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# Thermoelectric Energy Harvesting

*Chris Gould*

## Abstract

Thermoelectricity can be used to generate electrical power from temperature gradients or differences in naturally occurring geothermal heat and rocks, or from waste heat in man-made equipment and industrial processes. Thermoelectric energy harvesting systems are finding commercial applications to replace or recharge batteries in low power electronic systems. This chapter provides the fundamental thermoelectric theory related to power generation, including the theoretical analysis and numerical calculations required to calculate the thermoelectric efficiency and electrical power generated when a single thermoelectric couple, and a 127 couple thermoelectric module, are subject to different temperature gradients. A thermoelectric energy harvesting system, incorporating a low power boost converter and DC to DC converter, coupled with electrical energy storage in supercapacitors, is presented and enables a thermoelectric energy harvesting system to provide sufficient electrical power to operate low power electronic components and systems. The short-term challenge for thermoelectric energy harvesting is to become a cost effective and practical solution to replace batteries, and to be scaled to provide sufficient power to operate electrical rotating machines such as low power motors and pumps. The long-term challenge is to improve the efficiency, power output, and cost of thermoelectric modules and energy harvesting systems, and to develop from low power to low-to-medium power applications.

**Keywords:** thermoelectric, Seebeck, temperature difference, temperature gradient, thermal power generation

## 1. Introduction

Energy harvesting is an ideal platform to foster research and the commercial application of thermoelectric power generation. The use of naturally occurring temperature gradients or differences found in geothermal heat and rocks, or by man-made waste heat in machinery and industrial processes, can be used to generate electrical power by thermoelectricity. The concept of using thermoelectricity to generate electrical power has been discussed for some time, and is considered to be an environmentally friendly and renewable technology, although thermoelectricity is often overlooked in discussions surrounding renewable energy sources, partly due to the relatively low levels of electrical power generated from a thermoelectric module, which is typically in the milliwatt to watt range, and the low conversion efficiency of between 5 and 10% [1]. However, with the addition of power electronics, coupled with electrical energy storage in electric double layer capacitors, also known as supercapacitors, the instantaneous electrical power output from a thermoelectric power generation system can be increased to a useful level, and can output sufficient electrical power to operate low power electronic

systems, recharge or replace batteries in many applications. Furthermore, thermoelectricity can be used in applications where other energy harvesting techniques could not be used, i.e., where light is not available for photovoltaic power generation, or wind for electromagnetic generation, or can be used in combination with other energy harvesting technologies in order to enhance a systems overall performance. The technology is not limited to low power applications, with an on-going focus and research into thermoelectric power generation from waste heat in the automotive market, and is extensively used to provide power to deep-space spacecraft.

The technology has several advantages when used for power generation; thermoelectric modules can function in harsh environments; are relatively small in size and weight; there are no moving parts and very low, if any, maintenance requirements; electrically quiet in operation; do not import dust or other particles; can be oriented in any direction; and the same module can be used for power generation, cooling and heating. The main disadvantage of thermoelectricity is the relatively low conversion efficiency and thermoelectric figure of merit  $Z_T$ .

Thermoelectricity has undergone stages of significant interest, research and development, along with periods of inactivity and decline. The scientific principle and potential application of thermoelectric power generation has been known for some time and can be described as the generation of electrical power, via the Seebeck effect, when two dissimilar conducting materials are connected together at one end and subject to a temperature gradient or temperature difference. The fundamental scientific discoveries applicable to thermoelectricity were discovered in the 1800s, with the most important for power generation being the Seebeck effect discovered by Thomas Seebeck in 1821. It should be noted that thermoelectricity can also be used for cooling and heating applications, where a source of DC power is applied to a thermoelectric couple or module's input terminals, resulting in one side of the couple or module reducing in temperature and the other side increasing in temperature and acting as a heat pump. This cooling and heating effect is primarily due to the Peltier effect, discovered in 1834 by Joseph Peltier, and to a lesser extent the Thomson effect in 1855 by William Thomson, later known as Lord Kelvin. Recognition should also be made to Alessandro Volta as an early pioneer in thermoelectric research. The technology developed slowly until the 1930s, when rapid improvements in all areas of thermoelectricity occurred and by the mid 1960s, practical thermoelectric devices emerged for niche applications in aerospace cooling and spacecraft power. Progress in efficiency improvement slowed and research peaked in 1963, followed by a steep decline in activity that was to continue for nearly three decades [2]. However, around 1990 there was renewed interest in thermoelectricity due to a combination of factors, notably environmental concerns regarding refrigerant fluids, alternative refrigeration and interest in cooling electronics [3]. Contemporary interest in the technology is driven by an increasing awareness of the effect of climate change on the planet's environment, a renewed requirement for long-life electrical power sources and energy harvesting technologies, and the increasing miniaturization of electronic circuits and sensors [4]. In recent years, interest has grown in the use of ambient energy sources to power low power electronic systems, with thermoelectricity being one of the most promising and applicable energy harvesting technologies for commercial exploitation.

## **2. Background thermoelectric theory**

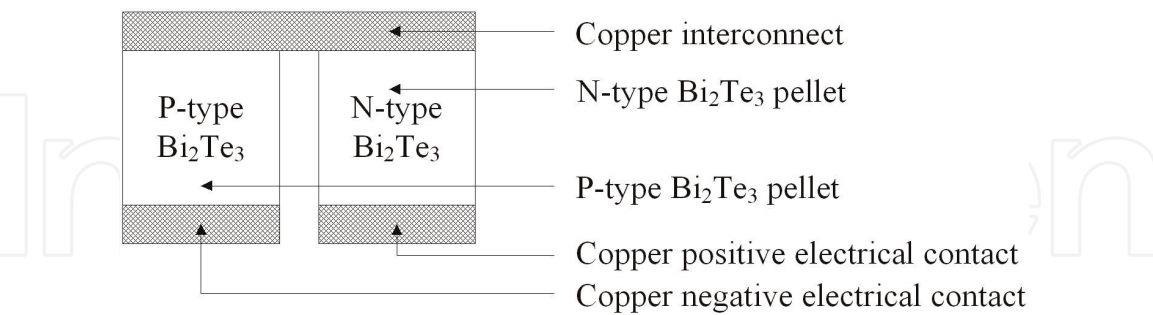
This section will present the fundamental thermoelectric theory related to thermoelectric power generation for a single thermoelectric couple, and a 127 couple thermoelectric module.

