismuth telluride (Bi2Te3) alloy:** It is a semiconductor that has high electrical conductivity but is not good at transferring heat. The best working temperature of this class of material is below 450°C. Bismuth telluride materials with high figure of merit (ZT) and TEG modules, as shown in Fig. 6, have high conversion efficiency of more than 8% over temperatures of 25°C to 250°C and are widely utilised in energy generation and refrigeration.

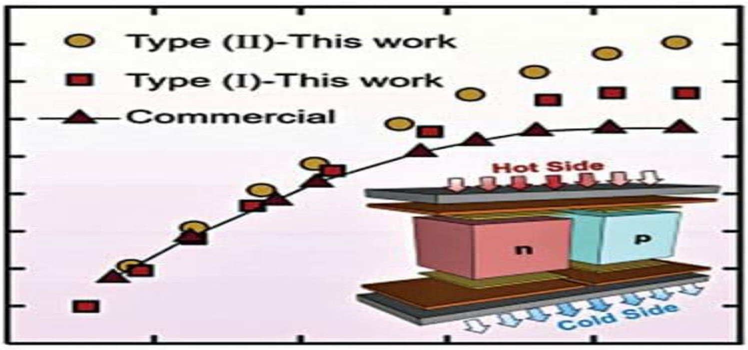
   

   Fig. 6: Conversion efficiency of improved BiTe material

   With improved techniques, p-type BiTe TE material that has average ZT of 1.08 and n-type BiTe with 0.84 ZT has been made. The significant enhancement in ZT could be achieved through compositional and defect engineering.

   Type I module is constructed using p-type Bi0.5Sb1.5Te3 and n-type using Bi2Te2.7Se0.3S0.01. Type II material is constructed from p-type Bi0.4Sb1.6Te3 and n-type Bi2Te2.7Se0.3S0.01Cu0.01 materials. Fig. 7 and Fig. 8 show the Seebeck coefficient and figure of merit of these two types of improved BiTe materials, respectively.

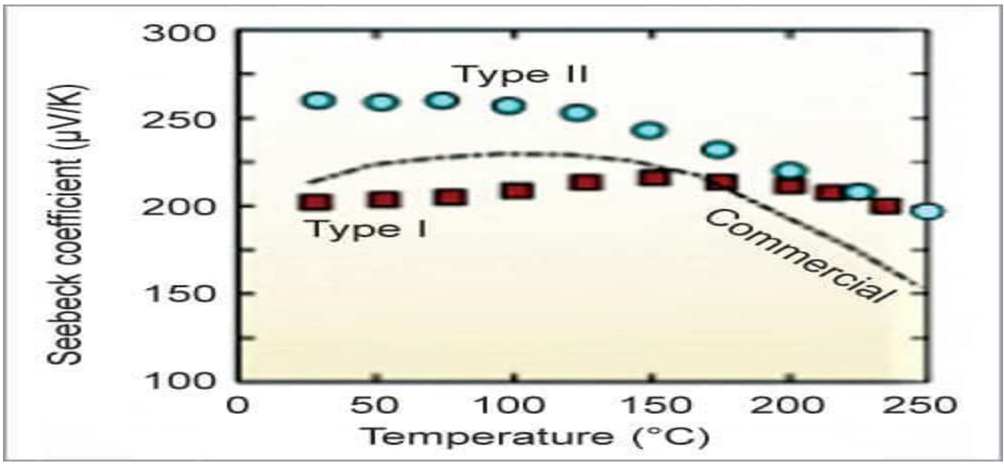


Fig. 7: Seebeck coefficient of improved Type I and Type II BiTe material

2. **Lead telluride (PbTe) alloy:** Low conversion efficiency is a big obstacle that impedes large scale application of TE materials for power generation. Lead telluride alloy is recognised as an excellent compound for power generation in the mid temperature range of 500-800°K. It has highly symmetric rock salt crystal structure, which is chemically and thermally stable. Lead telluride can be made either a p-type or n-type semiconductor.

