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Energy harvesting power supply for wireless sensor networks

Investigation of piezo- and thermoelectric micro generators

Nils Edvinsson

UPPSALA
UNIVERSITET

**Teknisk- naturvetenskaplig fakultet
UTH-enheten**

Besöksadress:
Ångströmlaboratoriet
Lägerhyddsvägen 1
Hus 4, Plan 0

Postadress:
Box 536
751 21 Uppsala

Telefon:
018 – 471 30 03

Telefax:
018 – 471 30 00

Hemsida:
http://www.teknat.uu.se/student

Abstract

Energiutvinnande kraftkälla för trådlösa sensornätverk

Energy harvesting power supply for wireless sensor networks

Nils Edvinsson

Computers and their constituent electronics continue to shrink. The same amount of work can be done with increasingly smaller and cheaper components that need less power to function than before. In wireless sensor networks, the energy needed by one sensor node borders the amount that is already present in its immediate surroundings.
Equipping the electronics with a micro generator or energy harvester gives the possibility that it can become self-sufficient in energy.
In this thesis two kinds of energy harvesters are investigated. One absorbs vibrations and converts them into electricity by means of piezo-electricity. The other converts heat flow through a semiconductor to electricity, utilizing a thermoelectric effect. Principles governing the performance, actual performance of off-the-shelf components and design considerations of the energy harvester have been treated.
The thermoelectric micro generator has been measured to output power at 2.7 mW and 20 degree Celsius with a load of 10 Ohms. The piezoelectric micro generator has been measured to output power at 2.3 mW at 56.1 Hz, with a mechanical trim weight and a load of 565 Ohms. In these conditions the power density of the generators lies between 2-3 W/square meter.

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Ämnesgranskare: Anders Rydberg
Examinator: Martin Sjödin
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Energy harvesting power supply for wireless sensor networks – investigation of piezo- and thermoelectric micro generators

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Abstract

Computers and their constituent electronics continue to shrink. The same amount of work can be done with increasingly smaller and cheaper components that need less power to function than before. In wireless sensor networks, the energy needed by one sensor node borders the amount that is already present in its immediate surroundings. Equipping the electronics with a micro generator or *energy harvester* gives the possibility that it can become *self-sufficient in energy*.
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Sammanfattning

Datorer och deras elektroniska beståndsdelar fortsätter krympa. Samma mängd arbete kan utföras med allt mindre och billigare komponenter som behöver mindre energi än tidigare. I trådlösa sensornätverk gränsar mängden energi som krävs för att driva en sensornod till den mängd energi som redan finns i nodens omedelbara omgivning. Genom att utrusta elektroniken med en mikrogenerator, eller energiutvinnare, finns möjligheten att den kan bli självförsörjande på energi.
I denna rapport undersöks två typer av energiutvinnare. Den ena typen absorberar vibrationer och konverterar dem till elektricitet genom piezoelectricitet. Den andra typen konverterar ett värmeflöde genom en halvledare till electricitet genom att utnyttja en termoelektrisk effekt. Principerna som styr energiutvinnarnas prestanda, prestanda hos komponenter från hyllan och överväganden vid energiutvinnarens utformning har behandlats. För den termoelektriska mikrogeneratorn har effekter på 2.7 mW vid 20°C uppmätts vid en last på 10 Ω. För den piezoelektriska migrogeneratorn har en effekt på 2,3 mW vid 56 Hz och mekanisk trimvikt uppmäts med en last på 565 Ω. Effekttäheten för dessa generatorer och förutsättningar ligger mellan 2-3 W/m^2.

Preface

The purpose of this thesis is to investigate basic behaviour of energy harvesters and see what available products can manage in this role. At the time of this thesis, energy harvesting is a new and growing field. The products investigated have originally been designed to be used in another capacity, such as actuators, sensors or in cooling and are thus not optimized for maximum power output when used as energy harvesters. The information obtained is intended to aid in the choice of electronic components and general design of sensor nodes.

The thesis treats the piezoelectric and the thermoelectric energy harvesters. This choice is based on availability; the components investigated are readily available. The power supply circuits available on the market intended for energy harvesting are also designed for these kinds of input.

The author of this thesis is Nils Edvinsson and it was written for his Bachelor of Science degree in Engineering Physics.

The client of this thesis is Uppsala University and its role has been in providing equipment, subject examiners, supervisors and premises.
Subject inspector is Anders Rydberg, Uppsala University, Department of Engineering Sciences and thesis supervisor is Mathias Grudén, Uppsala University, Department of Engineering Sciences.

During the writing process, the author worked with an energy harvester power supply as a member of a project group, whose purpose was to develop and realize a wireless sensor network. With hardware and support from UPWIS AB, a project participant, the group prototyped a wireless sensor network for the Swedish Transport Administration. At present, it has survived its first deployment on a train and is under evaluation.

The author wishes to thank everybody involved for their support and help. Without them, finishing both the thesis and the project would have been most difficult. Special thanks are extended to the project colleagues, Malkolm Hinnemo, Filip Zherdev and Thomas Edling, and to his supervisor Mathias Grudén, for their valuable input (and output).

Nils Edvinsson,
Uppsala, April 2012.

Content

1. Introduction

1.1 Wireless sensor networks

Wireless sensors sense natural phenomena like temperature, pressure, acceleration, etc. and then transmit the sensor data via radio. Sensors, wireless or not, play an important role in technical systems since they give a picture of the systems status. Complex systems may need a range of sensor data to be processed before assessing the state of the system and the measurements may need to be taken very often to reflect quick changes. Some systems may require a large area covered or present difficult communications problems. These are factors that tend to increase the number of needed sensors. By collecting the sensors in a wireless sensor network, some of the problems may be alleviated: Signals can be rerouted around difficult obstacles through the network. Synchronized transmissions from several nodes simultaneously can increase communications range. A busy sensor node can have its sensor data processed by idle nodes somewhere else in the network.

1.1.1 Power supply for wireless devices

Wireless devices are easy to place and install with no wires needed but on the downside comes the problem of power supply. The conventional way to power wireless devices are by battery, which works well when the number of devices are small and the batteries are easy to replace. If this is not the case other solutions are needed to retain the advantages of a network configuration. If a battery would last as long as the rest of the node, the power supply problem would be solved. Factors such as size and weight and ability to hold charge over time limits the use of conventional batteries. Fuels such as gasoline and hydrogen acts as energy reservoirs in conventional large scale systems. More exotic energy reservoirs are the nuclear powered assemblies in space probes. By combining an on-board generator with a suitable form of energy storage the size of a complete network node could possibly be reduced and the service interval would increase, reducing cost. The size of the node affects the energy requirements; generally smaller devices need less energy.

1.1.2 Energy harvesting

Energy harvesting is a unifying term for methods and techniques that utilizes energy sources that are normally insufficient and of too low quality. They are characterized by low energy density and high availability. The energy harvester is in general a small device, on the centimetre scale, and typically outputs electrical energy. It is used in devices with a low energy demand, such as in sensors and micro circuitry. Waste heat, ambient electromagnetic radiation and vibrations are typical energy sources for an energy harvester. The energy is harvested by a micro generator whose construction is dependent on the type of energy source and the mode of operation. Vibrations can for instance be harvested by a mechanical device or a solid state device. Conventional energy sources such as solar and wind can also be utilized. In some cases large scale technology is simply miniaturized. Further considerations like physical size, power demand, robustness, etc. affect the design. By utilizing energy harvesting, shortcomings of today’s sensor node powering scheme can be remedied. The on-board battery can be shrunk or eliminated, which in turn reduces the environmental impact of the node and battery production costs. Since no wires are needed, nodes can be placed in sealed systems and the network connections are more resilient against disruptions. The possibility of low production costs, small size and no maintenance allows for the use of a much larger number of sensor nodes than today.

1.1.3 Application for energy harvesting

Train cars today are monitored from stationary detectors for faults in the wheel area to warn for accidents and reduce wear on the rail. At present, the detectors can only detect severe damage, when an alarm is triggered the train car needs to be removed from traffic.

