THERMAL ENERGY HARVESTING FOR WIRELESS SENSOR NODES WITH CASE STUDIES

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ABSTRACT

Over the last decade, wireless computing and mobile devices have decreased in size and power requirements. These devices traditionally had significant power requirements that necessitated the use of batteries as their power source. However, as the power requirements are reducing, with wireless sensor nodes rarely exceeding 75mW, alternative means of power provision become available. One of these alternatives is the use of thermal energy harvesting from waste heat or environmental sources. This report discusses the field of thermal energy harvesting, with a particular focus on those thermal technologies that provide direct electricity as output. There are a number of technologies in this field. The general technologies discussed in this report are thermoelectric devices, such as devices utilising the Seebeck effect, thermocouples and, thermionics. Sources of thermal energy discussed include solar, the human body, vehicle exhaust systems and subsurface heating. Solar has an obvious advantage of being a very large source of energy. Cases studies are presented to show magnitudes and the daily variation of power output from Seebeck style thermoelectric devices. Overall, this report reveals that while present thermal energy harvesting technologies suffer from very low efficiencies, there are a number of promising technologies that are increasing in reliability and efficiency. This, along with a continuing decrease in power requirements on the demand side of the equation, marks thermal energy harvesting as a very promising field of research.

1. INTRODUCTION

A modern wireless sensor network consists of individual sensor nodes which measure various environmental variables. These variables depend on the application and can range from simple physical parameters, such as temperature or humidity, to more abstract parameters like indications of local flora and fauna through the distinctive sounds of a frog or the location of a cow in a particular paddock. This information can be stored as data at the node or relayed through the network, using wireless communications, for access by the user.

Recent advancements made in the miniaturisation of electronics have sparked a growing interest into the vast possibilities and applications of wireless sensor networks. This reduction of size, energy consumption and cost of the wireless sensor node components i.e. sensors, circuits, wireless communication; has made the vision of autonomous sensor networks deployed throughout the environment, a near reality. However, battery technology has been unable to keep pace with the exponential miniaturisation of electronics.

Battery life becomes the limitation in network deployment and the greater the potential for network deployment, the greater the liability for battery replacement. Thus alternative means to satisfy the sensor node's energy requirements are being actively explored [1]. One area which may prove useful in providing alternative energy supplies is to exploit a local temperature difference to generate power at the node.

A temperature difference existing between two locations will result in a flow of heat energy from hot to cold in an attempt to develop thermal equilibrium. The heat flow can be exploited to harness useful energy. This process is governed by the laws of thermodynamics therefore its efficiency, the ratio of the useful work extracted out, W, to the input heat, Q, is constrained by the fundamental Carnot efficiency. The Carnot efficiency applies to all heat engines and generators and can be expressed in terms of the hot, T_H, and cold, T_C, temperatures as [2].

$$\eta = \frac{W}{Q} = \frac{T_H - T_C}{T_H} \tag{1}$$

This shows that the efficiency is very low for small to modest temperature differences. As an example, a heat source, 5K above room temperature (298K), could be used to harness energy with an efficiency of 1.7%. Even if that heat source was increased to 373K the maximum efficiency would only be 25%. The Carnot efficiency is the limit or maximum theoretical efficiency; real world conversion devices however do not achieve efficiencies as high as this. As will be shown in later sections current commercial devices operate below 40% of the Carnot efficiency.

The low efficiencies of this process necessitate a large amount of heat to be transferred in order for a device to harvest useful amounts of work. The transfer of heat can occur in three different ways; via conduction, convection and/or radiation. Roundy *et al* [3] derives an analysis to demonstrate the power levels achievable from temperature gradients by assuming heat conduction through a material. At small scales and temperature differentials convection and radiation would be negligible compared to conduction and as such the amount of heat flow can be given by;

$$q = k\frac{\Delta T}{L} \tag{2}$$

Where q is the heat, k is the thermal conductivity of the material, ΔT is the temperature difference and L is the length of the material.

Although thermal power harvesting, across large temperature differentials spanning hundreds of degrees Kelvin, has been available for many years, the focus of this study are those technologies which are able to utilise the smaller ambient temperature differences available at the site of a sensor node. These temperature differences exist in many everyday situations, such as between an animal body and surrounding air, or between soil and air, and are often in the range of one to tens of degrees Kelvin.

2. CONVERSION METHODS AND TECHNOLOGIES

There are many types of heat engines designed to extract useful work from sources of heat, examples of which range from thermally powered wrist watches, the internal combustion engine in a car to nuclear power plants. These engines can be broadly classified into two categories; mechanical and solid state. For the wireless sensor node application of harvesting tiny amounts of power from small ambient temperature gradients, solid state devices offer the best potential as they lack moving parts thus are robust and require low maintenance. In fact, life testing of thermoelectric devices has shown their capability for over 100,000 hours of continuous operation [4]. They are compact and light, noiseless in operation, are highly reliable and eliminate power losses in extra conversion steps needed for mechanical engines. An overview of the different solid state thermal energy harvesting techniques currently available is given

2.1 Thermoelectric

Thermoelectricity is by far the dominant solid state conversion technique so a more in depth description will be given for it over other techniques. It involves the direct conversion of heat into electricity and was discovered by Thomas John Seebeck in 1821 when he found that current would flow through two different metals joined in a loop while their ends were held at different temperatures. This phenomenon is now known as the Seebeck effect; a thermoelectric EMF will be produced across two different metals or semiconductors in the presence of a temperature difference.

Modern thermoelectric devices use n and p type bismuth telluride semiconductors instead of two different metals. Their operation can be seen in Figure 1. The two semiconductors are connected electrically in series and thermally in parallel with one end exposed to a heat source and the other to a cooler side in a configuration known as a thermocouple. The temperature difference is conducted through the two carriers, one an n-type material and the other a p-type material. A voltage difference is generated by this temperature difference at the base of the electrodes. The charge carriers in the n-type material have a negative charge producing a current from the cold to hot side whereas the carriers in the p-type material have a positive charge producing a current from the hot to cold side, with the total result of a current flowing anti-clockwise around the circuit shown.