   Recently researchers have enhanced the ZT of a sintered material to 1.8 (600°C) using a nanostructure forming technology. Further, an electrode material has been developed that contacts very well electrically and thermally with PbTe containing MgTe nanostructures, achieving a conversion efficiency of about 11% with hot side at 600°C and the cold side at 10°C.

   This breakthrough has made the way to convert waste heat and solar thermal power to large scale practical application. Because the nanostructures formed in the PbTe sintered material effectively scatter heat carrying phonons, but have no effect on the charge carrier transport, there is dramatic improvement in the ZT.

3. **Silicon-germanium alloy:** It is a kind of semiconductor that is often used for thermoelectricity generation with a working temperature around 1300°C. Combining Si and Ge allows to retain high electrical conductivity of both components and reduce the thermal conductivity due to the increased phonon scattering as Si and Ge have different lattice properties. Due to this reason Si-Ge alloys are currently the best TE material for high temperature application.

Conventional Si-Ge materials have ZT values of 0.9 and 0.5 at 1200K for n-type and p-type materials, respectively. By adopting nanocomposite approach reducing the grain size to around 5nm, ZT values can be increased by a factor of two and conversion efficiency can also be increased considerably. Ge is a scarce material and hence this alloy is costly. However, using only 5% of Ge it is possible to have Si-Ge alloy with improved performance.

The advantage of the newly developed nanocomposites is that its ZT values consistently remain above 1 over high temperature range between 600°C and 1000°C. Hence, these are the best TE materials for high temperature application for power generation by solar radiation, radioisotope devices, and waste heat recovery system. Table 2 shows the ZT values of bulk and improved nanostructured Si-Ge TE materials.

A thermoelectric device with a ZT of 1.25 will have an efficiency of about 10%. A segmented Si-Ge TE device over temperature range of 300K to 1300K will have an efficiency of about 12.1%.

Block diagram of a typical thermoelctric power harvesting system

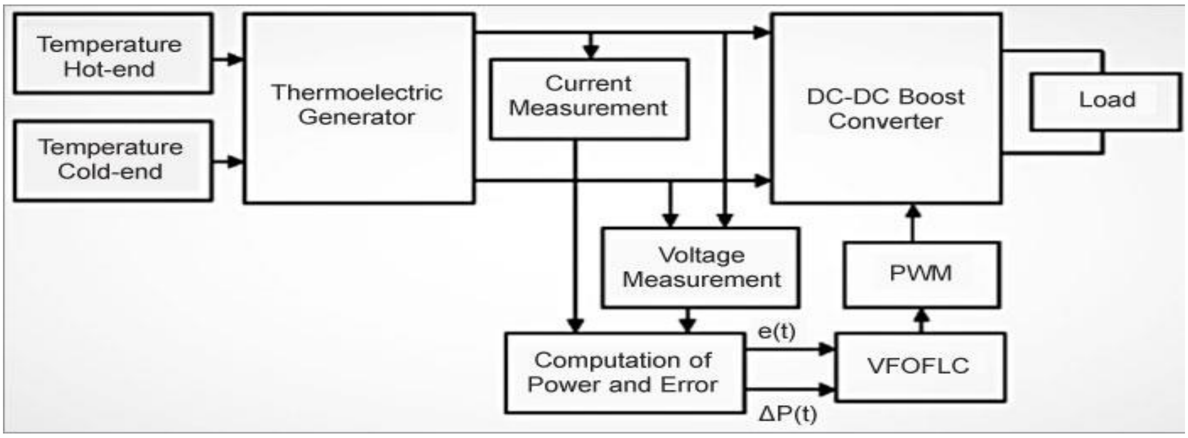


Fig. 10: Block diagram of thermoelectric power harvesting system

A thermoelectric power generation system has low energy conversion efficiency. According to the principle of maximum power transfer, the system would transfer the maximum power when the load resistance is equal to the internal resistance of the TEG. Based on this principle, several maximum power point tracking (MPPT) algorithms may be selected with different control logic to harvest the maximum power from the TEG. If a TEG is connected directly to the load, the load impedance will set the operating point which might result in the TEG output being less than the maximum output power.