A system that provides an earlier warning and status messages is desired. With it repairs and maintenance can be administered when the need arise instead of at fixed times and places or after a breakdown. This will reduce costs and increase service time. The system would need a group of sensors to accurately sense the current condition and the amount of sensors must be comparable with the many check-up points a manual inspection would go through. If every sensor node was to be powered by ordinary batteries, the replacement work to keep the network running would only add to the ordinary maintenance check-up. Energy harvesting would remove this problem.

1.1.4 Duty cycling

With energy storage the power production and usage only need to be equal over a period of time. Power is amount of energy used (or produced) per time unit. The energy stored can be used quickly, which corresponds to high power usage, or slowly which gives low power. Saving energy for use later in a periodical manner is termed duty cycling. This allows a time for energy usage and a time for energy charging. The lower the input power, the longer the charge time becomes.

1.1.5 Power demand estimates

Murugavel Raju (2008) at Texas Instruments estimates power demand in electronics of medical use. Three kinds are considered: Implanted medical device, In-ear device and Surface-of-skin device. These are believed to need at least 10 µW, 1 mW and 10 mW respectively. Cottone (2007) compares linear length with power demand for known and possible future devices. It is stated, among other devices, that the typical power demand of electronics with the linear length of 1 to 10 cm, use 80 mW to 10 W. Smaller devices at 0.1 to 1 cm, would need 100 µW to 100 mW.

1.1.6 Project Clients

UPWIS AB and the Swedish Transport Administration have attempted to remedy the limitations from the stationary detectors using wireless sensor technology. A prototype circuit has been developed by UPWIS AB containing sensors, wireless communications, signal processing and energy management. The energy management module is prepared for several different energy harvesting inputs including vibration, thermoelectric and solar energy.

1.1.7 Scope of this thesis

This is a literature and feasibility study of possible technology for an energy harvesting power supply solution for the UPWIS AB circuit and similar electronics. Starting from the circuit provided by UPWIS AB, performance of a piezoelectric vibration energy generator and of a thermoelectric generator is assessed in laboratory conditions with respect to power output and size. Specific use of power by the circuit, such as duty cycling, is not investigated at this time. The UPWIS AB circuit was still under development during the writing of this text and its energy needs not entirely determined.

2. Available Technology

2.1 Piezoelectricity

Piezoelectricity converts mechanical energy into electrical energy, when under mechanical stress a voltage appears across the slab. It is a solid state phenomenon, a property of certain materials. Thus it is possible to convert mechanical forces and movements into electric energy without any moving parts or intricate machinery. The opposite is also true, if a voltage is applied the slab will deform.

One characteristic of piezoelectricity is that it appears at quite high voltages, up to thousands of volts. This makes it suitable for sensor applications since even slight disturbances give a clear signal.

The major applications of piezoelectric components are as sensors and actuators. Common sensor types are strain, pressure and sound which in turn can be used to detect motion and acceleration. Common actuator types are loudspeakers and linear motion. The movement is very small and precise and is for example used in ultrasound loudspeakers and servo motors such as in cameras. The high voltage capability also makes it suitable in electric spark generating devices.

2.2 Thermoelectricity

Thermoelectric effects connect a temperature difference to an electrical voltage and are a solid state phenomenon. The most common thermoelectric effects are the Peltier effect and the Seebeck effect: "The Seebeck effect and the reverse phenomenon, the Peltier effect, are the principal elements of thermoelectrics..." (Rowe, 1995).

The Peltier effect arises when current is lead through two different conductors in electrical contact. The effect is that one end is cooled and the other heated with the heat transported by the electrical current. The Seebeck effect is the opposite of the Peltier effect. In this case a temperature difference is applied which produces an electric current. The Peltier effect is used in cooling applications or in situations where precise temperature control is needed, reversing polarity switches the hot and cold sides. The advantages are its solid state operation, no moving parts, small size, weight and no noise while the disadvantages are price and efficiency.

Compared to other cooling technology it is quite small making it possible to cool or temperature stabilize components in crammed spaces or in mobile systems. The Seebeck effect is used mainly in temperature probes but also in small scale electric generation, such as charging batteries, where heat is readily available. The efficiency is poor which makes this kind of electricity generation on a large scale very expensive. As a generator it is used mainly in mobile and specialized applications.

2.3 Electromagnetic induction

Electromagnetic induction is a phenomenon that connects mechanical force to an electrical current. The force drives a magnetic field to change inside a pickup coil, which through electromagnetic interaction will produce an electrical voltage at its terminals. The opposite would be an electrical motor or an electrical actuator. Generation of electricity through induction is the main way large scale electric power is produced. It requires some moving parts and the movement is linear or rotational. Induction generators are relatively cheap to build but are heavy and bulky, in part by design.

2.4 Electromagnetic radiation

The electromagnetic radiation, known as radio, is a traveling wave of changing electromagnetic fields. This changing em-field can be received by an antenna and rectified to a current without any moving parts. The amount of energy collected is dependent on the distance to the source or sources and the shape and size of the antenna. The frequency and wavelength of the radiation determines what shape and size the antenna should have to work optimally. It is desired that the antenna as an energy receiver is broad banded, can collect as many frequencies as possible.

2.5 Wind

Wind energy is kinetic energy of air in motion and the energy available depends on the wind speed. Wind power is a growing technology for large scale electricity production. On the micro scale wind becomes more available since small movements and gusts can be collected but then the energy content is low. Utilizing wind to power electronics also has the drawback that some part or another must be exposed to the wind and cannot be shielded from destructive forces.

2.6 Solar

Solar power is radiation from the sun reformed in a solid state process inside a solar cell to electricity. It is used in a variety of applications from small scale devices like calculators to large scale commercial power production. Since solar panels needs light it cannot be used in dark environments and need transparent shielding. It is also susceptible to dirt and dust coatings.

3. Theory and principles

3.1 Heat and thermal energy

Thermodynamically, "**Heat** is defined as *the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference"* (Çengel et al., 2008).
The energy form is called *thermal energy*, what is meant by concepts like *heat flow* is that thermal energy is transferred from a warm system to a cold system.
Heat energy at the microscopic level is thought of as kinetic and rotational energy in the atoms and molecules of the system. Increasing the temperature is equivalent to raising the energy and speeds of the particles. This is why fluids and gases expand when heated since the molecules will collide which in turn creates a certain pressure. In solids where movement is restricted, the heat energy makes the atoms vibrate.

3.1.1 Energy in a classical monatomic gas

If the particles of the system are single atoms and not molecules, such as in helium or neon gas, they only have kinetic energy, "*A"* in figure 1 below. There is nothing to rotate or vibrate, as in *"B"* and "C*"*. A classical gas is an idealization of a gas where the

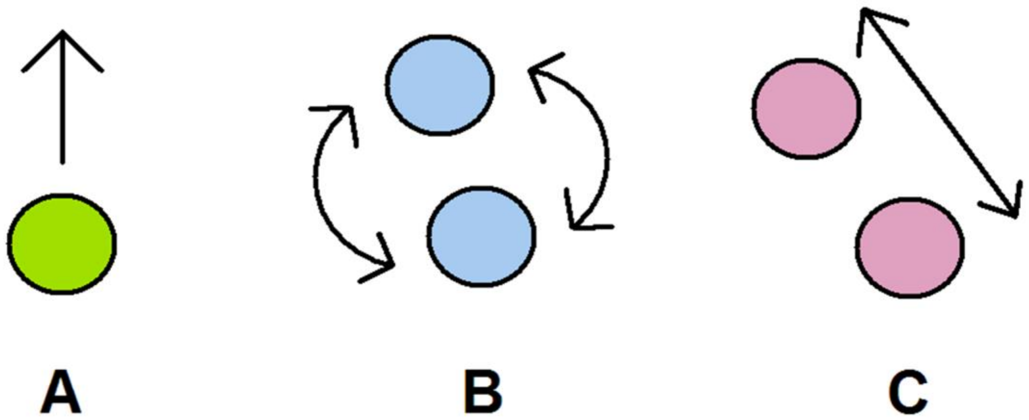

Figure 1: Heat energy in classical gasses. In A, heat energy is supplied to a monatomic gas which can only move about. In B and C heat energy is supplied to a diatomic gas. In B, the energy causes the molecule to rotate and in C it causes the atoms of the molecule to vibrate about its center of gravity.

molecules do not interact with each other. Assuming energy is only transferred by heat, the internal energy of a system is

$$U = \frac{3}{2} NkT \tag{3.1}$$

where N is the number of particles of the system, k is *Boltzmann's constant* and T the temperature.