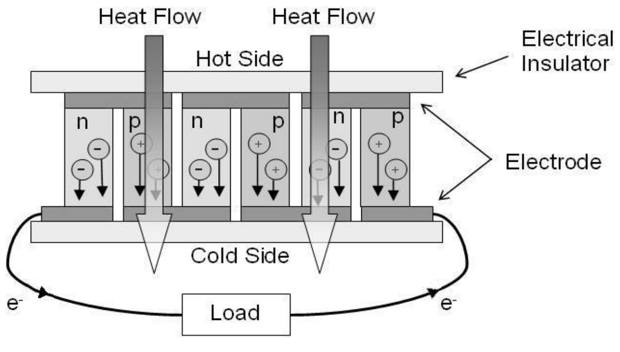

Figure 1. Thermoelectric module concept [1].

The voltage produced across a thermoelectric device is proportional to the temperature difference across it and to the difference between the Seebeck coefficients, $S_1(T)$ and $S_2(T)$, of the two materials. The p and n type semiconductors have a positive and negative Seebeck coefficient respectively. As the Seebeck coefficients are functions of temperature, the value of the voltage across a thermocouple exposed to a temperature difference, T_H - T_L, can be found from the integral in equation 3. This voltage is generally quite small so many thermocouples are usually connected in series to form a 'thermopile' in order to achieve useable voltages. The power harvested by a thermocouple, or thermopile, is proportional to the square of the voltage and therefore the temperature difference.

$$V = \int_{T_L}^{T_H} (S_1(T) - S_2(T))dT \quad (3)$$

Ferrari *et al* [5] investigated using a thermoelectric generator to power a wireless sensor node. The paper presents the characterization of three different commercial thermoelectric modules designed for heating/cooling applications. Their analysis included the effects of electrical load resistance, thermal conductivities of the thermoelectric and heat exchanger modules and different temperature gradients. They found that thermoelectrics could be used for their application of powering a wireless sensor node consuming 32mW, when the temperature difference exceeded 30K.

The efficiencies of thermoelectric generators have remained low and unchanged for the past 50 years. The reason for this is that in order to exploit a temperature gradient the thermoelectric device must be a good electrical conductor to allow the flow of charge but be a thermal insulator to maintain the temperature difference. This is contrary to most conventional materials as good electrical conductors are also good thermal conductors therefore a large portion of energy is transferred across the device as heat and not as electrical energy. The dimensionless thermoelectric figure of merit, ZT, is a measure of this ability and is roughly proportional to the device's efficiency[6]. ZT is given by equation 4, where σ is the electrical conductivity, λ is the thermal conductivity and S is the Seebeck coefficient. It has remained around the value of 1 for more than 50 years however modern research into thermoelectric materials is improving this by a factor of over 2 [7].

$$ZT = \frac{\sigma S^2}{\lambda}\left(\frac{T_H - T_L}{2}\right) \quad (4)$$

Improving this ZT value is crucial for the widespread implementation of thermoelectric converters as typical commercial converters currently operate at efficiencies of less than 6%.

2.1.1 Thermoelectric materials and figures of merit ZT

A whole field has evolved to improve the ZT value for thermoelectric devices involving research into nanoscale thermoelectric materials. Venkatasubramanian *et al* have quoted an improvement of ZT to a value of 2.4 by using Bi2Te3/Sb2Te3 super lattice devices which control the transport of heat carrying phonons and charge carrying electrons in the super lattice [7]. Through the fine-tuning of carrier levels they have updated this ZT value to greater than 3.5 in more recent work [8]. Joint research efforts between MIT and Boston college has increased the efficiency of bismuth antimony telluride thermoelectric devices to a ZT value of 1.4 by crushing it into a powder consisting of an average particle size 20 nanometers then sintering it into bars or disks at high temperatures. These new bars have a much finer crystalline lattice structure than the original material which consisted of millimetre size grains [9]. Many other approaches and materials are currently being investigated with more improvements to the ZT value expected in coming years.

2.2 Thermionic and Thermo-tunnelling

Another type of solid state heat engine which has been around for decades is that based on thermionic conversion. A thermionic converter is a system in which electrons are ejected via thermionic emission from a hot electrode over a potential barrier to a cooler electrode. The barrier the electrons must overcome is known as the work function of the material and is essentially the heat of vaporization of the electrons from the surface. Due to this the thermionic conversion works best with large temperature differentials. Although thermionic conversion has better efficiencies than thermoelectric devices, its reliance on high temperatures would make it unsuitable for most wireless sensor applications.

A method similar to thermionic conversion is thermo-tunnelling which narrows the potential barrier using properties of quantum physics known as quantum tunnelling. This technology seems plausible to use for small temperature gradients for lower power applications [10]. In order for this effect to be useable at the much lower temperatures envisaged for sensor networks the two surfaces need to be held at very close separations – nanometres – over large areas, with no part actually touching thus causing an electrical short circuit. Methods that allow manufacturing of this gap are being researched. One current method is to electro deposit layers of two metals such as silver and titanium. The newly created material is then thermally shocked so it breaks at the interface. This leaves an atomically rough surface that fits together very well. The gap is then adjusted using piezo devices [30].

2.3 Power Management Systems

The voltage and power output from a thermal energy harvesting device is dependent on the temperature difference across it. As this temperature difference fluctuates so too does the voltage and power output. The sensor node electronics require power at specific voltage levels with varying current and duty cycles depending on the task. The mismatch between the output power from the harvesting device and the input power required by the electronics necessitates power management systems.

A power management system interfaces the irregular output from the energy harvester to a robust source usable by the electronics. It generally does this in three stages; input power conversion, energy storage and then output power conversion. The input power conversion step needs to facilitate the flow of energy from the thermal energy harvesting device into the storage while trying to maximise the power and efficiency. This is achieved through such strategies as load matching and maximum power point tracking. Different storage devices require different charging profiles to maximise their capacity and it is the job of the power management system to implement this. Distinct required voltages are achieved through DC/DC conversion. Becker *et al* demonstrate the power management considerations employed to enable thermal harvesting in aircraft [11].

3. HEAT SOURCES AND APPLICATIONS

3.1 Solar

The surface of the Earth receives about 1kW/m^2 of peak power from the Sun. This offers enormous potential for energy harvesting. Rather than use the conventional solar conversion method of photovoltaics, a growing field is exploring converting this energy indirectly to electricity through thermal energy harvesting.

On a large scale, arrays of mirrors are used to reflect and concentrate the Sun's power to a single point where the temperature rises to hundreds of degrees Celsius. On a smaller scale suitable for wireless sensor nodes, a black surface facing the Sun will absorb the sun's rays and heat up relative to its shaded underside. The difference in temperature of the top and bottom faces can be used to generate power by sandwiching a thermal energy harvester between them.