The MPPT technique is considered an efficient mechanism to improve the performance of TEG by increasing the conversion efficiency. In this system, the operating point of the TEG is moved promptly towards an optimal point to increase energy harvesting by using a variable fractional order fuzzy logic controller (VFOFLC) based MPPT technique. The variable tracking step size is applied using a dynamic variable fractional factor whose value is calculated based on the voltage output of the TEG. The fraction order term introduced in the MPPT algorithm would contract or expand the input domain of the fuzzy logic controller to shorten the tracking time and maintain a steady-state output around the maximum power point.

Optimization of the TEG

It has been found that the output power is correlated with the geometry of the device. By changing the leg height and the number of thermoelectric pellets to an optimum value it is possible to maximise electric power or efficiency at given operating conditions. There is interdependence between optimal leg geometry and the electrical load resistance.

If number of legs is low, the energy conversion is low, because the load resistance (RL) is not sufficient to obtain an adequate high voltage and vice versa. A reduction of the leg length leads to a reduction of the electrical resistance, and an increase of the leg length leads to the higher temperature difference across the TEG. If the geometric parameters like leg length, number of semiconductor pellets, the base area ratio of the semiconductor columns are optimised, the output power and thermal efficiency are considerably improved.

The shape of the legs of TEG devices has considerable effect on the device performance. The conventional rectangular leg shape found in commercial TEGs is not the optimal shape for heat-to-power energy conversion. The hourglass shaped TE legs result in more than double the electrical potential and maximum power compared to conventional rectangular shape. The trapezoid leg with the largest cross-sectional area at the hot side results in about double the electrical potential and a 50% increase in the power output compared to the conventional rectangular shape. The electrical output power values, if optimised, can be 890% higher than a random value without optimisation.

Heat sink is required at the TEG when a high heat flow rate is applied on the hot side of the TEG. In order to have quick heat dissipation at the cold side cooling radiators are provided there, so that bigger temperature difference across the TEG can be obtained. The fins attached to the heat sinks are very important for enhancing the heat transfer at the hot and cold sides. The heat transfer increases when the number of fins are increased and the fin height is more, due to more heat transfer area. However, increase of heat transfer area is limited to an optimum value beyond which the change in the output electrical power becomes less significant.

The thermal resistance of the heat sink (Rhs) is:

Rhs=(Theat sink - Tamb)/Qh

where, Theat sink is the sink temperature, Tamb is the environmental temperature, and Qh is the heat flow. Experimental results show that increasing the thermal resistance of both cold and hot side heat sinks by 10% improves the electrical output power by 8%.

Aerogel

Aerogels are a class of synthetic porous materials derived from a gel, in which the liquid component has been replaced with a gas without collapsing the gel structure by freeze-drying. It can be made from silica, carbon, iron oxide, gold, copper, polymer, etc.

The final product is extremely porous (80-98% porosity) with very little solid material; up to 99.8% of the aerogel may have nothing but air. It has a typical density of about 0.001gm cm–3. Its thermal conductivity is extremely low, about 0.017W/mK, which makes the material an ideal insulator. It can be made transparent.

By reducing heat losses and simultaneously being transparent, aerogels allow a solar plant to operate at higher temperature and at higher efficiency without using any vacuum device. These advantages make an aerogel assisted solar thermal plant very economical and eliminates lot of maintenance problems.

Concentrated high-efficiency Solar Thermoelectric Generator

A solar thermoelectric generator (STEG) is a solid-state device that can convert solar energy at around 15% efficiency.

It has three sections: solar absorber, thermoelectric generator, and the thermal management system comprising insulation, heat exchangers, and vacuum/aerogel enclosure, etc.

There are no moving parts and there is no need of high-temperature operating fluids. Its robustness in harsh temperatures makes it very useful for standalone power conversion or making hybrid solar thermal power generator in conjunction with a PV system.