3.1.2 Heat capacity of a classical monatomic gas

The heat capacity of a system is a measure of the increase in temperature of the system for the heat energy put into it. On average, assuming no melting occurs, it is

$$C = \frac{dU}{dT} = \frac{đQ}{dT} \tag{3.2}$$

The heat capacity of a system at constant volume, containing an ideal or perfect classical monatomic gas, is given by:

$$C_V = \frac{3}{2} Nk \tag{3.3}$$

Here the C_V means the heat capacity at constant volume, N is the number of gas molecules and k the Boltzmann's constant, as in (3.1) above.

3.1.3 Heat capacity of electrons

Electrons in a metal can be treated like a classical gas, with some modifications. In a solid metal the atoms are arranged in some regular crystal structure with electrons filling the space between them. Some of the electrons act as charge carriers and move about freely inside the crystal. They are single particles and can only have kinetic energy, no vibrational or rotational. Thus they can be considered as an *electron gas*. By using quantum mechanical statistics to the free electrons, it can be shown that the contribution to the heat capacity of the solid from the electrons is linear in temperature. As the temperature increases the major part of the heat capacity is overtaken by crystal lattice vibrations. (Zemansky & Dittman, 1997).

Mandl (2006) derives an expression for the heat capacity per electron, the specific heat:

$$c_V(T) = \frac{\pi^2}{2} k \frac{1}{T_F} T \tag{3.4}$$

With N free electrons, the heat capacity of a system becomes just

$$C_V(T) = \frac{\pi^2}{2} k \frac{1}{T_F} NT = \frac{\pi^2}{2} \frac{T}{T_F} Nk \tag{3.5}$$

T_F is the Fermi temperature, or Fermi energy, which quantum-mechanically corresponds to the energy level of the electron in the topmost shell of the atom at zero Kelvin. In temperature terms, this is quite large. Zemansky and Dittman estimates this temperature to around 50 000 K for copper. When comparing (3.3) with (3.5), it is seen that under ordinary temperatures, the contribution from electrons is quite small compared to a classical gas, due to the high value of T_F.

3.1.4 Heat conduction

Heat flow through a material depends not only on the temperature difference dT between the ends of the thermal conductor, but also on the thermal conductivity constant K of the material and of the cross sectional area A available for the heat to flow through. The total rate of heat flow $\frac{đQ}{dT}$ through a body is also dependent on the distance between the hot and cold side, x.

This is stated in *Fourier's heat conduction formula:*

$$\frac{đQ}{dT} = -KA\frac{dT}{dx} \tag{3.6}$$

3.1.5 Heat dissipation

In many applications it is desirable to remove excess heat and keep the components within a preferred temperature range. To accomplish this, heat is typically led away into a *heat sink*. A *heat sink* is to be thought of as a system at a certain temperature and being so large that the heat from the application does not raise the temperature of the heat sink. A common example of this arrangement is a computer cooling fan, with the air in the room as the low heat/cold reservoir. As long as the air in the room is colder than the computer, heat is transferred from the computer to the air.

3.1.6 Convection

Convection occurs where a solid and a fluid or a gas, with different temperatures, are in thermal contact. *Natural or free convection* is convection where the surrounding fluid flows by change in its density; the heat transferred to it causes the fluid to expand. In f*orced convection*, the convection flow is caused by external forces other than change in density, such as by wind or via a pump. Forced convection normally increases the heat transfer since more medium passes by. As a way to increase the energy transfer between solid and fluid, the *surface area* of the solid can be increased by adding fins. The greater the surface area, the better the thermal contact with the fluid. However, the flow through the fins is also slowed by the increased surface area.

3.2 Doping of materials and charge carriers

Most electronics are made from semiconducting materials. They are used in components like diodes and transistors and many of these are used to form more complex components. The processors in ordinary computers are very complex from this point of view and contain millions. Electric current is defined as amount of charge passed over a period of time. The current constitutes of *charge carriers*. These can be electrons, which are negative charge carriers, but also the absence of electrons, termed *holes*, which behaves as positive charge carriers. The concentration of charge carriers determines if the material is a conductor or insulator, increasing charge carrier concentration gives increasing electric conductivity. Semiconductors are named from the property that they both behave as electrical insulators and as conductors having a charge carrier density somewhere between conductors and insulators. By a process called *doping* small amounts of other elements are inserted into the semiconductor to modify the charge carrier concentrations. Some materials are not semiconducting prior to doping, others like silicon and germanium are semiconductors even without dopants. Such materials are called *intrinsic semiconductors.* The material can be n or p-doped, excess of negative or positive charge carriers, respectively. Dopants are called *donors* for n-dopants and *acceptors* for p-dopants. Thus an n-doped material contains a donor substance and a p-doped material contains an acceptor. In silicon and germanium elements like phosphorus, arsenic and antimony are donors while barium, aluminium, gallium and indium are acceptors. (Kittel, 2005).

3.3 The Seebeck effect

"An electrical potential (voltage) is generated within any isolated conducting material that is subjected to a temperature gradient; this is the absolute Seebeck effect, ASE." (D. M. Rowe, Daniel D. Pollock, et al. 1995).

Electrons carry heat, and since they carry electrical charge it is possible to affect heat flow with electrical fields. A *thermocouple* can be done by joining two dissimilar conductors electrically in one end and then apply a temperature differential from one end over to the other. It is equivalent to connecting the conductors in series and the temperature differential in parallel. This will create an electrical voltage over the unconnected ends, which is the Seebeck effect. In figure 2 below, the voltage would appear between A and C. If a voltage is applied over A and C, that is, the Seebeck *reversed*, heat is transported from one end to another, see figure 3. This effect is called the *Peltier effect* and is primarily used in cooling applications. The Seebeck and Peltier effect follow each other since they are caused by the same mechanisms; they cannot appear independently.

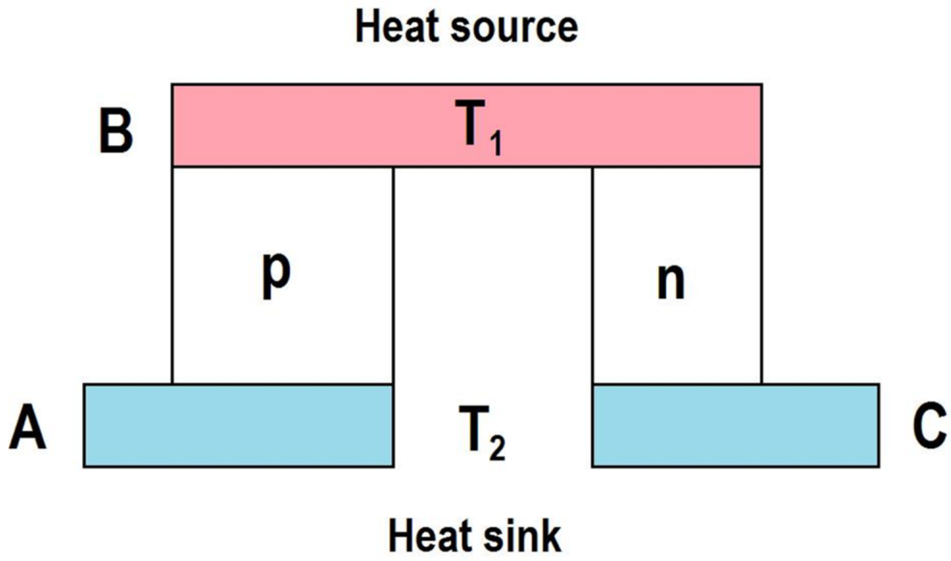

Figure 2: Example of setup for Seebeck effect. Two dissimilar conductors p and n are electrically connected in one end by conductor B. Conductors p and n experience a temperature differential, T1 and T2, between their ends. Thus, a voltage appear between A and C.