2.1 Standard thermoelectric couple and module construction

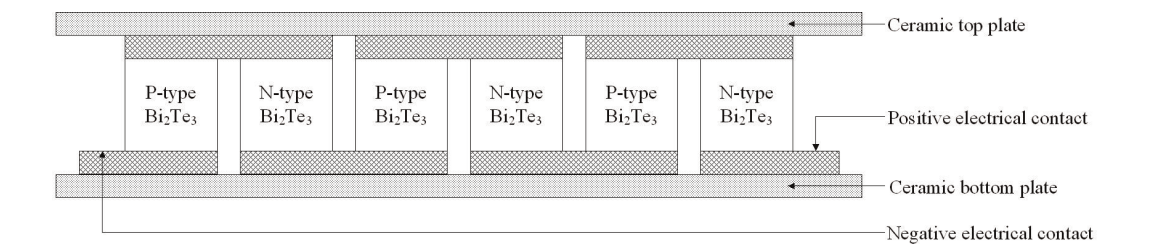
A single thermoelectric couple is constructed from two ‘pellets’ of semiconductor material usually made from bismuth telluride ( $\text{Bi}_2\text{Te}_3$ ), as this material has been found to show the most pronounced thermoelectric effects around room temperature. One of these pellets is doped with acceptor impurity to create a p-type pellet, the other is doped with donor impurity to produce an n-type pellet. The two pellets are physically linked together on one side, usually with a small strip of copper, and mounted between two ceramic outer plates that provide electrical isolation and structural integrity. A single thermoelectric couple, as shown in **Figure 1**, is generally of limited practical use, as the rate of useful power generated due to the Seebeck effect is very small. Practical thermoelectric modules are constructed with several of these thermoelectric couples connected electrically in series and thermally in parallel, with modules typically containing a minimum of three thermoelectric couples, as shown in **Figure 2**, rising to 127 couples for larger devices [5].

2.2 The principle of thermoelectric power generation for a single thermoelectric couple

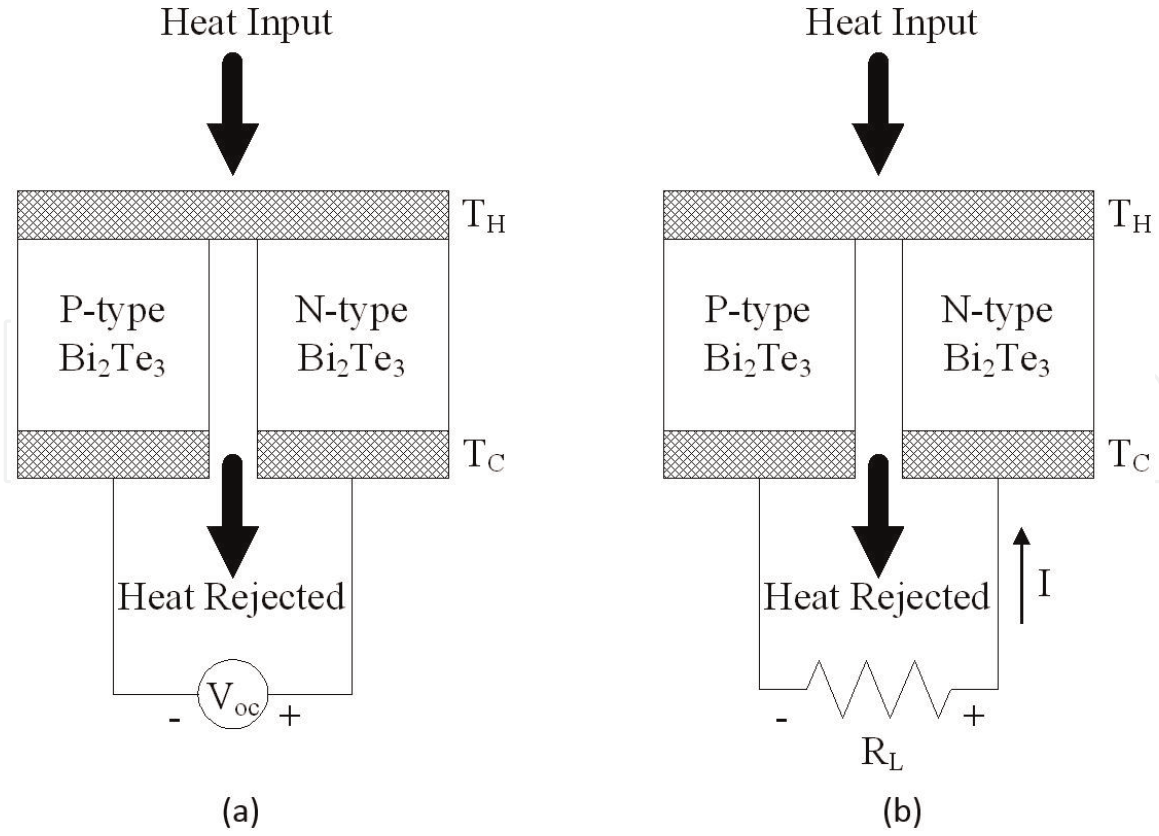
If a temperature difference is maintained between two sides of a thermoelectric couple, thermal energy will move through the p-type and n-type pellets. As these pellets are electrically conductive, charge carriers are transported by this heat. This movement of heat and charge carriers creates an electrical voltage called the Seebeck voltage. If a resistive load is connected across the thermoelectric couple’s output terminals, current will flow in the load and an electrical voltage will be generated at the load [6]. A schematic diagram of a single thermoelectric couple, configured for thermoelectric power generation, with the output terminals of the couple connected to a volt meter in order to measure the open-circuit voltage  $V_{oc}$  is shown in **Figure 3(a)**, and connected to a resistive load  $R_L$  in **Figure 3(b)**.



**Figure 1.**  
*A single thermoelectric couple.*



**Figure 2.**  
*A three couple thermoelectric module.*



**Figure 3.** A single thermoelectric couple configured as a thermoelectric generator with a volt meter measuring the open-circuit voltage  $V_{oc}$  (a) and in (b) with a load resistor  $R_L$  connected across the couple's output terminals [7].

### 2.2.1 Calculating the thermoelectric couple open-circuit voltage $V_{oc}$

According to [8], if we consider the thermoelectric couple in **Figure 3** (a), and assume that no other heat arrives at the cold side  $T_c$  other than through the two thermoelectric legs, the thermoelectric couple open-circuit voltage  $V_{oc}$  can be found by:

$$V_{oc} = (\alpha_p - \alpha_n)(T_h - T_c) \text{ measured in volts} \quad (1)$$

where  $\alpha_p$  and  $\alpha_n$  is the Seebeck coefficient of the p-type and n-type pellets of the thermoelectric couple respectively, and may be found quoted in manufacturer literature or obtained by practical measurement. Typical values for  $\text{Bi}_2\text{Te}_3$  thermoelectric couples are  $\alpha_p$  of around  $230 \times 10^{-6} \text{ V/K}$  and  $\alpha_n$  of around  $-195 \times 10^{-6} \text{ V/K}$  [9].  $T_h$  is the surface temperature of the hot side of the thermoelectric couple, and  $T_c$  is the surface temperature of the cold side of the thermoelectric couple, measured in Kelvin.