The efficiency of STEG depends on both the efficiency of solar absorber and on the thermoelectric efficiency of the device. There are mainly two approaches to increase the efficiency of STEG devices: increasing temperature difference between the hot and cold ends and using improved materials with ZT more than 1. Recently, several nanostructured materials have been developed that have higher ZT values suitable for STEG.

There are two routes to increase the temperature difference in a STEG: first, optical concentration of sunlight enabling to increase the heat flux at the absorber surface, and second by providing thermal concentration where the area of a highly thermally conducting absorber is greater than area of the thermoelectric legs increasing the heat flux through the legs.

It is possible to construct a durable STEG device with more than 15% efficiency using improved material consisting of a segmented n-type leg composed of skutterudite and La1Te4 and p-type leg of skutterudite and Yb14MnSb11, and also using nanostructured Bi2Sb3 based alloys (all these three types have an effective ZT of about 1.4 to 1.6 at 800K).

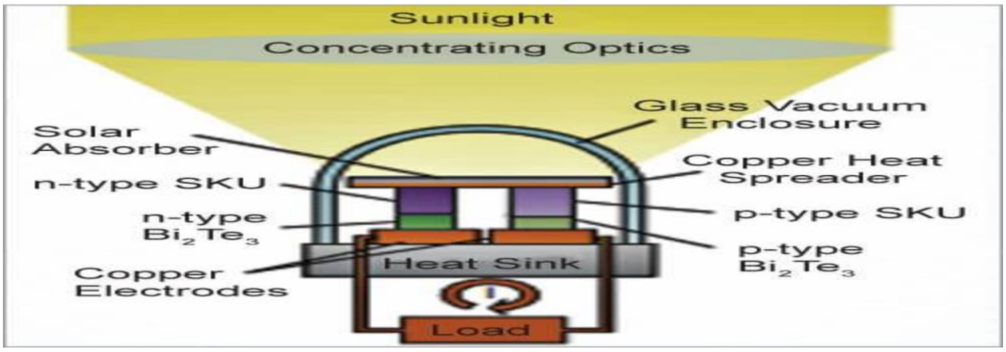


Fig. 11: Schematic arrangement of concentrated STEG system

Operating temperatures across Thot-Tcold=900°C–200°C are maintained using fresnel lens to concentrate sunlight. In order to reduce heat losses from the solar collector a vacuum system is provided, which is costly. Skutterudite is a type of arsenide mineral having general formula as TPn3, where T is a transition metal like Co, Rh, or Ir, and Pn is Sb, As, or P. Typical arrangement of STEG system is shown in Fig. 11 and Fig. 12.