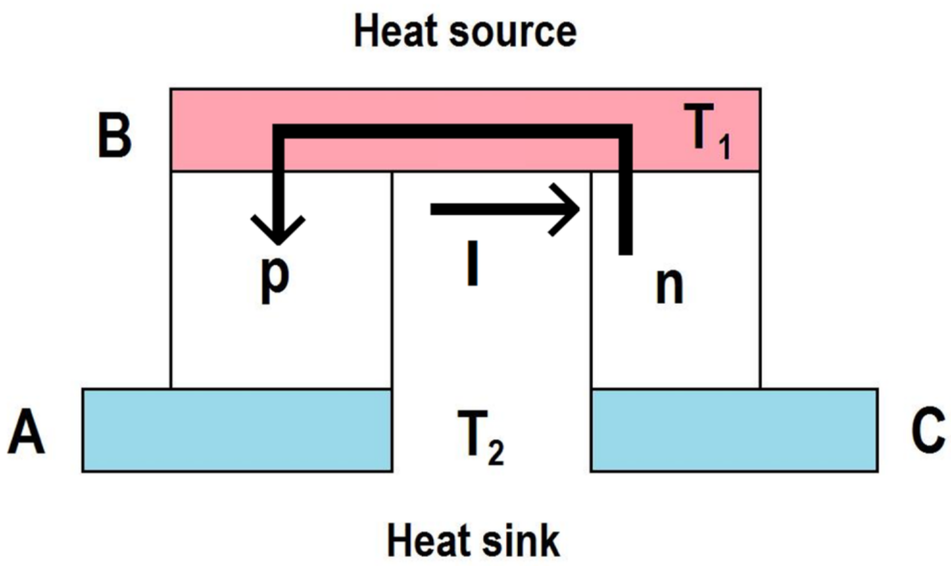

Figure 3: The n-doped leg has an excess of electrons and since they can be treated as a gas they will expand when heated to the p-doped leg which corresponds to a region of low pressure. Since electric current I is defined for positive charges, it is directed in the opposite electron flow direction.

3.4 Piezoelectric Effect

The piezoelectric effect is the appearance of an electrical voltage in a crystal when under mechanical stress. This is a solid state phenomenon and is dependent on the arrangement of the atoms in the crystal. The stress shifts the arrangement of the atoms and thus causes an electrical polarization which disappears when the stress is removed.

3.4.1 The crystal lattice

Solid materials have their constituent atoms arranged in some sort of structure. They are joined together by the electromagnetic force. If the arrangement is regular and periodic the solid have a crystal structure. The lattice is the coordinate system of the crystal with a periodic configuration of atoms at every point. A lattice point can consist of atoms, ions or ion pairs, see figure 4 below.

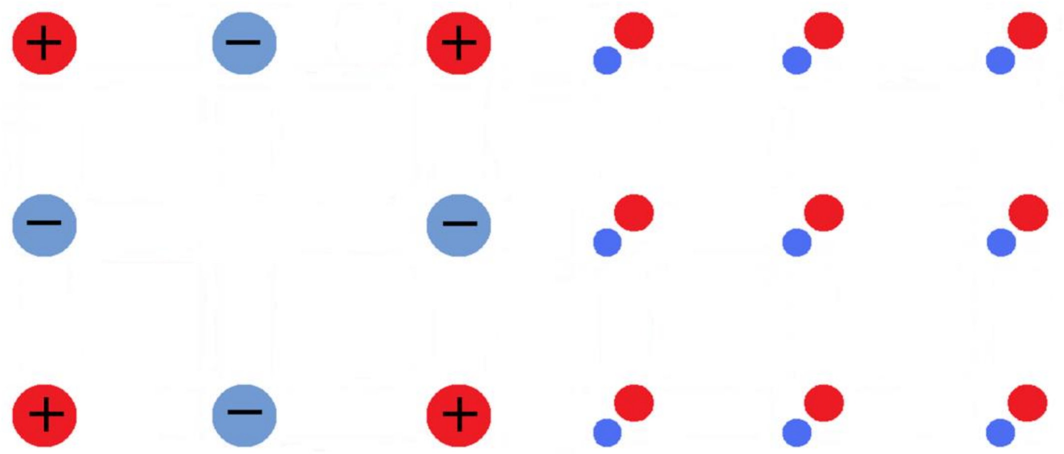

Figure 4: Examples of regular and periodic crystal lattices. They are both electrically neutral but contain charged particles. The lattice to the left have one atom at every lattice point, whereas the lattice to the right has two.

3.4.2 The piezoelectric crystal

The charge distribution of a crystal is normally arranged so the total charge is zero and the crystal is electrically neutral. Mechanical force can in some crystal structures disturb this equilibrium enough so that a voltage appears across the crystal, as in figure 5 below.

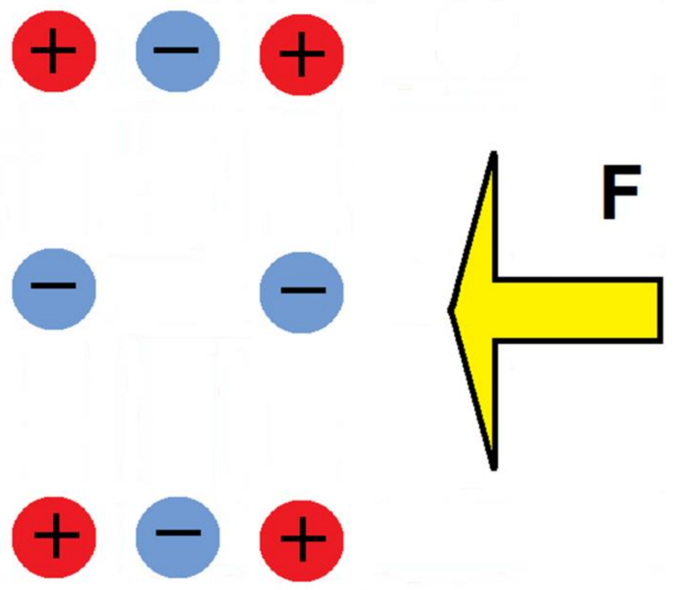

Figure 5: The crystal lattice is compressed by a mechanical force F, causing a polarization in the material. A net negative charge appears in the middle and a positive charge at top and bottom.

3.5 Electric relations

3.5.1 Voltage output from a thermocouple

The voltage output V from a number N of thermocouples depends on two parameters, the temperature differential ΔT and the heat conducting area. Laird Technologies relates in their *Thermoelectric handbook* these parameters below:

$$V = 2N\left[\frac{I\rho}{G} + \alpha\Delta T\right] \tag{3.7}$$

I is the electric current through the thermocouple, ρ the resistivity and α is the Seebeck coefficient, which is a coefficient relating voltage with temperature. It is dependent on the choice of materials. G is the area or length covered by the thermocouples.

3.5.2 Charging of a capacitor

The energy E_C stored in the electric field in a capacitor is given by

$$E_C = \frac{1}{2}CV^2 \tag{3.10}$$

where C is the capacitance of the capacitor and V is the open circuit voltage.
The power in a capacitor charging current, P_{AVG}, is then given by

$$P_{AVG} = \frac{\frac{1}{2}CV^2}{\Delta T} \qquad (3.11)$$

where ΔT is the charging time. This allows for measuring the average power in irregular currents.

3.5.3 Voltage of a thin piezoelectric wafer

Kittel (2005) gives a schematically one dimensional expression for the polarity in one direction in a piezoelectric crystal:

$$P = Zd + E\epsilon_0\chi \qquad (3.11)$$

P is the electric polarization, Z the stress, d the piezoelectric constant of the material, E the electric field and $\epsilon_0\, \chi$ the dielectric susceptibility. Mechanical stress is a force acting on a surface inside a solid. Since a solid is a continuous medium, force applied in one direction generally produces forces in other directions as well.

3.6 Mechanical vibrations

Vibrations are periodic movement about some centre point. In the ideal one dimensional case there is only one linear force that is responsible for the entire motion. This case is called the *simple harmonic oscillator*.