Yu *et al* [12] investigated the use of a hybrid power system for wireless sensors which incorporated solar and thermoelectric conversion. Solar photovoltaic (PV) cells heat up when in operation, so to harness this waste heat they attached thermoelectric harvesters underneath the cells with a heat sink underneath the thermoelectric harvesters to the atmosphere.

In their experiments, for a solar irradiance of 744 W/m^2 and ambient temperature of 34°C, they found that the rear of the PV cells reached 61°C. In other research by Wang [13], it was found that the rear of solar cells reached over 70°C in stronger summer light. The advantages of harvesting this relatively large 30-40°C temperature difference are twofold. Firstly and most obviously the thermoelectric devices are harvesting and providing extra power to the sensor node. The second benefit is that the presence of the thermoelectric device increases the efficiency of the solar cell. This is due to the fact that a PV cell's efficiency drops with increasing temperature by about 0.4% of total efficiency per degree. By including the thermoelectric device to harness heat energy from the cell its temperature drops and efficiency increases. In their experiment Yu *et al* found that the rear of the cells equipped with thermoelectric harvesters were 13°C colder than those without and measured a 5.2% increase in their efficiency.

Other research by the same authors showed the operation of such a hybrid PV/thermal solar system was used to successfully power an actual sensor node [14]. They developed an intelligent power management system to control the flow of energy between the two sources (PV and thermal), the storage (ultracapacitors and lithium ion batteries) and the load (sensor node).

3.2 Ground to Ambient Air

The temperature of the air will vary across the day and night in response to changes in the incoming solar radiation. Soil temperatures vary in response to both solar radiation and conduction from the air. The temperature of the soil changes at a slower rate than that of the air due to the larger thermal mass of the soil. This creates a temperature difference between the air and the ground. This is shown in data taken from the Australian Bureau of Meteorology's East Sale Airport station in 2007, figure 2.

Figure 2 shows the temperatures of the air and ground at 10cm and 100cm as recorded at 9am over a year. The air temperature is seen to vary greatly on the daily basis compared to the soil temperature. The temperature at 10cm depth follows the fluctuations in the air more than the temperature at 100cm which is seen to remain more constant on the short term and varying sinusoidally with the changing seasons across the year. The largest temperature difference is 10.7 K with an average difference of 2.5K existing between the air and the 100cm soil temperature.

These temperature differences can be used to drive a thermal generator. Figure 2 illustrates this concept. The data shown in Figure 2 is provide by the Australian Bureau of Meteorology and is from East Sale in southern Victoria. The air side heat exchanger emits or receives thermal energy from the ambient air, depending on whether the air is cooler or warmer than the soil. Likewise the soil heat exchanger receives or emits thermal energy from the ground at a desired depth. The heat pipe then transfers this heat to/from the thermoelectric device allowing the temperature gradient across tens of centimetres of soil to be applied directly across the much thinner thermoelectric device.

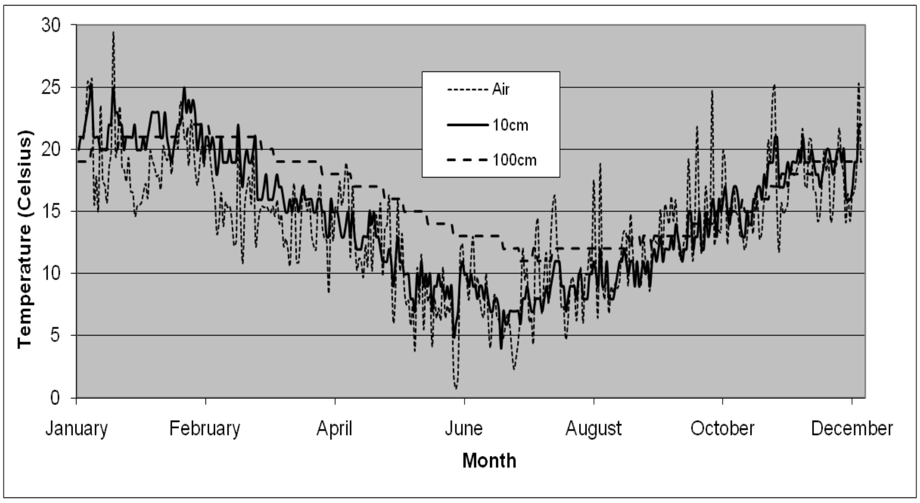

Figure 2. Measured temperatures for air and at soil depths of 10cm and 100cm at 9am.

Stevens first proposed this energy harvesting idea and has shown that using a maximum power approach rather than a maximum efficiency approach will lead to the greatest energy harvest output [16]. The low temperature differences encountered in this application lead to very low fundamental conversion efficiencies which can only be counteracted through large amounts of heat transfer. In order to maximise the flow of heat through the system while maintaining an optimal operating temperature difference the thermal conductance of the thermoelectric device must match the sum of all the external thermal conductances. This is analogous to load matching in electrical circuits for maximum power transfer and has the effect in this application of splitting the total air/soil temperature drop evenly between thermoelectric device and the heat exchangers. In later work he showed that there is an optimal depth at which the ground side heat exchanger should be buried and which theoretically leads to a 7% increase in the temperature difference across the thermoelectric device over the difference which could be achieved by placing the heat exchanger at an infinite depth [16].

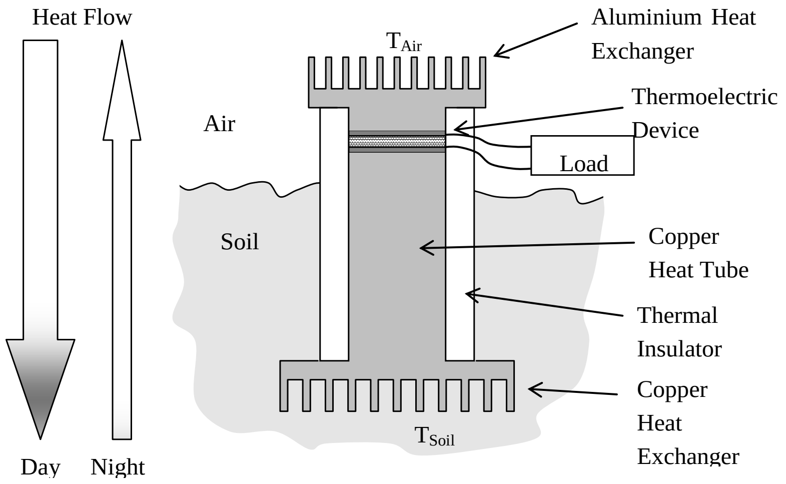

Figure 3.Simplified diagram of temperature harvesting device [1].