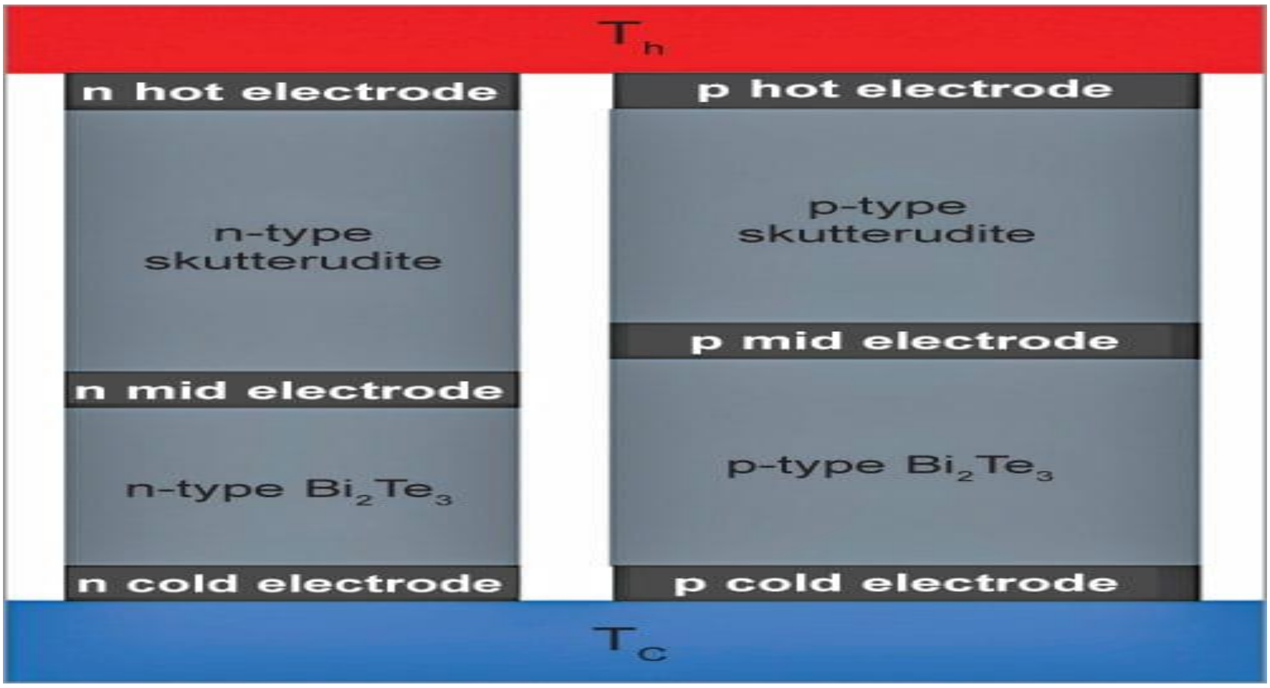


Fig. 12: Arrangement of composite segmented thermoelectric LEG

Another excellent way to reduce heat losses is by using high-temperature transparent aerogels for insulation instead of vacuum system, as shown in Fig. 13.

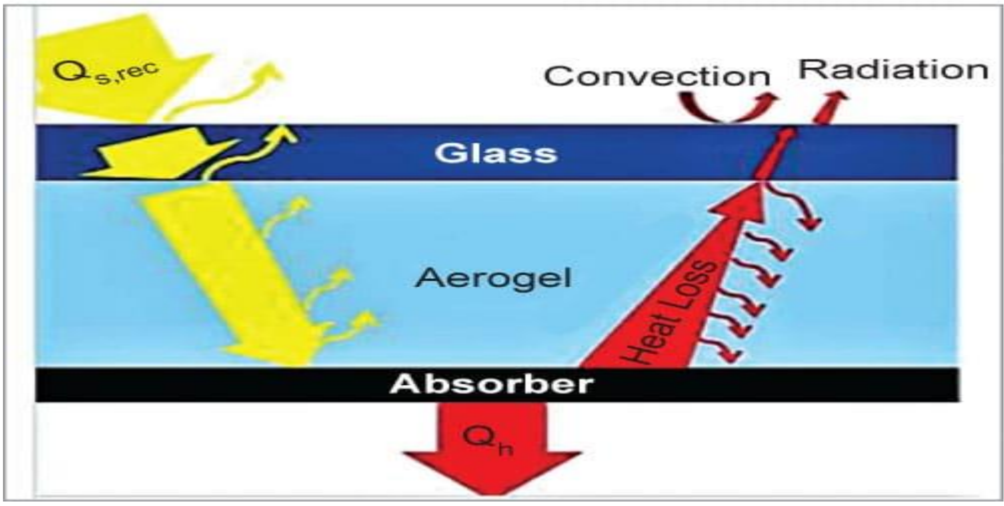


Fig. 13: Transparent aerogel for insulating STEG

Aerogel, being transparent but an excellent insulator, allows sunlight to enter but blocks the heat from escaping from the receiver of the STEG. It offers many advantages like higher efficiency, minimises heat loss, boosts solar thermal conversion, eliminates costly vacuum system and its maintenance cost. Due to efficient thermal transport system provided by aerogels, most of the solar radiation is absorbed by the cermet composite pad attached to the thermoelectric elements.

It is desirable to thermally insulate the TE legs to suppress lateral heat leaks that degrade thermal efficiency. Encapsulation of thermoelectric legs with aerogels prolongs the life of TE devices.