3.6.1 Simple harmonic oscillator

Thornton & Marion (2004) state the equation for the one dimensional harmonic oscillator. The equilibrium position is at $x=0$, so that x is the displacement of the particle. The restoring force is assumed linear in position with a proportionality constant k, so that twice the displacement of the mass doubles the force:

$$F = -kx \qquad (3.12)$$

The particle mass is m. Under these conditions the equation of motion is

$$\frac{d^2x}{dt^2} + \frac{k}{m}x = 0 \qquad (3.13)$$

And with

$$\frac{k}{m} = \omega_0^2 \tag{3.14}$$

the equation becomes

$$\frac{d^2x}{dt^2} + \omega_0^2 x = 0 \tag{3.15}$$

The particle moves one-dimensionally, only in the *x* direction during time *t*. The *ω* is the angular frequency of the particle and states how rapidly it vibrates. One solution in *x(t)* of this equation is

$$x(t) = Asin(\omega_0 t - \delta) \tag{3.16}$$

Here *A* is the amplitude, displacement from the centre point or equilibrium, whereas *δ* is a phase shift, which displaces the whole wave. The origin of this function can be chosen so *δ* disappears.

3.6.2 Energy content in a one dimensional harmonic oscillator

Thornton & Marion (2004) further state the kinetic and potential energies in this system.

3.6.2.1 Kinetic energy

The kinetic energy *T* of a particle is

$$T = \frac{1}{2} m \frac{dx}{dt} \tag{3.17}$$

Using the previous result for *x(t)*, the kinetic energy for the oscillator is

$$T = \frac{1}{2} kA^2 cos^2(\omega_0 t - \delta) \tag{3.18}$$

3.6.2.2 Potential energy

The potential energy *U* can be calculated from the amount of work done on the particle when it is moved under influence of the force. With a linear restoring force *F*, the potential energy becomes

$$U = \frac{1}{2}kx^2 \tag{3.19}$$

Inserting the expression for x previously stated, the potential energy for a simple harmonic oscillation becomes

$$U = \frac{1}{2}kA^2 sin^2(\omega_0 t - \delta) \tag{3.20}$$

3.6.2.3 Total energy of the system

The total energy E of the system is the sum of the kinetic and potential energies.

$$E = T + U \tag{3.21}$$

Inserting the known expressions for T and U in oscillations, E becomes

$$E = \frac{1}{2}kA^2 cos^2(\omega_0 t - \delta) + \frac{1}{2}kA^2 sin^2(\omega_0 t - \delta) \tag{3.22}$$

and through a trigonometric relation,

$$E = T + U = \frac{1}{2}kA^2 \tag{3.23}$$

As Thornton & Marion states, this is a general result for linear systems. In this ideal case the energy is independent of time and thus of frequency. The total energy in the vibration is proportional only to the square of the amplitude.

3.6.3 Damping

In physical systems energy is generally not conserved. In vibrations damping is always present and manifests in a decrease in amplitude with time if no driving force maintains the motion. Thornton & Marion argue that damping generally is assumed not to be a function dependent on position, like the restoring force. In a viscous fluid, resistance of motion generally increases with velocity, so for simplicity it is assumed damping is a function of velocity and so of angular frequency ω.

The equation for damped motion is generally

$$\frac{d^2x}{dt^2} + b\frac{dx}{dt} + \frac{k}{m}x = 0 \tag{3.24}$$

Previously, the angular frequency ω, force constant k and mass m, was related in

$$\frac{k}{m} = \omega^2 \tag{3.25}$$

Similarly, a damping parameter β relates mass m with another constant b in

$$\beta = \frac{b}{2m} \tag{3.26}$$

The parameter b is dependent on the situation in which the equation for a damped harmonic oscillator is solved.

The solution to the damped equation is

$$x_D(t) = Ae^{-\beta t}\cos(\omega_1 t - \delta) \tag{3.27}$$

3.6.4 Resonance

Resonance occurs when the driving force works in the same direction as the restoring force of the system. That is, the driving frequency ω_D has to match the natural frequency ω_0 of the system. In this case no energy is lost since no forces counteract each other. The result of resonance is a greatly magnified amplitude, since the energy E stored in the system is proportional to the amplitude squared, A^2.

In a physical system with a driving force, the resonance condition is

$$\omega_R^2 = \omega_0^2 - 2\beta^2 \tag{3.28}$$

3.7 Applications

3.7.1 The thermoelectric generator – TEG

A thermoelectric generator consists of two sides that are in thermal contact with the surroundings and between them are a number of thermocouple legs. These legs are *n*- and *p-doped* and electrically connected in series. The thermal surface is then traced by a line of connected thermocouples. When the thermal sides experience a temperature difference electric current starts to flow through the thermocouple legs, see figure 6 below.

The dimensions of the legs determine how well they conduct heat and electricity. In the ideal case all the heat is lead through the legs but in reality it also flows around them. It is then beneficial if other heat flow is restricted by insulating material. Of the available heat in the legs only a limited amount is converted into electricity. According to Lu and Yang (2010) the current maximum conversion efficiency lies around 5-6%.

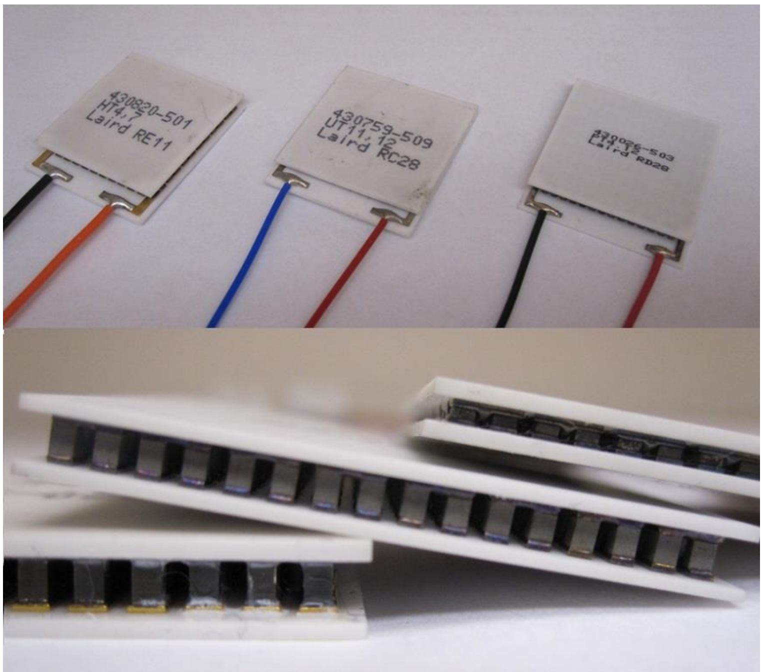

Figure 6: The investigated peltier elements. Top: Peltier element used as TEG, they are all 30x30 mm^2 wide. From left to right: HT4, UT11, PT4. Bottom: Close-up side view of the TEG: s. Note difference in size and number of legs. From left to right: HT4, PT4 and UT11.

3.7.2 The piezoelectric generator – PEG

The piezoelectric generator converts mechanical stresses in the material to electrical energy, see figure 7 below. It consists of a thin wafer or wafers which are subjected to mechanical forces. Often the wafers are covered in a durable material for protection.

The piezoelectric crystal at rest is electrically uncharged with differently charged regions cancelling each other out. When compressed or stretched the regions are shifted resulting in an electric polarization of the crystal. This voltage is the generators output.

The piezoelectric generator used here harvests mechanical energy from vibrations. The crystal wafers are laminated inside a flexible strip or beam mounted in a cantilever position. Its energy output is partly determined by the deflection of the tip which corresponds to amplitude. The other part takes into account the amount of crystal wafer that is being deflected.

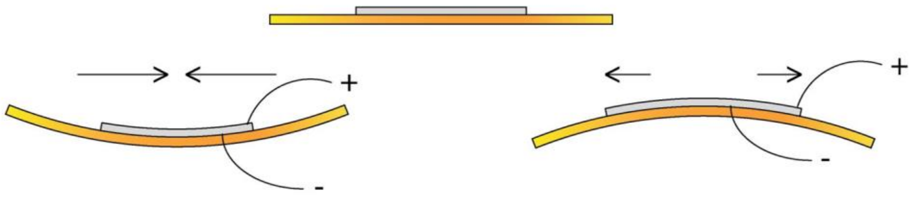

Figure 7: Piezo wafer being deformed by bending. Picture by Sonitron Support.

The conversion efficiency is dependent on the design and of the nature of the vibrations. In an investigation made by Koyama and Nakamura (2009) on cantilevered vibration harvesters in an array configuration they report a maximum conversion efficiency of around 8%.