Meydbray *et al* [17] experimented on the effects of the thermoelectric generator module surface area when exploiting the soil to ambient air temperature difference. They ran three modules with different surface areas for 110 hours with the results shown in Table 1, indicating a strong dependence on the surface area. Additionally, during the course of this experiment, their data also showed a large decrease in power output during times of cloud cover. Lawrence and Synder [18][18] investigated the performance of heat sinks for this method with theoretical results also showing power outputs in the order of 0.1mW.

Set up	Energy Total (mWh)	Power Average (mW)	Area (cm^2)
1	2.5	0.0228	9
2	7.8	0.071	33
3	63.3	0.575	131

Table 1. Power from TE modules of differing surface areas in soil thermal gradient [17].

3.3 Water to Ambient Air

Inspired by the concepts of ground to ambient air thermal energy harvesting outlined in section 3.2 coupled with the huge potential for wireless sensor networks in and around marine/aquatic environments, the present authors have investigated powering wireless sensor nodes by exploiting the temperature difference existing across the air/water interface [19][20]. This scheme is examined in the case study in section 4.

3.4 Transport

Wireless sensor networks offer huge capability for applications throughout the transport sector. For example as the accuracy of motor control units in automobiles increases, the need for improved real-time engine data for use in closed loop control arises. This and many other applications across the transport sector possess significant temperature gradients inherent throughout the working environment which opens many opportunities for sensors self powered by thermal energy harvesting.

For the automobile industry's use of sensors in engine bays, waste heat is available from a variety of sources, principally the engine block, exhaust and coolant flow. Bodensohn *et al* [21] report thermoelectric generators supplying autonomous sensor systems with up to 7mW of power utilizing the engine block, typically at temperatures around 450-500K, as the heat source.

Sensors being used for structural health monitoring in aircraft are poised to reduce inspection costs and increase safety. Becker *et al* [11] investigated system development for using thermal energy harvesting in aircraft applications and compared results against other feasible energy harvesters i.e. solar and vibration. Their results showed that expected power densities (W/kg) from thermal energy harvesting in aircraft to be orders of magnitude larger than for other harvesting methods.

Bailey *et al* [22] investigated using the transient thermal gradients which develop during an aircraft's flight to power structural monitoring wireless sensor nodes deployed throughout the aircraft. Using thermoelectric generators they looked to exploit the temperature gradients which may appear across the sensor node as the atmospheric temperature decreases with the aircraft's altitude. To enhance the value of the thermal gradient and its duration they used water as a thermal energy storage inside the generator due to its high specific heat and its fusion point (0^oC) being located within the aircraft's operating range allowing high energy storage. To give a rough upper bound on the available energy from this method they consider that changing 1mL of water from a ground temperature of 15^oC at take-off, to a cruising temperature of -60^oC, then back to ground temperature at landing requires 1.3 kJ of energy. They assessed this experimentally by using a $6mm^2$ thin film thermoelectric generator compressed between a 10mL tank of water and a piece of aluminium simulating the aircrafts structure. This module was then placed into an environmental test system which simulated the aircraft's temperature conditions on a typical 1 hour flight for a commercial airliner. They were able to extract 34J of energy which compared to the theoretical upper bound shows a system conversion efficiency of 0.3%.

It is recognized that the solar thermal energy absorbed by black asphalt roads is a large possible source for energy harvesting [23]. A traffic monitoring system such as that proposed by Coleri could benefit from utilising a thermal energy harvesting power system. They acknowledged that in order to extend the life of the sensor network, currently powered by a pair of AA batteries, to acceptable levels, extra relay nodes coupled with energy efficient routing would be needed [24].

3.5 Industrial Waste Heat

There are abundant sources of waste heat littered throughout industry which produce thermal gradients in machinery, process piping or vents etc. Waste heat recovery is a topic of much research and although this source is very site specific it is logical to power sensors developed to monitor such industrial equipment from the rich energy source they are attached to.

Draney [25] presented an autonomous "smart bearing" which is a combined sensor and bearing used for monitoring bearing health in harsh environments (e.g. turbine engines). The sensor provided temperature and vibration data via wireless transmission and scavenged thermal energy from the environment as thermoelectric generators can operate in high temperatures whereas batteries cannot.

Meydbray *et al* [26] investigated exploiting the temperature difference between solid structures and the ambient air. They reported an average power density on the order of $5mW/m^2$ from their air-solid structure setup with temperature differentials of ±4K. Although the setup detailed is very simple and no attempt at improving it appears to have been made, the power output indicates that further work may be useful in improving the overall efficiency and power available from this sort of process.

3.6 The Human Body

The human body self regulates its temperature at a constant 37^oC. Harnessing this against the ambient air temperature offers a source for thermal harvesting for sensor nodes applied on the human body. Many companies producing body worn products, for example watches, have already developed devices which utilise the small difference between our body heat and the ambient temperature, generating power on the order of microwatts demonstrating that similar techniques can be applied to sensor nodes [27]. In 1998 Seiko released the first wrist watch driven by body heat, the Seiko Thermic. It uses the small thermal gradient between the wearer's arm and the ambient air to generate microwatts of power which run the movement of its mechanical clock.

Thermal energy harvesting is not only applicable on the outer surface of the human body but can also be utilised internally to power implantable medical devices and sensors. Watkins *et al* [8] investigated using their advanced thin film superlattice thermoelectric technology [7] to harness electrical energy from the temperature differences which can exist between the inner surface of the skin and the core body temperature. These temperature differences are typically as low as 0.3 – 1.5 K but they showed that the power levels needed for pacemakers and other similar implantable medical devices are easily achieved with current thermoelectric technology.

These ideas can be extended to cases involving other warm blooded animals. CSIRO recently investigated providing virtual livestock fencing to limit the location of cattle, separate bulls from each other and protect environmentally sensitive areas, used GPS information in a wireless sensor network. This system was powered by solar panels but could equally be powered by thermal devices [28].

4. Case Study: The Use Of Environmental Heat

As can be seen in this chapter, energy from the differences in temperature between two objects can be used to generate useable electrical energy. Many devices can be used to generate power from heat transfer such as heat engines and thermoelectric devices. Solid-state thermoelectric devices are reliable and robust as they have no moving parts. The efficiency of such devices has remained constant for around 50 years but recent advances in the composition of the devices have shown efficiency gains approaching twice those previously achieved [7]. This has sparked renewed interest in the use and development of thermoelectric technology.