### 2.2.2 Calculating the resistance $R_p$ and $R_n$ of the thermoelectric couple pellets

The electrical resistivity  $\rho$  of each pellet can be found and/or measured, with a typical resistivity for p-type  $\text{Bi}_2\text{Te}_3$  thermoelectric pellets of around  $1.75 \times 10^{-3} \text{ Ohms-centimetre}$ , and for n-type  $\text{Bi}_2\text{Te}_3$  pellets of around  $1.35 \times 10^{-3} \text{ Ohms-centimetre}$  [10]. The resistance  $R_p$  of the p-type pellet can then be found by:

$$R_p = \frac{L_p \rho_p}{A_p} \text{ measured in Ohms} \quad (2)$$

where  $\rho_p$  is the electrical resistivity of the pellet in Ohms-cm,  $L_p$  is the length of the pellet in cm, and  $A_p$  is the cross-sectional area of the pellet in  $\text{cm}^2$  found by:

$$A_p = \text{width} \times \text{depth measured in cm}^2 \quad (3)$$

Similarly, the resistance of the n-type pellet  $R_n$  can be found by:

$$R_n = \frac{L_n \rho_n}{A_n} \text{ measured in Ohms} \quad (4)$$

### 2.2.3 The thermoelectric couple resistance $R_c$

The thermoelectric couple resistance  $R_c$ , ignoring the resistance of the copper interconnects, is the addition of the resistance of the two thermoelectric pellets:

$$R_c = R_p + R_n \text{ measured in Ohms} \quad (5)$$

The resistance of the copper interconnects is typically in the micro ohm region, and compared with the resistance of the  $\text{Bi}_2\text{Te}_3$  thermoelectric pellets, which tends to be in the milliohm region, is significantly smaller in value and hence can be considered as negligible.

### 2.2.4 Calculating the thermal conductivity $K_p$ and $K_n$ of the thermoelectric couple thermoelements (legs)

The thermal conductivity  $\lambda$  of each pellet can be found and/or measured, with a typical conductivity for a p-type  $\text{Bi}_2\text{Te}_3$  thermoelectric pellet of around  $1.2 \times 10^{-3} \text{ W/cm K}$ , and for an n-type  $\text{Bi}_2\text{Te}_3$  pellet of  $1.4 \times 10^{-3} \text{ W/cm K}$  [10]. The thermal conductivity  $K_p$  of the p-type thermoelement can be found by:

$$K_p = \frac{\lambda_p A_p}{L_p} \text{ measured in watts cm kelvin} \quad (6)$$

where  $\lambda_p$  is the thermal conductivity of the pellet in watts/cm kelvin,  $L_p$  is the length of the pellet in cm, and  $A_p$  is the cross-sectional area of the pellet in  $\text{cm}^2$ . Similarly, the thermal conductivity of the n-type pellet  $K_n$  can be found by:

$$K_n = \frac{\lambda_n A_n}{L_n} \text{ measured in watts cm kelvin} \quad (7)$$

It should be noted that the electrical resistivity  $\rho$  is the reciprocal of the electrical conductivity  $\sigma$  and can also be found using:

$$\sigma = \frac{I \times L}{V \times A} \text{ measured in siemens} \quad (8)$$

where  $I$  is the current through a constant cross-sectional area  $A$  and length  $L$  when a voltage  $V$  is applied [8].

### 2.2.5 Calculating the current $I$ when a load resistor $R_L$ is connected across the thermoelectric couple output terminals

If a load resistance  $R_L$  is now connected across the output terminals of the thermoelectric couple, as shown in **Figure 3(b)**, the current  $I$  can be expressed as:

$$I = \frac{V}{R_T} \text{ measured in amperes} \quad (9)$$

where  $V$  is the closed-circuit voltage, and  $R_T$  is the total resistance of the thermoelectric couple and the load. It is possible to find  $R_T$  using:

$$R_T = R_p + R_n + R_L \text{ measured in Ohms} \quad (10)$$

Using (Eq. (1)) and (Eq. (10)), the current  $I$  can be found by:

$$I = \frac{(\alpha_p - \alpha_n)(T_h - T_c)}{R_p + R_n + R_L} \text{ measured in amperes} \quad (11)$$

#### 2.2.6 The load current $I_L$ and the voltage generated at the load $V_L$

As the load resistor  $R_L$  is connected across the output terminals of the couple, the load current  $I_L$  is the same as the circuit current  $I$ , and the voltage generated at the load  $V_L$  can be found by:

$$V_L = I_L \times R_L \text{ measured in volts} \quad (12)$$

#### 2.2.7 The electrical power generated at the load $P_L$

The electrical power generated at the load  $P_L$  can be found using:

$$P_L = I^2 R_L \text{ measured in watts} \quad (13)$$

If we substitute (Eq. (11)) into (Eq. (13)), we obtain:

$$P_L = \left\{ \frac{(\alpha_p - \alpha_n)(T_h - T_c)}{R_p + R_n + R_L} \right\}^2 R_L \text{ measured in watts} \quad (14)$$

Alternatively, the electrical power generated at the load can be found by:

$$P_L = V_L \times I_L \text{ measured in watts} \quad (15)$$

In electrical and electronic engineering, the maximum power transfer between the generator and the load normally occurs when the load resistance is equal to the generator resistance, and if we consider the thermoelectric couple as an ideal model, with no heat lost through thermal radiation or conduction, and ignoring any effect of contact resistances, the maximum efficiency of a thermoelectric generator will not exceed 50%. It should be noted that if the load resistance is increased away from the value that gives rise to maximum power transfer, the power output of the thermoelectric generator will be reduced [8].

#### 2.2.8 Calculating the thermoelectric couple efficiency

The efficiency  $\eta$  of a thermoelectric couple can be found by:

$$\eta = \frac{\text{Energy supplied to the load}}{\text{Heat energy absorbed at the hot junction}} \quad (16)$$

The electrical power supplied to the load is  $P_L$ , and we now need to find the heat energy absorbed at the hot junction. A proportion of the heat that is absorbed at the

hot junction from the heat source  $T_h$  is used to balance the Peltier cooling effect in the thermoelectric couple, and an opposing flow of heat occurs due to the thermal conduction of the thermoelectric legs, and by Joule heating within the device. The cooling effect at the source  $Q_{source}$  can be found by:

$$Q_{source} = (\alpha_p - \alpha_n)I_L T_h \text{ measured in watts} \quad (17)$$

The opposing heat by conduction in the thermoelectric legs (or pellets) can be found by:

$$Q_{legs} = (T_h - T_c)(K_p + K_n) \text{ measured in watts} \quad (18)$$

where  $K_p$  and  $K_n$  are the thermal conductance of the p-type and n-type thermoelectric legs, respectively. The cooling effect is opposed by Joule heating  $Q_j$  within the thermoelectric legs, found by:

$$Q_j = \left( \frac{I^2(R_p + R_n)}{2} \right) \text{ measured in watts} \quad (19)$$

According to [8], it can be shown that half of the Joule heating passes to the sink  $T_c$  and half to the source  $T_h$ , with each half equal to (Eq. (19)). The expression for the heat energy absorbed at the hot junction, which is the same as the cooling power at the hot side of the thermoelectric couple  $Q_h$  can now be found by:

$$Q_h = (\alpha_p - \alpha_n)IT_h - (T_c - T_h)(K_p + K_n) - \frac{I^2(R_p + R_n)}{2} \text{ measured in watts} \quad (20)$$