The primary cause of deterioration of most thermoelectric materials is thermal decomposition or sublimation at high operating temperatures. For example, aerogel present near the surface of skutterudite material, such as CoSb3, prevents transport of Sb vapour by establishing a highly localised equilibrium Sb-vapour atmosphere at the surface of skutterudite.

Some solar absorbers are painted with black paint to increase the heat absorption and are fabricated from metal dielectric multilayer cermet composites that are capable of withstanding more than 950°C.

Photovoltaic/thermoelectric Hybrid System

Solar light and its thermal energy can provide sufficient electricity to meet the global energy demand. The range of wavelengths that photovoltaic materials generally use to convert into electricity is between 400nm and 1200nm, the ultra-violet (UV) and visible range. Excess solar radiation is wasted as heat, which decreases the efficiency of PV cells and lowers their life.

TEGs are bidirectional devices that act as heat engines, converting the excess heat into electricity through the thermoelectric effect. Thermoelectric devices utilise the IR region of sunlight to generate electricity and reduce the amount of heat that PV cells dissipate. It is possible to combine PV cells and TEGs to make a hybrid system that can generate more energy. The overall power output of this system would be the sum of the power output from the PV module and the TEG.

The hybrid systems generally follow two configurations—with or without reflective components.

With reflective arrangement the spectral splitting method splits the solar spectrum into two bands. The spectrum below the 800nm cut-off wavelength gets transmitted to the PV module and above 800nm to the TEG. This system has a reflective component called wavelength segregator or prism, where the PV module and the TEG are installed perpendicular to each other. When sunlight passes through the prism, a part of the sunlight is reflected at cut-off wavelength of approximately 800nm and is absorbed by the solar cell. The radiation that is longer than the cut-off wavelength—above 800nm—is reflected to the TEG, as shown in Fig. 14.

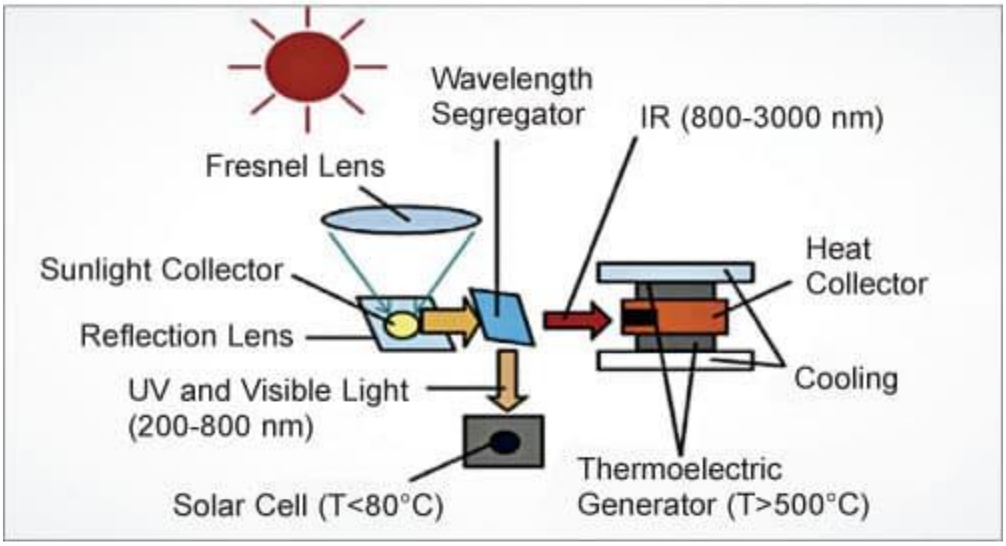


Fig. 14: Arrangement of hybrid pv/teg system using spectral splitting

The PV module and the TEG convert solar energy into electricity independently. A cooling system is installed on the TEG to maintain the temperature difference. A concentrator increases the light intensity and hence PV modules of reduced surface area can be installed, which results in a reduced installation and maintenance cost. The spectrum splitter allows for low operating temperature and hence maximising the conversion efficiency.