4. Experiments

The power output from commercially available peltier cooling elements and piezoelectric vibration harvesters was investigated.

4.1 TEG – Thermoelectric Generator

Three different models of peltier effect cooling elements from manufacturer Laird Technologies was investigated for their power generating abilities. The models are [PT4, 12, F2, 3030, TA, W6], [HT4, 7, F2, 3030, TA, W6] and [UT11, 12, F2, 3030], see figure 6 above. They were assigned working names PT, HT and UT respectively, corresponding to initial model name letters. The cooling elements consist of two electrically non-conducting plates. Between the plates are the thermocouple legs, conducting heat and electricity. Each model has a working area of 30x30 mm^2, the bottom plate having 4 extra mm for wire connections. The thickness varies, the PT is 3.2 mm, the HT is 4.1 mm and the UT11 2.41 mm thick. Each model has 127 pairs of legs.

4.1.1 Experimental setup

The thermo element was connected to a resistive load, measurements was taken with three different loads of 10, 100 and 565 Ω, circuit diagram in figure 8 below. The voltage over the load was then recorded. The thermo element was placed on a slab of flat brass at room temperature and a cooled slab of lead was placed on top of the element; a temperature probe was mounted on both sides of the thermo element. See figure 9 for a concept picture and figure 10 for a photo of the setup. The two probes consisted of aluminium plate with a cut out space for a platinum resistance thermometer. During the measurement the temperature difference between the lead and brass would decrease with time. Between all surfaces in contact a heat conducting paste was applied to increase thermal contact. The measurements on HT were taken without heat paste except for the last one with 565 Ω load, which was measured both with and without.

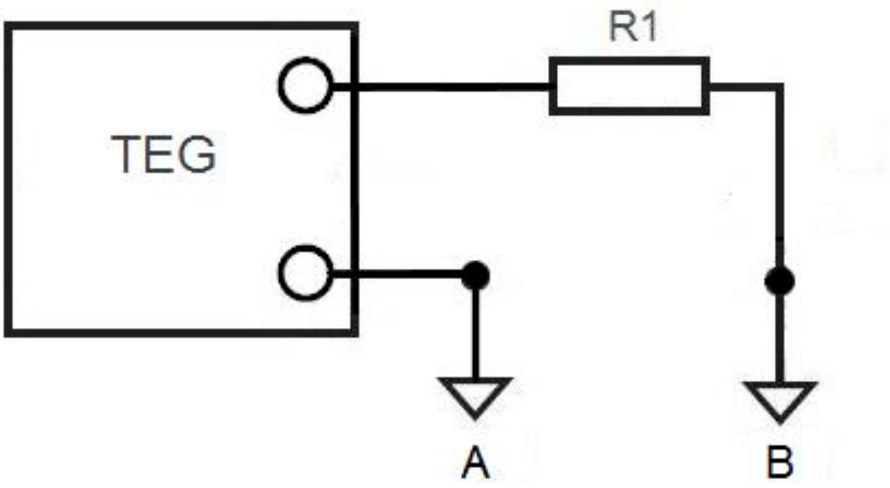

Figure 8: Measurement circuit of the TEG test setup, with R1 representing the different loads and A and B the voltmeter terminals.

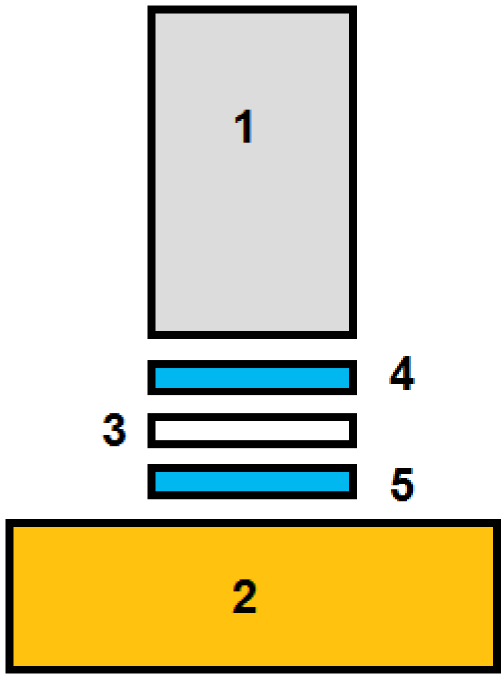

Figure 9: TEG test setup. 1 – Lead slab, 2 – Brass slab, 3 – TEG, 4 – Upper thermometer, 5 – Lower thermometer.

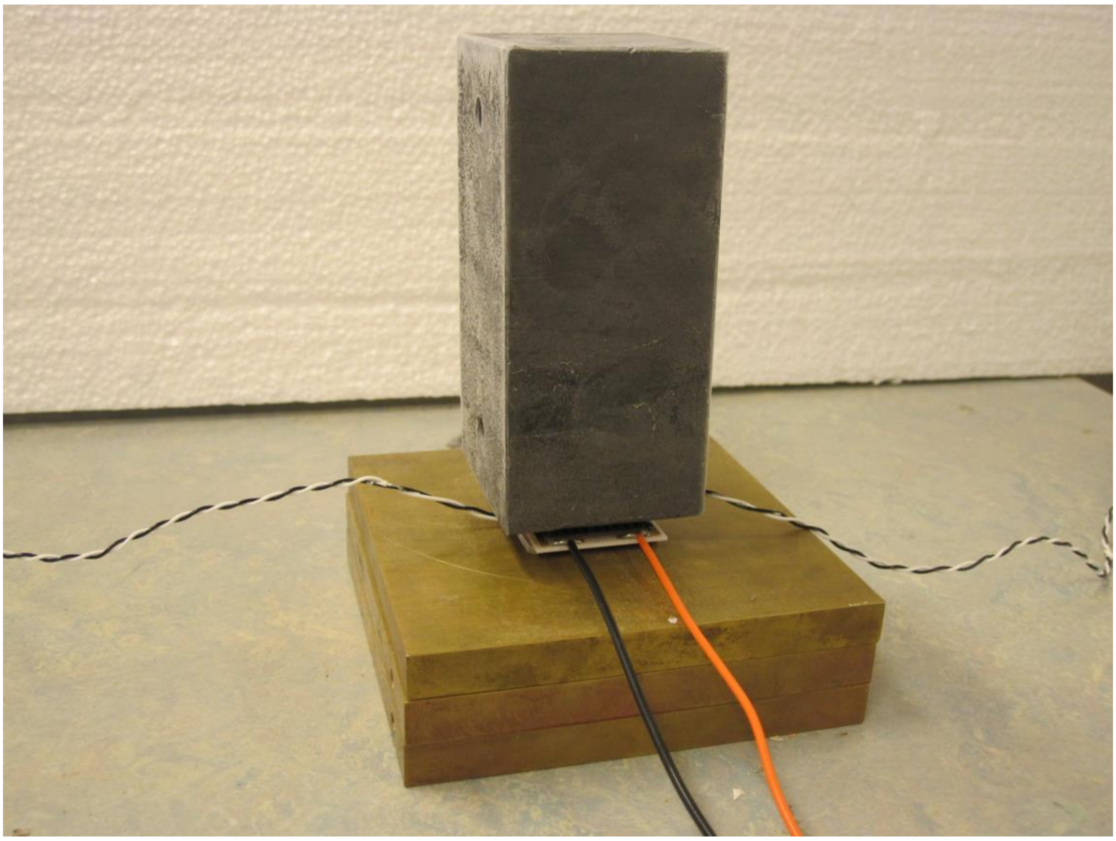

Figure 10: The setup with brass and lead slabs, TEG (black and orange cables) and two temperature probes on either side of the TEG (black and white cables).

4.1.2 The temperature probe

The two temperature probes used in the experiment are both of platinum resistance type. They are manufactured by Honeywell Sensing and Control; model HEL-705-U-1-12-00. The probe sense temperature by resistance of the platinum wire inside the probe. An aluminium casing held together by copper tape was made for the probes to fit in the test assembly. The casing is 30x30 mm wide to match the TEG:s. A photo of the sensor is shown in figure 11 below.