Hence, the efficiency of the thermoelectric couple  $\eta$  can now be found by (Eq. (16)), and written as:

$$\eta = \frac{P_L}{Q_h} \quad (21)$$

Substituting  $Q_h$  from (Eq. (20)) and  $P_L$  from (Eq. (14)) into (Eq. (21)), we obtain:

$$\eta = \frac{\left\{ \frac{(\alpha_p - \alpha_n)(T_h - T_c)}{R_p + R_n + R_L} \right\}^2 R_L}{(\alpha_p - \alpha_n)IT_h - (T_c - T_h)(K_p + K_n) - \frac{I^2(R_p + R_n)}{2}} \quad (22)$$

In thermoelectricity, efficiency is expressed as the dimensionless figure-of-merit  $Z$ , or more commonly, expressed as a function of the temperature over which the device is operated  $Z_T$ . The thermoelectric figure-of-merit  $Z$  describes the thermoelectric efficiency of a thermoelectric couple for a given pair of p-type and n-type thermoelectric materials, and is normally shown as:

$$Z = \frac{\alpha^2}{\lambda \rho} \quad (23)$$

where  $\alpha$  is the Seebeck coefficient of the thermoelectric couple,  $\lambda$  is the thermal conductivity, and  $\rho$  is the couple's electrical resistivity. In the context of this

discussion, the Seebeck coefficient of the couple is equal to  $(\alpha_p - \alpha_n)$ , the thermal conductivity  $\lambda$  is  $(K_p + K_n)$ , and the electrical resistivity  $\rho$  is equal to  $(R_p + R_n)$ , therefore (Eq. (23)) can be rewritten as:

$$Z = \frac{(\alpha_p - \alpha_n)^2}{(K_p + K_n)(R_p + R_n)} \quad (24)$$

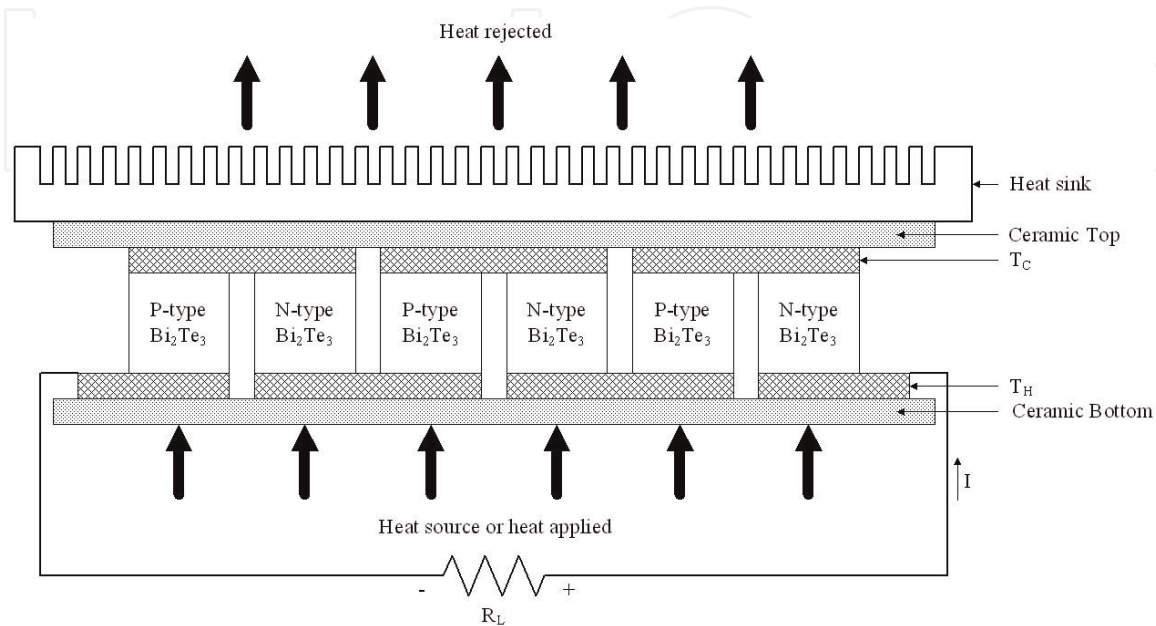
The thermoelectric figure-of-merit  $Z$  is commonly used to optimize the performance of materials used in the manufacture of thermoelectric couples. However, when stating the thermoelectric efficiency, it is more common to express it as a function of the temperature over which the device is operated, referred to as  $Z_T$ , which can be found by using (Eq. (23)) at a specific temperature, and is normally written as:

$$Z_T = \frac{\alpha^2 \sigma}{\lambda} \quad (25)$$

where  $\alpha$  is the Seebeck coefficient,  $\sigma$  is the electrical conductivity, and  $\lambda$  is the thermal conductivity of the couple at a specific operating temperature.

### 2.3 Thermoelectric module power generation

If we now consider a thermoelectric module that contains several thermoelectric couples connected electrically in series, and thermally in parallel, as shown in **Figure 2**, a small amount of electrical power, typically in the milliwatt range (mW), can be generated from a thermoelectric module if a temperature difference is maintained between two sides of the module. Normally, one side of the module is attached to a heat source and is referred to as the ‘hot’ side or  $T_H$ . The other side of the module is typically attached to a heat sink and is called the ‘cold’ side or  $T_C$ . The heat sink is used to create a temperature difference between the hot and cold sides of the module. If a resistive load  $R_L$  is connected across the module’s output terminals, electrical power will be generated at the load when a temperature difference exists between the hot and cold sides of the module due to the Seebeck effect. A



**Figure 4.**  
A thermoelectric module configured for thermoelectric power generation.

schematic diagram of a thermoelectric module, operating as a thermoelectric power generator, is shown in **Figure 4**.

According to [11] the thermoelectric module open-circuit voltage  $V_{oc}$  can be obtained by:

$$V_{oc} = \alpha_m(T_h - T_c) \text{ measured in volts} \quad (26)$$

where  $\alpha_m$  is the thermoelectric module's average Seebeck coefficient in volts per kelvin and may be found quoted in manufacturer's literature. If a load resistance  $R_L$  is now connected across the output terminals of the thermoelectric module, the current  $I$  can be found by:

$$I = \frac{V}{R_m + R_L} \text{ measured in amperes} \quad (27)$$

where  $V$  is the closed-circuit voltage and  $R_m$  is the thermoelectric module's average resistance in Ohms. As the Seebeck coefficient and module resistance are temperature dependent, their values should be calculated at the average or mean module temperature  $T_m$  given by:

$$T_m = \frac{T_h + T_c}{2} \text{ measured in kelvin} \quad (28)$$

The voltage at the load  $V_L$  can be found by:

$$V_L = I_L \times R_L \text{ measured in volts} \quad (29)$$

where the current at the load  $I_L$  is equal to the circuit current  $I$ . The electrical power generated by the module at the load can then be found by:

$$P_L = I_L^2 \times R_L \text{ measured in watts} \quad (30)$$

or by using:

$$P_L = V_L \times I_L \text{ measured in watts} \quad (31)$$

The efficiency  $\eta$  of the thermoelectric module can be found by:

$$\eta = \frac{P_L}{Q_h} \quad (32)$$

The cooling power at the hot side of the thermoelectric module  $Q_h$  can be found by:

$$Q_h = (\alpha_m)IT_h - (T_c - T_h)(K_m) - \frac{I^2(R_m)}{2} \text{ measured in watts} \quad (33)$$