Thermoelectric legs have different values of ZT at different temperatures. Hence the TE material selected depends on the operating temperature. Generally, bismuth telluride is used under 500K, lead telluride between 500-900K, and germanium silicon above 900K operating temperatures.

In configurations without reflective component the PV module is placed as upper component and TEG device as lower component, as shown in Fig. 15. When sunlight falls on it, the PV device absorbs the UV and visible light and rest of the solar spectrum passes through the PV module to the underlying TEG. The IR radiation heats up the TEG top side creating a temperature difference with the cold side. The solar module is coated with tedlar PVF film that offers the best protection against UV, thermal, moisture, chemical and mechanical stress.
Combination of PV and TE generators can make a very efficient device for solar energy utilisation. A PV/TE hybrid system with high concentration ratio and using multijunction PV and Bi2Te3 thermoelectric legs has conversion efficiency of about 32%. The direct electrical contribution of the TEG to the hybrid system's efficiency is enhanced by increasing the Sun's concentration by about 300 times. Even higher efficiency and power values can be achieved by using more advanced PV devices and improved TE materials, with a potential to reach 50% total efficiency.

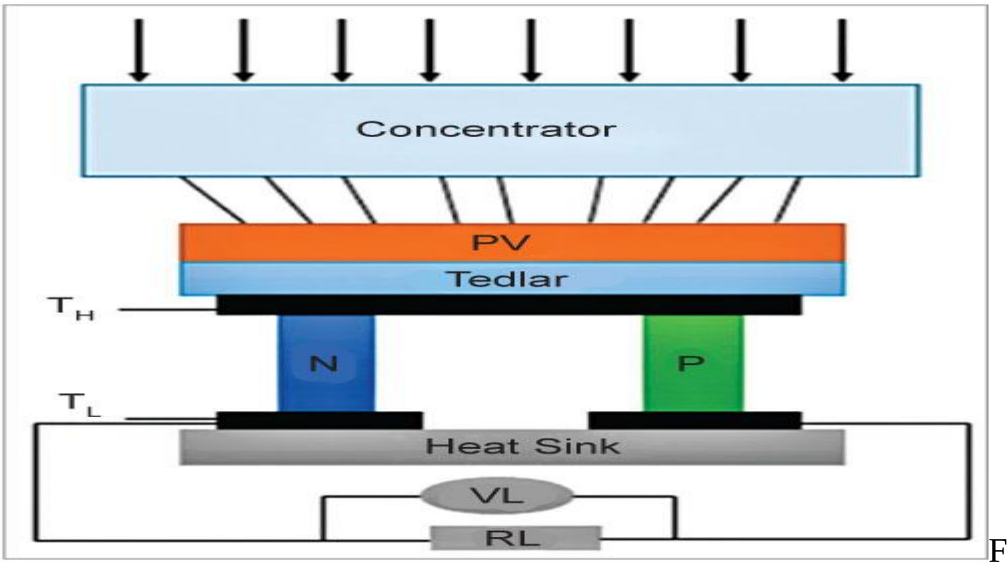


Fig. 15: Hybrid PV/TEG system without reflective component

Hybrid PV and Solar Thermal System

A technique that combines PV and solar thermal systems to efficiently convert solar radiation to electricity for immediate use and store the remaining inexpensive thermal energy (not utilised by PV) to convert to electricity on demand has been developed recently. It is called hybrid electric and thermal solar (HEATS) system. The prototype performs at 26.8% (with a potential to achieve 35.2%) solar to electricity efficiency and 81% dispatchability of electrical energy from thermal energy at an operating temperature of 775K using silicon PV cell (gallium arsenide PV cell can also be used).

HEATS contains a PV module as well as a thermal absorber to utilise the best of both. In this system photons in the PV band are directed to the PV cells whereas these are most efficiently converted into electricity. Low-energy photons (long wavelengths) that cannot be converted by PV cells and high-energy photons (short wavelengths), which would be converted inefficiently, are directed to the thermal absorber instead of being wasted.