The relationship between resistance and temperature is given in a polynomial:

$$R_T = R_0(AT + BT^2 + CT^3 + DT^4) \tag{4.1}$$

R_T is the resistance in Ω at temperature T in °C and R_0 the reference resistance at 0 °C. The coefficients A, B, C and D are material dependent. For the measurements a numerical solver was used to extract the temperature T from this relation.

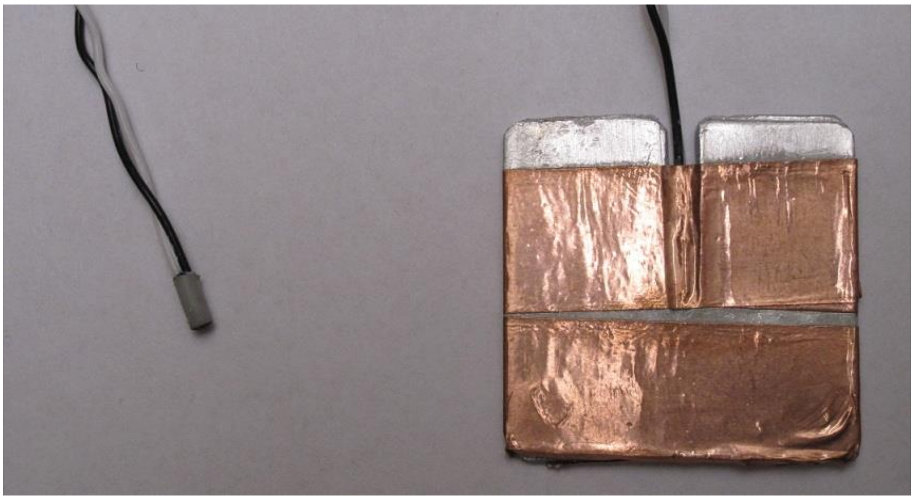

Figure 11: Temperature probe assembly. The platinum resistance thermometer to the left and the probe assembly with aluminum spacer plate and copper tape to the right.

4.1.3 Measurement of power output from a thermoelectric generator TEG

The cold lead slab was placed onto the thermo element and the voltage and current through the load was recorded. The temperature on both sides of the thermo element was read off as resistance. Via a known relationship between resistance and temperature, the power output at a certain temperature differential could be calculated.

4.2 PEG – Piezoelectric Generator

Two piezoelectric cantilever strips from manufacturer Midé Technology Corporation was investigated for their power generating abilities. The models investigated were Volture V21BL and Volture V22BL, see figure 12. Their size and natural (resonant) frequency are listed in table 4.2 below, with measurements referring to figure 13. The length *Y* refers to the length from tip to the clamp, it is this portion of the PEG that will oscillate.

Table 4.2: Midé Volture piezo strip size and frequency

Model	W [mm]	Y [mm] clamp	Z [mm]	A [mm]	X [mm]	B [mm]	Wafer area [mm^2]	Oscillating area [mm^2]	Natural frequency [Hz]
V21BL	90.4	56.5	84.1	16.8	35.6	14.4	512.64	949.2	110
V22BL	92.3	53.2	85.9	6.1	25.4	3.8	76.2	324.5	110

Figure 12: Midé Volture PEG; V21BL to the left, V22BL to the right.

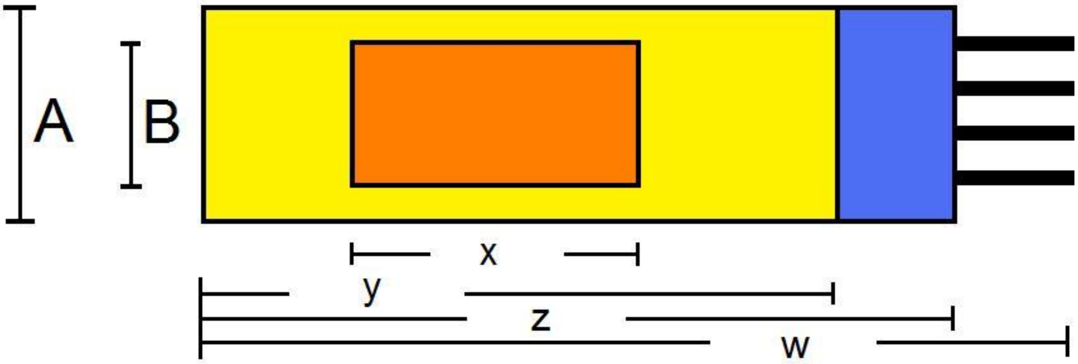

Figure 13: Principal components of the PEG. Orange: Piezocrystal wafer. Yellow: Composite casing. Blue: Plastic connector. Black: Metallic leads. Letters correspond to lengths listed in table 4.2.

4.2.1 Experimental setup

Each piezoelectric strip was mounted on a loudspeaker membrane; see photo in figure 14 and concept picture in figure 15. The strip was first clamped down with plastic clamps onto a plastic fastener. The fastener in turn was then screwed onto a socket attached onto the membrane. A function generator drove the speaker membrane in a frequency interval of 1 to 200 Hertz. The driving voltage was maintained at constant value. The output signal from the piezoelectric device was connected to an oscilloscope and to a rectifier bridge. A 565 Ω resistor and a 33 µF capacitor was connected in series with the DC poles of the rectifier bridge, see circuit diagram in figure 16. The capacitor voltage was monitored with a voltmeter and the charging time was taken with a manual stop watch.

The impact of adding a trim weight to the piezo strip was also investigated. The trim weight was a screw-nut with mass 1.85 grams. It was taped at the end of the strip.

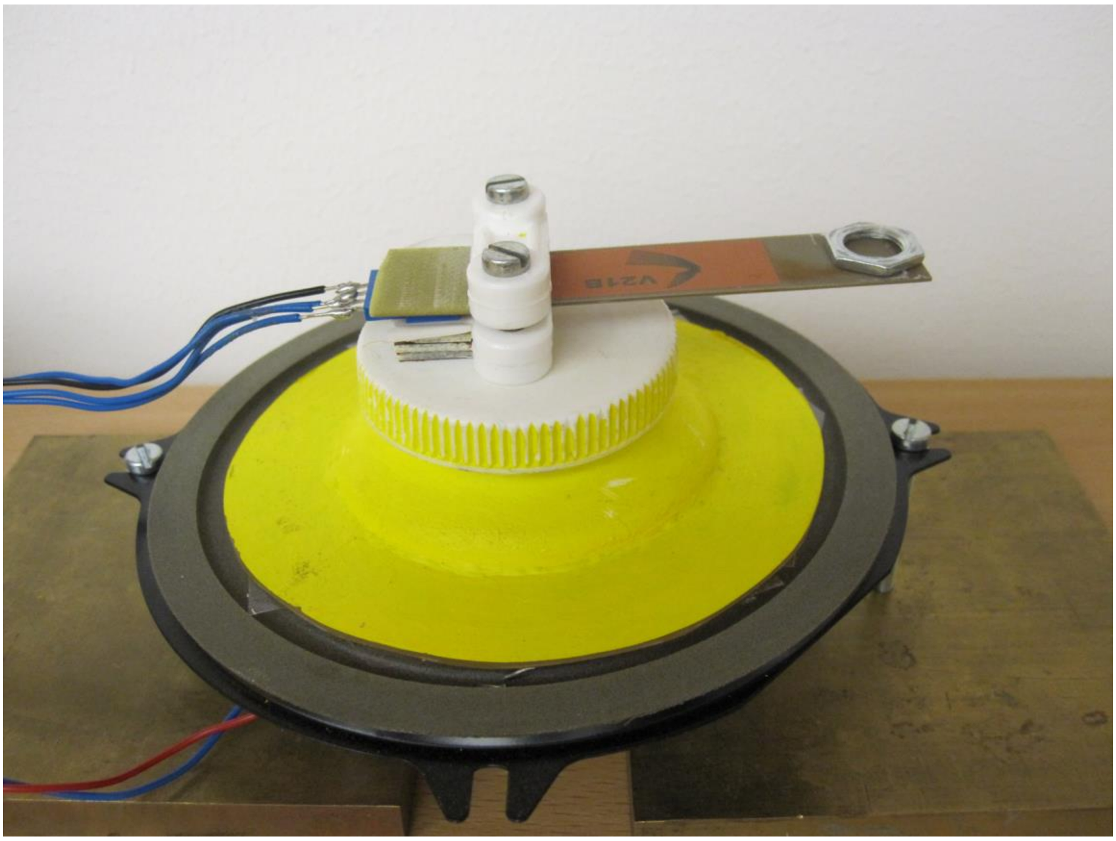

Figure 14: Piezo assembly with trim weight.