The efficiency  $\eta$  of the thermoelectric module can now be found by:

$$\eta = \frac{\left\{ \frac{(\alpha_m)(T_m)}{R_m + R_L} \right\}^2 R_L}{(\alpha_m)IT_h - (T_c - T_h)(K_m) - \frac{I^2(R_m)}{2}} \quad (34)$$

The thermoelectric figure-of-merit  $Z_T$  can be found using:

$$Z_T = \frac{\alpha_m^2 \sigma_m}{\lambda_m} \quad (35)$$

where  $\alpha_m$  is the module's average Seebeck coefficient,  $\sigma_m$  is the average electrical conductivity, and  $\lambda_m$  is the module average thermal conductivity, at a specific operating temperature.

## 2.4 A numerical analysis of a thermoelectric power generation module

If we consider a thermoelectric module, [12] have published some general material properties data for a 127 thermoelectric couple module. For the purpose of this analysis, we will use a hot side temperature  $T_H$  of 400 K, and a cold side temperature  $T_C$  of 300 K. The Seebeck coefficient and module resistance is temperature dependent, hence, their values should be calculated at the average module temperature  $T_m$  given by:

$$\begin{aligned} T_m &= \frac{T_h + T_c}{2} \text{ measured in kelvin} \\ T_m &= \frac{400 + 300}{2} \\ T_m &= 350 \text{ Kelvin} \end{aligned} \tag{36}$$

According to [12], with an average module temperature of 350 K, the module thermoelectric parameters are; a Seebeck coefficient  $\alpha_m$  of 0.05544 V/K; a module resistance  $R_M$  of 4.6491 Ohms; and a thermal conductivity  $K_M$  of 0.4422 W/K.

### 2.4.1 The thermoelectric module open-circuit voltage $V_{oc}$

The thermoelectric module open-circuit output voltage  $V_{oc}$  can be found by using (Eq. (26)) as:

$$\begin{aligned} V_{oc} &= \alpha_m(T_h - T_c) = 0.05544 \times (400 - 300) \\ V_{oc} &= 5.544 \text{ V} \end{aligned}$$

### 2.4.2 Connecting a load resistor $R_L$ across the output terminals of the module

If we set the load resistance  $R_L$  to the value of the internal resistance of the thermoelectric module  $R_M$  of 4.6491 Ohms, the load resistance becomes:

$$R_L = 4.6491\Omega$$

### 2.4.3 The closed-circuit voltage $V$

The open-circuit voltage  $V_{oc}$  was calculated in 2.4.1, and in this case, when a load resistor  $R_L$  is connected across the output terminals of the thermoelectric module, the closed-circuit voltage  $V$  is:

$$V = 5.544 \text{ V}$$

### 2.4.4 The circuit current $I$

With a load resistance  $R_L$  connected across the output terminals of the module, the current  $I$  can be found by (Eq. (27)) as:

$$I = \frac{V}{R_M + R_L} = \frac{5.544}{4.6491 + 4.6491} = \frac{5.544}{9.2982}$$

$$I = 0.596 \text{ A}$$

#### 2.4.5 The load current $I_L$ and the voltage generated at the load $V_L$

The load current  $I_L$  is the same value as the circuit current  $I$ , hence:

$$I_L = 0.596 \text{ A}$$

The voltage generated at the load can be found by (Eq. (29)) as:

$$V_L = I_L \times R_L = 0.596 \times 4.6491$$

$$V_L = 2.7710 \text{ V}$$

#### 2.4.6 The electrical power generated at the load $P_L$

The electrical power generated by the module at the load can now be found by (Eq. (30)) as:

$$P_L = I_L^2 \times R_L = 0.596^2 \times 4.6491$$

$$P_L = 1.6514 \text{ W}$$

or by using (Eq. (31)) as:

$$P_L = V_L \times I_L = 2.7710 \times 0.596$$

$$P_L = 1.6515 \text{ W}$$

#### 2.4.7 The efficiency of the thermoelectric module $\eta$

The cooling power at the hot side of the thermoelectric couple  $Q_h$  can be found by (Eq. (33)) as:

$$Q_h = (\alpha_m)IT_h - (T_c - T_h)(K_m) - \frac{I^2(R_m)}{2}$$

$$Q_h = ((0.05544) \times 0.596 \times 400) - ((300 - 400)(0.4422)) - \frac{0.596^2(4.6491)}{2}$$

$$Q_h = 13.2169 - (-100 \times (0.4422)) - \frac{0.3552 \times (4.6491)}{2}$$

$$Q_h = 13.2169 + 44.22 - 0.8257$$

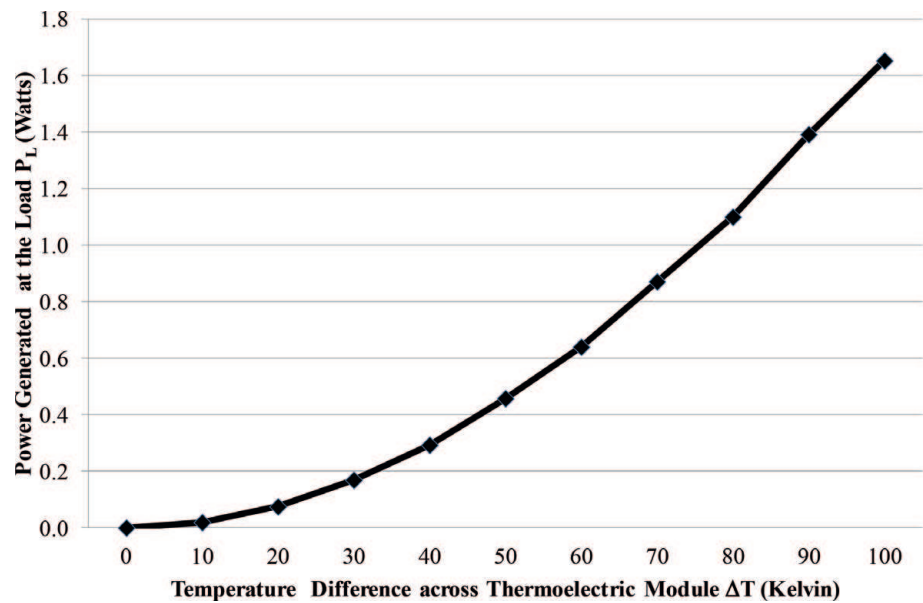
$$Q_h = 56.62 \text{ W}$$

Hence, the efficiency of the thermoelectric module  $\eta$  can now be found by Eq. (32) as:

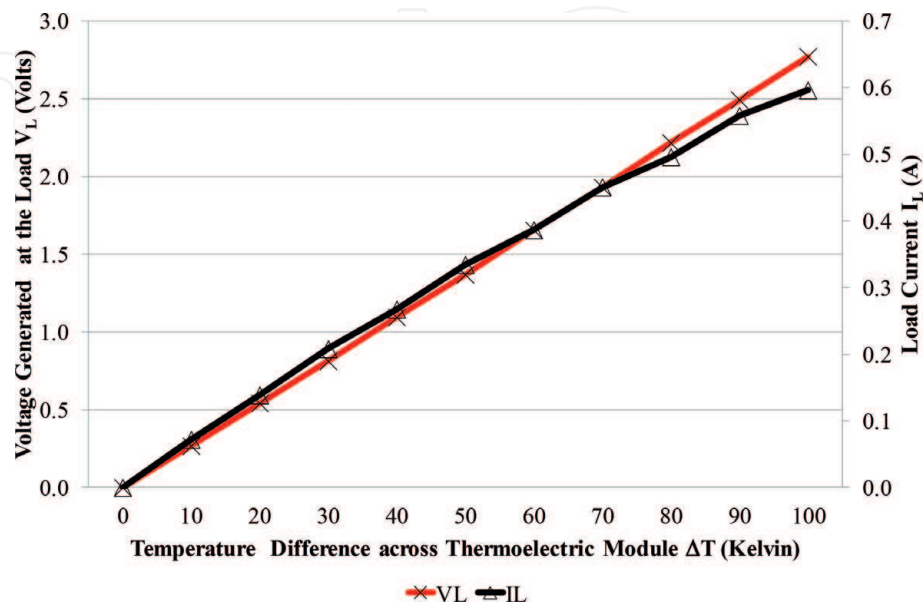
$$\eta = \frac{P_L}{Q_h} = \frac{1.6515}{56.62}$$

$T_H$	$T_C$	$T_m$	$\Delta T$	$\alpha_m$	$K_m$	$R_m$	$R_L$	$V_{oc}$	$V_L$	$I$	$P_L$	$Q_h$	Efficiency
K	K	K	K	V/K	W/K	$\Omega$	$\Omega$	V	V	A	W	W	$\eta$ %
300	300	300	0	0.05343	0.35	3.72	3.72	0.00	0.00	0.00	0.00	0.00	0.00
310	300	305	10	0.05343	0.35	3.72	3.72	0.53	0.27	0.07	0.02	4.65	0.41
320	300	310	20	0.05418	0.36	3.91	3.91	1.08	0.54	0.14	0.08	9.55	0.79
330	300	315	30	0.05418	0.36	3.91	3.91	1.63	0.81	0.21	0.17	14.40	1.17
340	300	320	40	0.05477	0.37	4.10	4.10	2.19	1.10	0.27	0.29	19.81	1.48
350	300	325	50	0.05477	0.37	4.10	4.10	2.74	1.37	0.33	0.46	24.90	1.84
360	300	330	60	0.05519	0.39	4.28	4.28	3.31	1.66	0.39	0.64	30.98	2.07
370	300	335	70	0.05519	0.39	4.28	4.28	3.86	1.93	0.45	0.87	36.33	2.40
380	300	340	80	0.05542	0.42	4.47	4.47	4.43	2.22	0.50	1.10	43.19	2.55
390	300	345	90	0.05542	0.42	4.47	4.47	4.99	2.49	0.56	1.39	48.82	2.85
400	300	350	100	0.05544	0.44	4.65	4.65	5.54	2.77	0.60	1.65	56.62	2.92

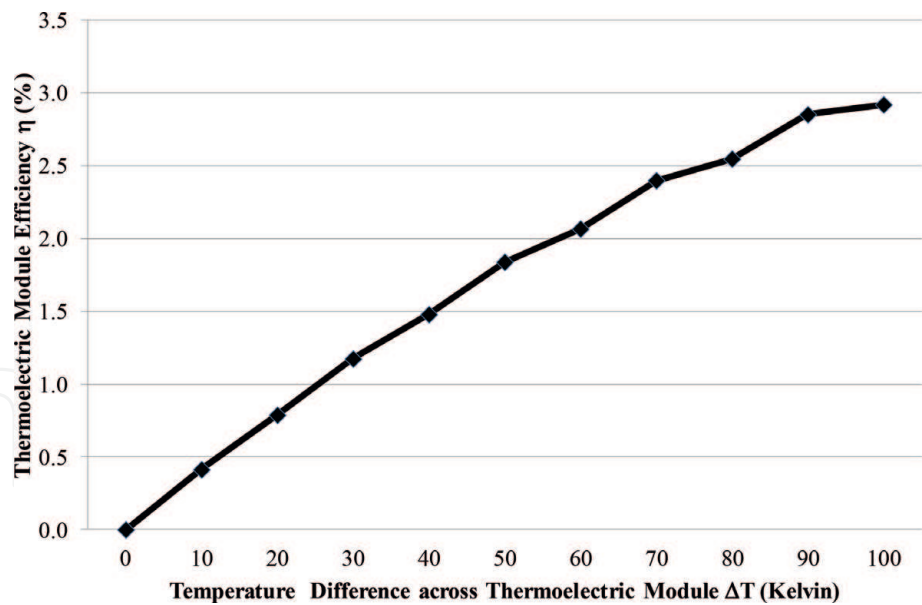
**Table 1.**  
Summary of performance characteristics of a 127 couple thermoelectric module obtained by theoretical calculation.



**Figure 5.**  
Power generated at the load  $P_L$  with a temperature difference  $\Delta T$  between 0 and 100 Kelvin (theoretical results).



**Figure 6.**  
Voltage  $V_L$  and Current  $I_L$  generated at the load with a temperature difference  $\Delta T$  between 0 and 100 Kelvin (theoretical results).



**Figure 7.**  
Thermoelectric module efficiency with a temperature difference  $\Delta T$  between 0 and 100 K (theoretical results).

$$\eta = 0.0292$$

$$\text{or } \eta = 0.0292 \times 100 = 2.92\%$$

2.4.8 Numerical analysis of the 127 couple thermoelectric module configured for thermoelectric power generation with a temperature difference  $\Delta T$  varied between 0 and 100 K

A summary of the performance characteristics of the 127 couple thermoelectric module obtained by theoretical calculation is shown in **Table 1**. The temperature difference  $\Delta T$ , which is equal to  $T_H - T_C$ , has been varied between 0 and 100 kelvin, in 10 kelvin steps, and the results calculated. The thermoelectric module's power generated at the load  $P_L$ , voltage  $V_L$ , current  $I_L$ , and efficiency  $\eta$ , is shown in **Figures 5–7** respectively. The results demonstrate the theoretical electrical power generated by a 127 couple thermoelectric module is typically in the mW to watt range when the module is subject to a temperature difference from 10 to 100 K.