Modern thermoelectric devices commonly use bismuth telluride (BiTe) doped to n- and p-type semiconductors. These are connected electrically in series and thermally in parallel. For this case study the hot side is provided by connection to a black disk illuminated by the sun, while the cold side is connected to a heat exchanger immersed in water. Water has a high thermal mass and also good convective heat transfer properties, which makes it ideal for use as a heat sink. The water temperature of large bodies of water remains relatively constant during a day, regardless of large air temperature fluctuations. The difference in temperature between the water and ambient air temperature could be used as a natural thermal gradient.

Individual nodes within a network will have power requirements that are dependant on aspects like transmission and reception cycle and data sampling frequency. For example the Fleck ™ series of nodes operates at 3.3V and consumes 30-40mA when transmitting, 15-20mA when receiving data and 1-2mA when idle. With a well designed duty cycle a node will consume much less than 50mW. This power consumption does not include the power required by the sensors or other equipment attached to the node.

Because of this low power requirement thermoelectric devices may be suitable where a temperature difference of a few degrees Kelvin can be found. For example, Ferrari *et al* [5] and Knight and Collins [19] investigated using a thermoelectric generator to provide sufficient power for a wireless sensor node. Ferrari *et al* presents the characterization of three different commercial thermoelectric modules designed for heating/cooling applications. Their analysis included the effects of electrical load resistance, thermal conductivities of the thermoelectric and heat exchanger modules and different temperature gradients. They found that thermoelectrics could be used for their application of powering a wireless sensor node consuming 32mW, when the temperature difference exceeded 30K.

Figure 4 shows the result of some of their work, displaying the maximum power density generated by the three different thermoelectric generators vs. temperature difference.

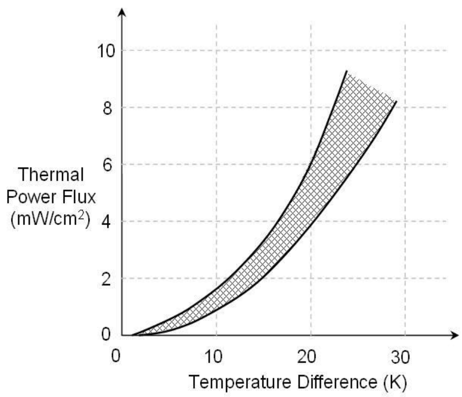

Figure 4. Power flux generated by example Thermoelectric Generators. [5]

4.1 Experimental Details

4.1.1 Collector design

The basic design of the module is shown in Figure 5. The design uses a simple 40mm x 40mm square aluminium block to sink the heat into the water on the cold side. The thermoelectric device is sandwiched between a circular disk, which has been painted matt black, and the aluminium heat sink. Heat transfer paste is used to facilitate good heat flow at each of these junctions. A foam collar was placed below the disk and that assembly slid through a hole in a circular acrylic disk. This acrylic disk has a number of fasteners around its periphery which mate with the acrylic dome which covers the device. This dome assembly floats by virtue of a foam raft.

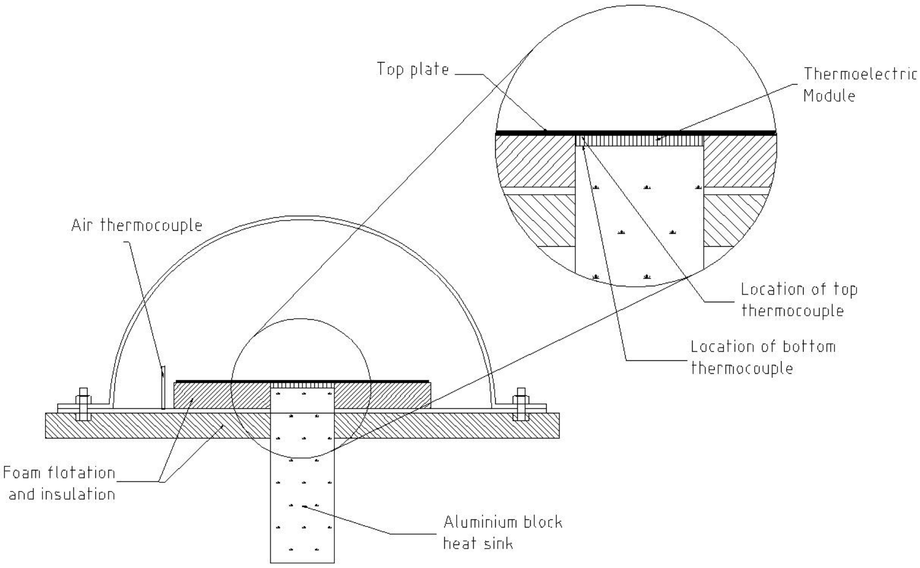

Figure 5. Collector design [19].

4.2 Experimental Variations

Many aspects of the module design can be varied to examine the effect on output power levels; in this paper we will vary just two features. The first series of tests measured the effect of changing the collector disk size. Small, medium and large disks were used to provide heat to the TEM. The small disk had a diameter of 160mm, the medium disk had a diameter of 200mm and the largest disk had a diameter of 240mm.

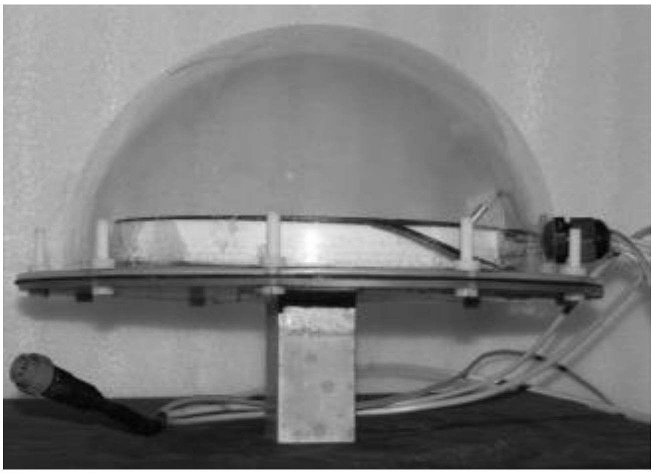

Figure 6. Experimental module showing the acrylic dome and interior foam

The second series of tests varied the number of thermo electric modules, connected in series. One, two and four TEMs were connected in series each with a medium sized collector disk. Although it may appear that connecting four devices in series should quadruple the power output, a secondary effect is introduced: By having 4 devices there is four times the conduction area for any heat difference. Thus the heat flow will be altered and the dome with four TEMs will have a lower temperature difference between the hot side and cold side.