This technique improves overall system efficiency and provides additional thermal energy, which can be stored at low cost to be used for electricity generation or for heating on demand. Dispatchability is the ratio of electricity generated from heat engine and total electricity generated by both heat engine and the PV modules. The arrangement of HEATS is shown in Fig. 16.

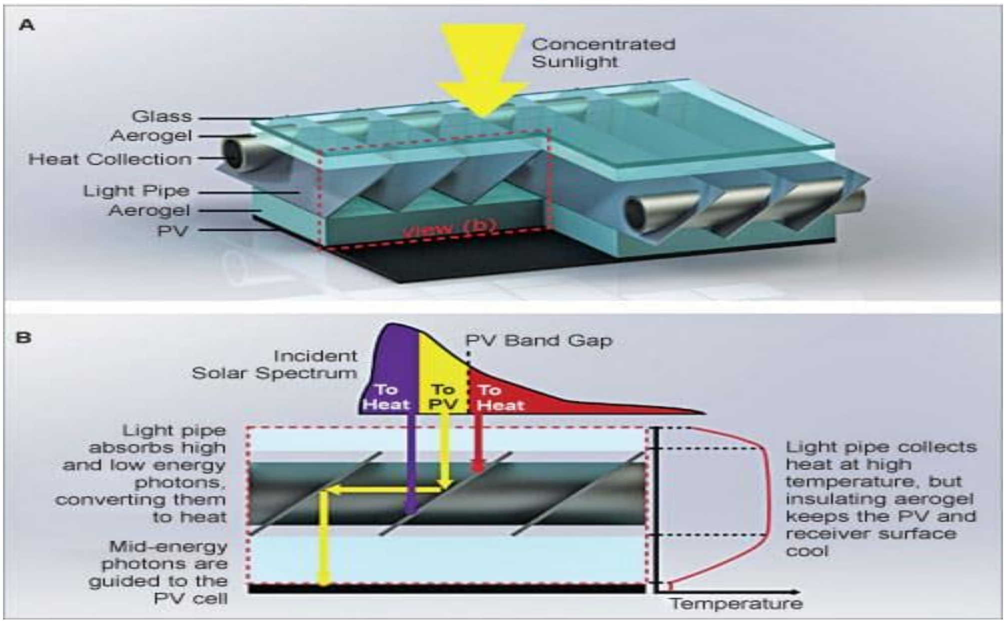


Fig. 16: Hybrid PV and solar thermal system

Fig. 16(A) shows the receiver concept with a cutaway section to show its internal structure. The HEATS receiver is used in conjunction with a solar concentrator, like a parabolic trough or a linear Fresnel reflector, to increase the intensity of solar radiation. The stacked structure consists of a glass protective cover, a thermally insulating transparent aerogel layer, the spectrally selective light pipe (SSLP), followed by another insulating transparent aerogel layer, and finally the PV module.

The SSLP structure consists of a series of parallel fins attached to the heat collection pipes carrying a heat transfer fluid like Therminol VP-1, which collects the thermal energy absorbed by the SSLP. The SSLP structure is formed from parallel fins made of a thermally conductive copper sheet substrate coated with a spectrally selective material in multilayers.

The SSLP absorbs high and low energy photons as thermal energy, while directing the mid energy photons to the PV module down below as shown in Fig. 16(B). Transparnt aerogel on either side allows the light to pass through but does not allow the heat to escape as it is an excellent insulator.

The aerogel layers serve to thermally insulate the SSLP from the PV module to keep the latter cool. It ensures that the SSLP can be operated at a high temperature without heat loss while the PV module and the glass cover remain at a safe low operating temperature. The transparent silica aerogels used have high solar transmittance of about 96% and low thermal conductivity of about 0.055W/m/K. As aerogels are not very strong, it is ensured that no load is transferred to it.

The advantages of hybrid PV-thermal system are mainly: (a) both solar thermal and PV cells can be housed in the same module and operated simultaneously, (b) the solar energy that would have been lost otherwise, if single PV module was used, can be recuperated usefully, and (c) the amount of energy that is generated per unit area by this tandem system is more and the payback period is less due to more energy extraction.