3. Thermoelectric power generation and energy harvesting system

Thermoelectric power generation systems have typically needed to have a very high temperature gradient across the thermoelectric module(s) in order to achieve a useful electrical power output. This limitation has been a barrier to the successful application of this technology for power generation, and limited the technologies use to mainly niche applications, for example, in deep-space spacecraft power. However, with parallel developments in the area of electrical energy storage in supercapacitors, and low power DC to DC converters and boost converters, it is possible to develop a thermoelectric energy harvesting system that will operate from very low temperature gradients of around 1 K and be able to output useful power levels. This was previously very difficult to achieve and would have required several thermoelectric modules to be connected electrically in series, and thermally in parallel, increasing the overall system weight, size, and cost, and would only

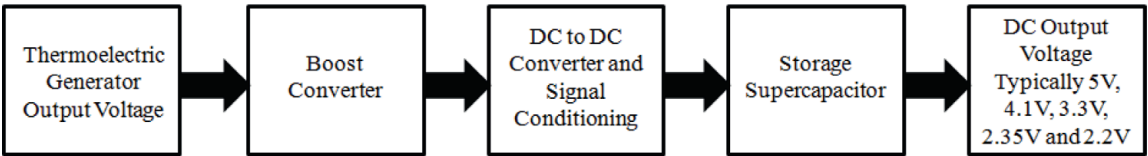
achieve relatively small levels of power generation unless a significant temperature gradient could be achieved across the modules.

The thermoelectric output voltage generated by a standard thermoelectric module can be boosted to a useful and stable level by using a low power boost converter and DC to DC converter. If the electrical power output from the DC to DC converter is then accumulated and stored for future use in a supercapacitor, it is possible to increase the potential output current of the system, and hence the overall power output of the thermoelectric energy harvesting system. A simplified block diagram of a thermoelectric energy harvesting system is shown in **Figure 8**, highlighting the five main stages of the system. The energy stored in the supercapacitor can be accumulated over time and released to the load when required. In some applications, it may be advantageous to use a voltage regulator after the supercapacitor in order to maintain a stable output voltage to the load.

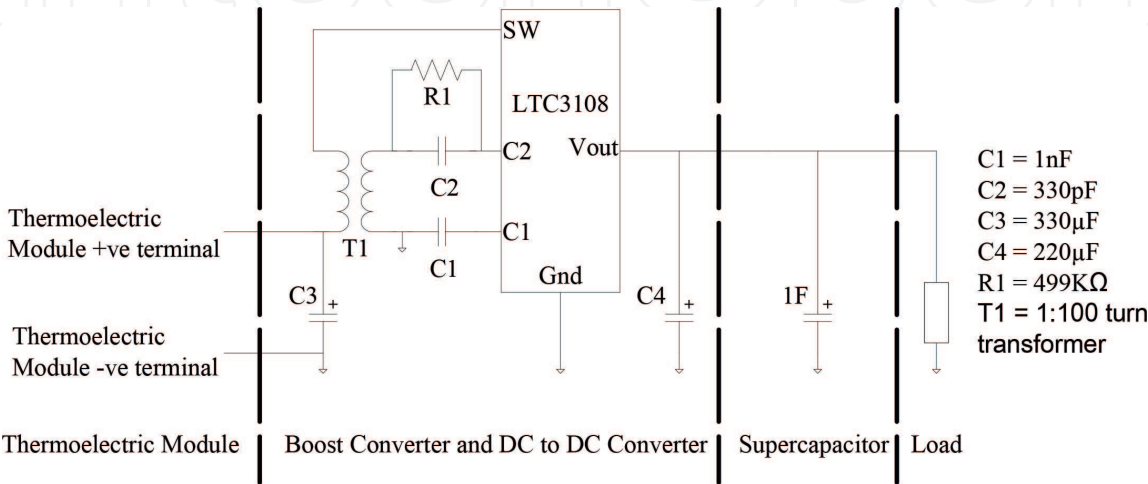
In general, the duty cycle of the electrical load is a critical factor in determining the design of a thermoelectric energy harvesting system. As highlighted earlier, the output power of a single thermoelectric module is often too low to power other electrical and electronic components directly unless a significant temperature difference or gradient is available, or several thermoelectric modules are connected together electrically in series and thermally in parallel. The use of temporary electrical storage in supercapacitors leads to a focus on the duty cycle of the load, as it is necessary to ensure the capacitor can be recharged before the load becomes active to ensure repeatable and reliable operation.

3.1 Thermoelectric energy harvesting circuit

A thermoelectric energy harvesting circuit to power an electronic load is shown in **Figure 9**, and is based around a Linear Technology LTC3108 step-up DC to DC converter. The thermoelectric module output voltage is in the mV range when the



**Figure 8.**  
*Simplified thermoelectric energy harvesting block diagram [14].*



**Figure 9.**  
*Thermoelectric energy harvesting circuit [14].*

module is subject to a small temperature difference, and is boosted to a useful level by the LTC3108 step-up converter. The LTC3108 uses a boost converter, in the form of an external step-up transformer, an internal MOSFET and associated circuitry within the DC to DC converter, to increase the voltage from the thermoelectric module. Within the converter, a MOSFET switch is used to form a resonant step-up oscillator using an external 1:100 turn transformer and a small coupling capacitor  $C3$  of around 330  $\mu\text{F}$ . The frequency of oscillation is determined by the inductance of the transformer secondary winding and is typically in the range of 10–100 kHz. The AC voltage that is developed on the secondary winding of the transformer is boosted and rectified using an external charge pump capacitor  $C1$  of 1 nF and the internal rectifiers within the DC to DC converter. The DC to DC converter itself is powered via the internal VAUX circuitry, from the input voltage supplied by the thermoelectric module, and when the VAUX supply exceeds 2.5 V, the main output of the DC to DC converter  $V_{out}$  becomes operational and can be programmed by the user to one of four regulated voltages of; 2.35; 3.3; 4.1; and 5 V [13]. The converter operates at very low input voltages of 20 mV, which can be achieved when a 1 K or higher temperature difference exists between the ‘hot’ and ‘cold’ sides of the thermoelectric module. Dependent on the input power received from the thermoelectric module, the DC to DC converter output  $V_{out}$  will be charged over time up to its regulated voltage [13], and in this case, the 1F supercapacitor will charge up to 5 V at a maximum current of 4.5 mA.

### 3.2 Evaluation of the thermoelectric energy harvesting system

For the purpose of evaluation, a Melcor CP1.4-127-045L thermoelectric module and HX8-202-FM heat sink is connected for power generation, with a hot side temperature  $T_H$  of 323 K, and a temperature difference between both sides of the module  $\Delta T$  of 9 K, the thermoelectric module’s open-circuit voltage is 310 mV. An LTC3108EDE step-up DC to DC converter evaluation board, configured to output 5 V on the  $V_{out}$  pin, was connected to the thermoelectric module output terminals as shown in **Figure 9**. When the thermoelectric module is connected to the LTC3108 converter, the module’s output voltage and current is 116 mV at 30 mA. The boost converter and DC to DC converter increase the thermoelectric output voltage and supply a stable voltage of 5 V at 0.4 mA to the 1F storage supercapacitor, charging the supercapacitor. The 1F supercapacitor reaches maximum charge after approximately 3 h [14]. Increasing the temperature difference across the thermoelectric module, and therefore increasing the thermoelectric module’s output power, would have the effect of increasing the output current of the DC to DC converter, up to a maximum of 4 mA, reducing the capacitor charge time significantly.