4.3 Experimental results

4.3.1 Variation of Collector Size

Three collector sizes, 160, 200 and 240mm, were tested. The collector plate consists of a round aluminium plate, painted with a matt black paint. The data for this was collected over a three day period in mid winter. The output power from each of the collector areas is shown in Figure 7 along with the solar insolation data. The insolation data was collected from an on-site weather station located approximately 50m away.

The slight dip that occurs in the power output at 12:45 is caused by a shadow cast from a nearby wind turbine tower, which did not shade the Insolation data collection location.

Insolation data is on the secondary axis and shows that the day was cloud free until early afternoon. The solar insolation data shows a peak of more than 635W/m^2 which is a typical mid-winter value for the Newcastle latitude. The power output tracks the insolation data well and shows that the collector with the largest diameter provides the largest output. The peak output from the largest collector is 47mW, the medium size collector has a peak output of 31mW and the smallest collector has an output of 22mW.

The fact that the larger collector has the largest power output should not be particularly surprising. Of more interest is the normalised power output for each size disk. This is achieved by normalising power output against disk area and gives a value of power flux for each disk and an indication of the efficiency of the process. The results for this calculation are shown in Figure 8.

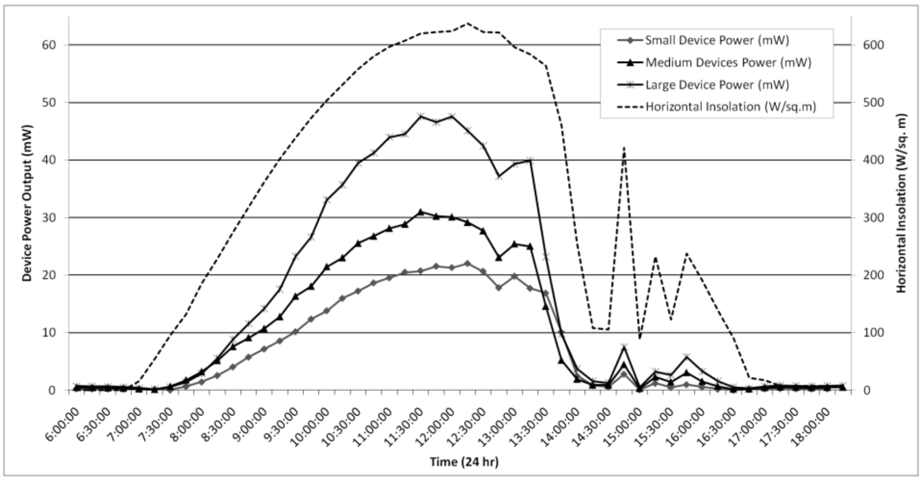

Figure 7. Power output across three different sized collectors.

This data shows some important results. Firstly the power output from the devices is quite low and peak efficiencies are between 1% and 2% for all devices. Although low compared to solar photovoltaic technology, this is quite high for thermoelectric devices and is driven by the design of the device: Each collector is covered by a plastic dome. This has the effect of increasing the temperature inside the dome like a miniature greenhouse. The domes are made of an acrylic which allows visible light to pass but is opaque to infrared light. The black plates reflect infrared but this is blocked by the dome and increases the temperature inside the dome. The use of the dome has effectively boosted the power output from a mid-winter sun to a typical mid summer sun value.

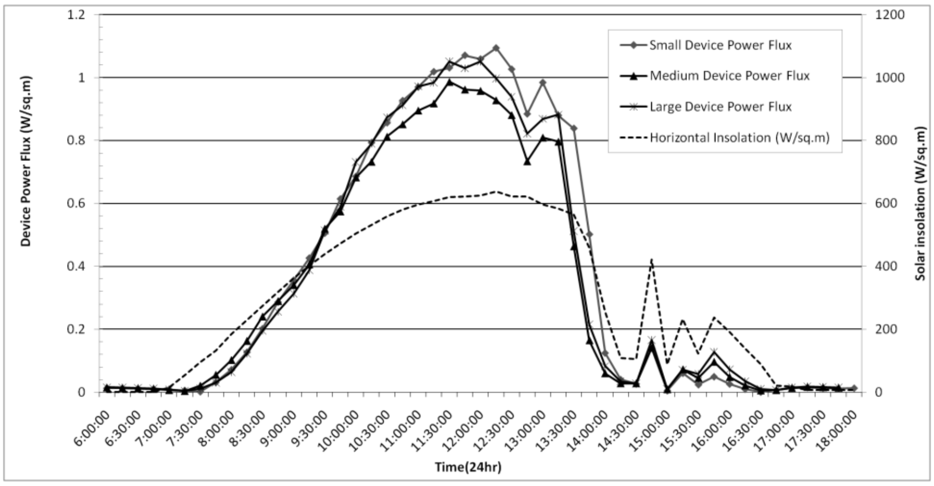

Figure 8. Solar Insolation and Device Power Flux.

The next important result is that the small device has the largest power output flux. This indicates that the ratio between collector area and the TEM device area is closer to optimal. The TEM to collector area is 8% for the small collector, 5.1% for the medium collector and 3.5% for the largest collector. Although the largest collector will gather the largest amount of energy from the sun it will not use it optimally and in fact requires a TEM device larger than the one 40 x 40mm device used. In order to get an 8% ratio the TEM device needs to be 60 x 60mm or two to three of the 40 x 40mm devices could be used (two devices would have an area ratio of 7.1% and 3 would have a ratio of 10.6%). This result correlates with previous work published in [20].

4.3.2 Variation of Number of Thermoelectric Modules

Another variable tested in this case study is the number of thermoelectric modules. Although the previous section indicates quite useable levels of power coming out of the domes, the reality is that this power is only practical if it is capable of recharging a battery or being converted to a voltage sufficient to power a wireless device. The CSIRO Fleck ™ requires a voltage range between 3.3 and 8V. Figure 9 shows the output power from the first range of experiments where one thermoelectric module was used with three different sized collectors. This data shows that the peak voltage output for the largest collector is just 530mV. The peak output from the smallest device (which had the highest power flux) is just 360mV. At such small levels a multi-stage voltage doubler would be required to get to any practical battery recharging level. Typically these voltage doublers use components that have potential drops corresponding to that across diodes and microcontrollers. This is in the region of 500-700mV. This would indicate that even the large collector would have issues utilising the harvested power in any practical way.

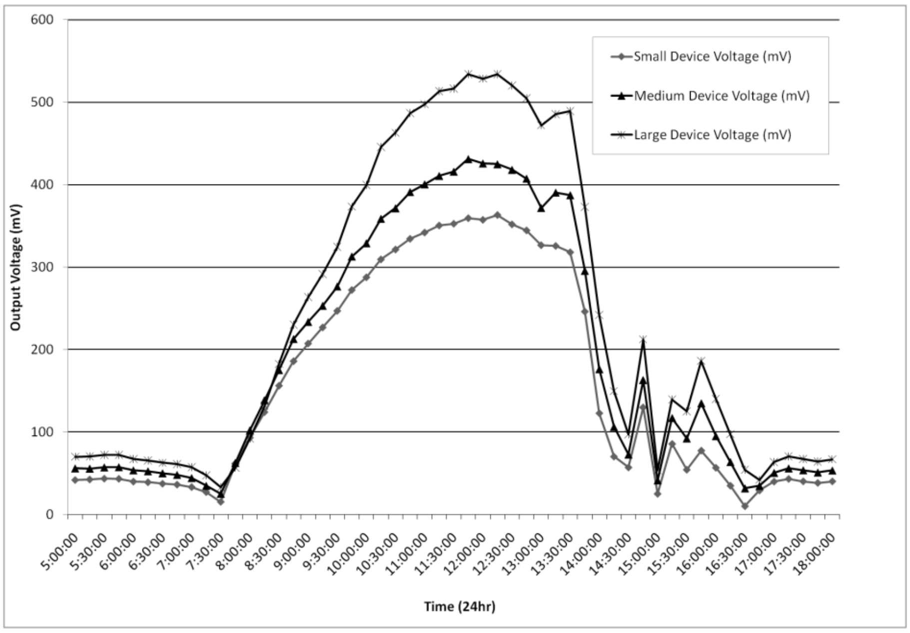

Figure 9. Output voltage from three different sized collectors and one TEM.

One solution to this may be to connect a number of thermoelectric modules in series to increase the output voltage. In order to keep the output power conditions comparable, the load resistance has to be increased in line with the number of devices used. The base resistance for this test was 6Ω for each TEM. The described test involved three different devices. The first device had one TEM with a 6Ω load, the second had two TEMs with a 12Ω load, and the third device had four TEMs in series and was loaded with 24Ω.

The results for this series of tests are shown in Figure 10. The solar insolation data indicates that for this particular day the maximum solar resource was 620W/m^2. The results indicate that the voltage output has increased in line with the number of modules connected in series. The peak output voltage from four thermoelectric modules connected in series is 935mV. This would be useable in a standard voltage doubler circuit. The peak voltage out of just one module was 320mV and the device with two modules in series peaked at 550mV. These would not be useful in any practical sense due to predicted voltage requirements of any power conditioning circuitry.

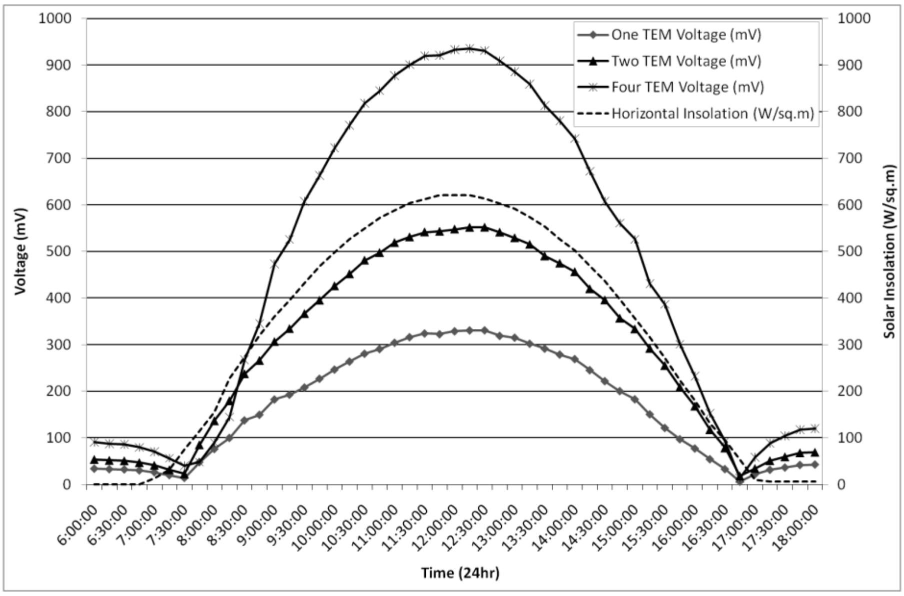

Figure 10. Output voltage from multiple thermoelectric modules in series.

The output power for the three different test points is shown in Figure 11. Insolation data is on the secondary axis and shows that the day was cloud free with a peak of more than 620W/m2 which is slightly lower than previous data (635W/m2) and allows direct comparison of other output data. The power output for each variation of collector module tracks the insolation data well and shows that the collector with four TEMs in series has a maximum power output of 36mW. The collector with 2 TEMs in series peaks at 25mW and the device with one TEM peaks at 18mW. The collector size for each of these three devices was the medium disk. The medium disk data from the first series had a peak output of 30mW from one TEM.

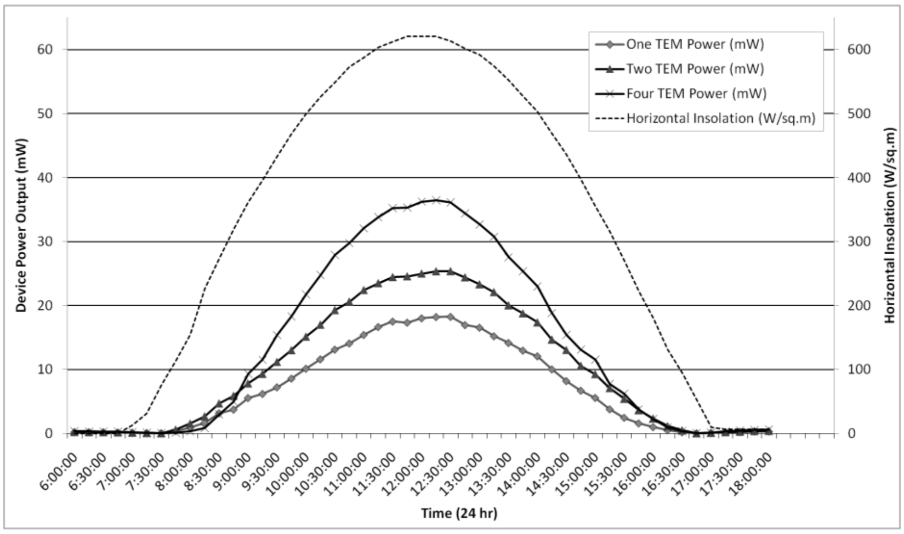

Figure 11. Output power from multiple thermoelectric modules in series.