If an electrical load is connected across the supercapacitor output terminals, the supercapacitor will discharge and supply electrical power to the load. For evaluation purposes, a number of different electrical loads have been tested, and successfully operate from the electrical power delivered from the supercapacitor during discharge including; a piezoelectric buzzer; light emitting diode (LED); humidity sensor; pressure sensor; low power microcontroller; DC motor; and a miniature electronic water pump.

The piezoelectric buzzer, LED, humidity sensor, and pressure sensor can be powered for a considerable amount of time before the 1F capacitor becomes discharged. For example, a Maplin electronic KU58 piezoelectric buzzer operates between 3 and 12 V with a maximum input current of 2.38 mA at 5 V, and successfully operates above 3 V for 18 minutes, and is still audible for in excess of one and a half hours when connected to the 1F supercapacitor. The miniature electronic water pump, DC motor, and low power microcontroller operate successfully from the 1F

supercapacitor, however, the evaluation system would benefit from scaling the storage 1F capacitor appropriately to enable stable operation for significant periods of time. Notwithstanding this, and focusing on the miniature electronic water pump, an RS components 702-6894 electronic micropump that has an operating voltage of 1.2–6 V was connected to the output terminals of the 1F supercapacitor. The pump inlet and outlet tubes were connected together to form a 10 cm length of plastic tube, filled with water, and was seen to successfully pump this water around the tube for approximately 1 min and 30 s. Once the water pump minimum supply voltage of 1.2 V was reached during the first 35 s of the supercapacitor's discharge, the pump continued to operate, although at a reduced flow rate than observed earlier. The water pump draws a maximum input current of 72 mA at 5 V and can achieve a maximum flow rate of 150 ml per minute [14].

In general, a device with a; low input voltage; low current consumption; and a wide operating input voltage range; can be powered for a considerable amount of time directly from the supercapacitor. It should be noted that the performance of the two test circuits can be improved, with the addition of a resistor in series with the load in order to limit the current drawn by the load, or by using a voltage regulator after the supercapacitor, with an appropriate output capability, which would supply a stable output voltage to the load [14].

#### **4. Discussion**

The electrical output power obtained from a standard thermoelectric module is relatively small and in the mW range unless a significant temperature gradient can be achieved across two sides of the module, however, in common with other energy harvesting technologies, if the output voltage of the thermoelectric module is boosted to a useful level, i.e., to common battery supply voltages of; 5; 3.3; 1.5 V etc.; by using low power boost converters and DC to DC converters, and electrical energy storage in supercapacitors, practical thermoelectric energy harvesting systems can be realized which can output sufficient electrical power to operate low power electrical and electronic systems. This approach leads to a focus on the electrical load's duty cycle. Systems that rely on boost conversion and energy storage require the storage capacitor to be recharged in periods of load inactivity to enable continuous operation over an extended period of time. If the electrical load requires continuous power to operate, and the output power of the thermoelectric module is too low to power the load directly, the storage supercapacitor will eventually discharge completely and be unable to continuously power the load. However, in many applications the load does not need to be continuously powered—electronic sensors, microcontrollers, and RF networks often only need to make periodic readings, processing, and transmission cycles, and can be put into a low power 'sleep' mode when not in operation, drawing only a low quiescent current until 'waking-up' and drawing full current, allowing the supercapacitor time to recharge to a fully charged state. Applications where the electrical load is powered intermittently have become a focus for implementing low power thermoelectric energy harvesting systems.

The contemporary focus on low power energy harvesting systems will enable new thermoelectric applications to emerge and be realized. Thermoelectricity is commercially successful, having previously found applications in power generation for deep-space spacecraft power, military, and other niche applications. Recent focus has enabled thermoelectricity to replace or recharge batteries in low power electronic systems.

The short-term challenge for thermoelectric energy harvesting is to become a cost effective and practical solution to replace batteries in mainstream applications where access to temperature gradients or differences is available. Commercial success is often found in niche applications where there is a definite need and advantage, as the direct comparison with standard battery powered systems can highlight disadvantages of cost, size, weight, and complexity. However, as high volume thermoelectric applications emerge and are realized, the direct comparison with batteries will improve. Furthermore, with appropriate scaling and development, electrical rotating machines such as low power motors and pumps can be powered by a thermoelectric energy harvesting system, opening new applications and industries for exploitation.

The long-term challenge is to improve the efficiency and output power of thermoelectric modules, to develop new thermoelectric materials and module fabrication technologies, to reduce the cost of thermoelectric modules and energy harvesting systems, and to develop thermoelectric energy harvesting systems from low power to low-to-medium power applications.

## 5. Conclusions

Thermoelectric energy harvesting systems can be implemented to generate sufficient electrical power from naturally occurring or man-made heat sources to provide power to low power electrical and electronic components and systems. The duty cycle of the electrical load is, in general, a critical factor in determining the feasibility of implementation as, without the addition of power electronics and electrical energy storage, the output power of a single thermoelectric module is often too low to power other electrical and electronic components directly unless a significant temperature difference or gradient is available, or several thermoelectric modules are connected together electrically in series and thermally in parallel. To overcome this limitation, energy harvesting systems typically employ a low power boost converter and DC to DC converter to increase the thermoelectric module's output voltage to a useful level, i.e., 5, 3.3, or 1.5 V, and use a supercapacitor for temporary electrical energy storage and to provide power to an electrical load. The use of temporary storage in supercapacitors leads to a focus on the duty cycle of the load, as it is necessary to ensure the capacitor can be recharged before the load becomes active again to ensure repeatable and reliable operation. Successful applications have tended to be where there is a distinct need and advantage for implementation, and by replacing or recharging a battery in remote locations which are difficult to maintain and service. The short-term challenge for thermoelectric energy harvesting is to become a cost effective and practical solution to replace batteries in mainstream applications where access to temperature gradients or differences is available, and to be scaled to provide sufficient electrical power, and for the required duration, to enable electrical rotating machines such as low power motors and pumps to operate. The long-term challenge is to improve the efficiency and output power of thermoelectric modules, to develop new thermoelectric materials and fabrication technologies, to reduce the cost of thermoelectric modules and energy harvesting systems, and to develop thermoelectric energy harvesting systems from low power to low-to-medium power applications.

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### **Author details**

Chris Gould  
Staffordshire University, Stoke-on-Trent, United Kingdom

\*Address all correspondence to: [c.a.gould@staffs.ac.uk](mailto:c.a.gould@staffs.ac.uk)

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