4.3.3 Comparison of Ideal and Measured Power Output.

A comparison of the ideal and measured output for one of the devices is provided in Figure 12. The determination of the ideal power output is based on a calculation using the power factor of the thermoelectric device. This is a relatively simple calculation and the equation for this is shown in equation 1, where KPF is the power factor for the particular TEM, *a* is the area and ΔT is the temperature difference across the Seebeck device.

$$P = K_{PF} a \Delta T^2 \tag{5}$$

For this particular TEM, the power factor is 0.09μW/(mm^{2}K^2) and the area of the device is 1600mm^2. Figure 12 indicates that the ideal power output is larger than the measured power output by about three times. This difference is mainly explained by the different load resistance and the experimental temperature. The ideal power output is calculated based on using a matched load, which is one where the load resistance is the same as the internal resistances of the TEG, to ensure maximum power transfer. For this style of TEG the matched load is approximately 10Ω, with the variation dependent on the actual temperature difference across the device and variations in manufacturing methods and materials. The detailed experiments used a load resistance of 6Ω. In addition the ideal power output is calculated based on much larger operating temperatures, where the hot side is approximately 350K. The hot side for these experiments peaked at 310K and was usually much lower.

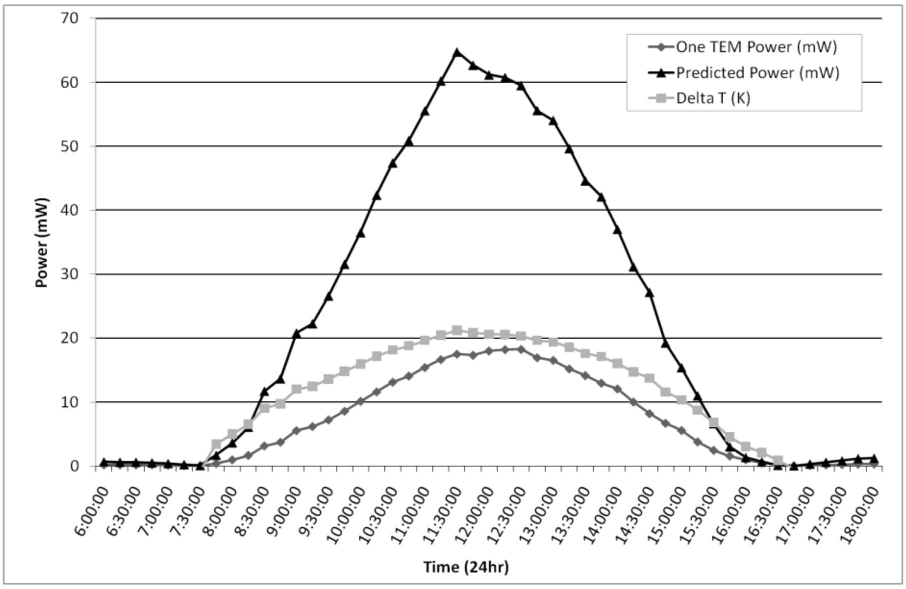

Figure 12. Experimental and predicted power output from a single TEM.

A second series of tests was run where the load resistance of the clear dome with heat sink module had been reduced from 100Ω to 9Ω by the addition of a 10Ω resistor in parallel with the 100Ω resistor. This second series of tests was performed at a farm dam at Armidale in northern NSW. As the volume of the dam was small compared to the initial deployment, the water temperature showed a larger variation. Due to space constraints for this paper the results will not be repeated for this second deployment. However, Figure 12 shows that this simple variation in load resistance has a marked effect on the power output. Recall from above that the power output of the three variations of clear dome was similar with a load resistance of 100Ω. When the load resistance of module 3 was dropped to 9Ω the peak power output climbed to 85mW, which is 58% of the ideal output of 146mW at the same conditions. In this case, the output from the two remaining clear domes was approximately 10mW. This is similar to the Newcastle deployment and indicates that the deployments were somewhat similar. These results are in line with [29]. Further work is required in this area to optimise these results.

The power output produced in these preliminary tests is enough to run a range of wireless sensors including the CSIRO wireless node. With improvements in load matching electronics and thermoelectric materials, it will become possible to use similar devices to power sensor nodes over much smaller gradients, even without solar assistance.

5. CONCLUSION

The continuing decrease in both size and power consumption of personal electronics and wireless nodes has driven a search for power sources that can power these devices indefinitely. While technologies such as solar or wind can be applied to particular locations, they are of little use in some locations, such as mine shafts or under dense tree cover. In these locations a more basic device has been considered. These devices generate power directly from thermal differences in the surrounding area.

The technologies considered for this energy harvesting include thermoelectric devices based on the Seebeck effect, thermionic and thermo-tunnelling devices. The sources of energy for these technologies include solar energy and the temperature difference between ambient air and local soil or water. One excellent resource of relatively high temperature energy is from vehicle exhausts and industrial waste heat. The forced cooling of the Seebeck cold side is also relatively easy to implement in these situations. Finally a reasonable source of heat is that of the body heat of mammals, including humans.

A case study using commercially available Seebeck devices across an air-water interface is discussed in detail. The output from this study peaks around 50mW for mid-winter sun, which is sufficient to power small wireless nodes. The issue of the quality of this power is discussed in terms of producing power at a useable voltage. One way to achieve sufficient quality power is by connecting multiple devices in series.

This report reveals that while present thermal energy harvesting technologies have low efficiencies, there are a number of promising technologies that are increasing in reliability and efficiency via increased ZT values. This, along with continued decreases in power requirements on the portable electronic side, marks thermal energy harvesting as a very promising field of research.

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