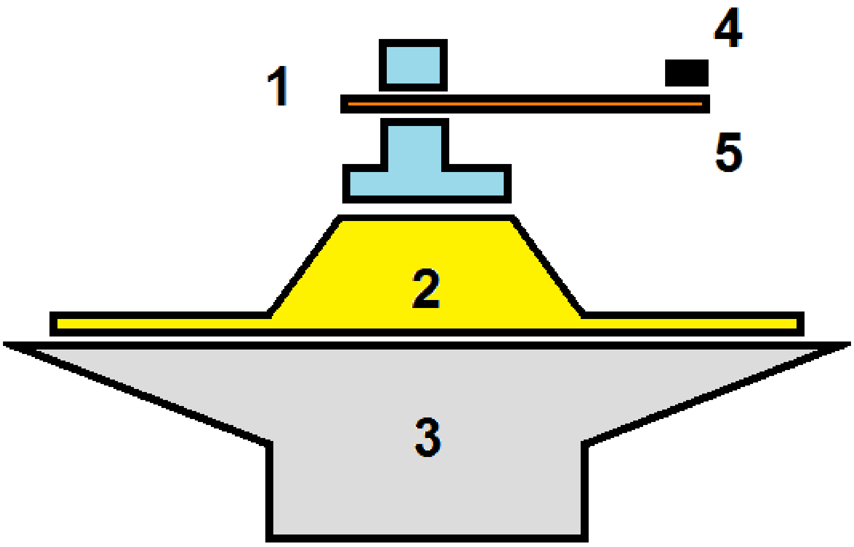

Figure 15: PEG test setup. 1 – Plastic clamp, 2 – Membrane socket, 3 – Loudspeaker, 4 – Trim weight and 5 – Piezo strip.

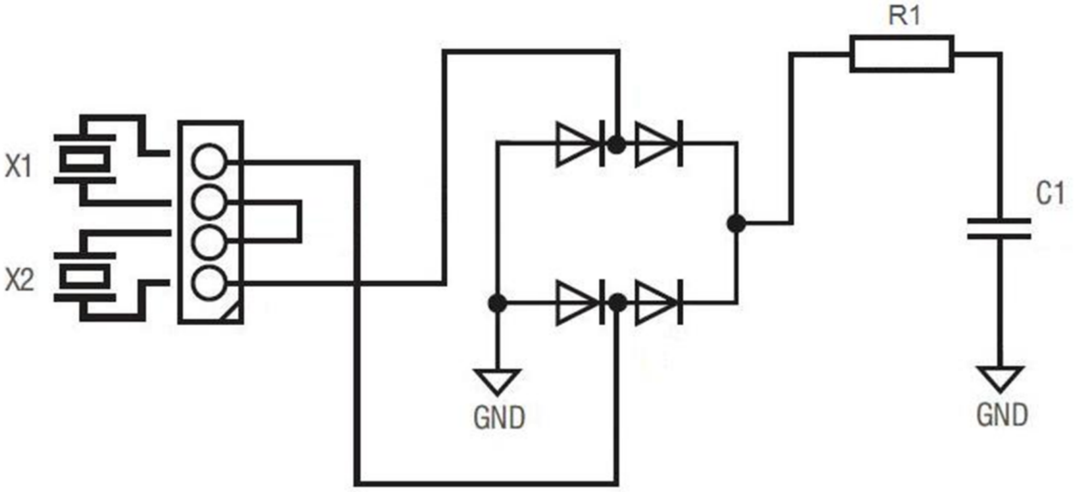

Figure 16: Circuit diagram of the measurement setup. X1 and X2 are the wafers on the strip, in the middle a rectifier bridge, R1 a resistive load and C1 the capacitor being charged.

4.2.2 Measurement of power output from a piezoelectric generator PEG

The capacitor charging was timed and the voltage level at that time was recorded. The charging time and other known parameters thus gave the average power output from the piezoelectric strip as a function of frequency. This method had the advantage that the actual amplitude and other physical parameters of the system need not be known.

4.3 Results

4.3.1 TEG – Thermoelectric Generator

The PT element seems to perform best of the three models at all loads. The lightest load gave the highest power outputs for all three models. The application of heat conduction paste on the HT element increased its power output significantly, roughly three times.

Table 4.3.1: TEG models power level at different temperature differentials.

Model	Load, R [Ω]	ΔT=20 °C, P [µW]	ΔT=15 °C, P [µW]	ΔT=10 °C, P [µW]	ΔT=5 °C, P [µW]
UT	10	750	430	194	49
UT	100	697	408	179	46
UT	565	120	71	35	8
HT*	10	854	479	235	69
HT*	100	507	292	148	58
HT*	565	73	41	18	5
HT	565	261	147	65	15
PT	10	2670	1533	723	178
PT	100	1552	882	410	104
PT	565	301	171	77	18

* = No heat paste was used during the measurement.

4.3.2 PEG – Piezoelectric Generator

The piezo strips showed a strong dependence on resonance frequency. As expected adding mass to the strip lowered the resonance frequency and increased the power output.
Power as a function of frequency is plotted in figure 17-20. A load of 565 Ω was connected in series with the capacitor in every measurement.

Table 4.3.2: PEG models power output at resonance frequency.

Model	Resonance frequency $\omega_R/2\pi$ [Hz]	Power at ω_R [µW]
V21BL	119.2	565
V21BL + trim weight of 1,85 g.	56.1	2320
V22BL	116.0	339
V22BL + trim weight of 1,85 g.	25.9	790

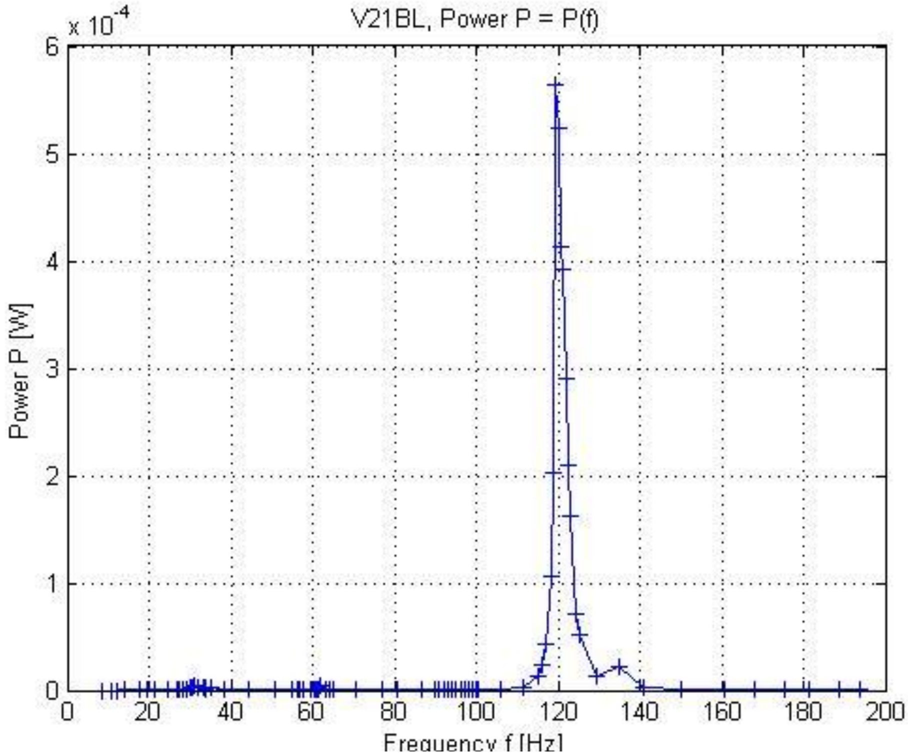

Figure 17: Plot of V21BL with no additional weight with power as a function of frequency.

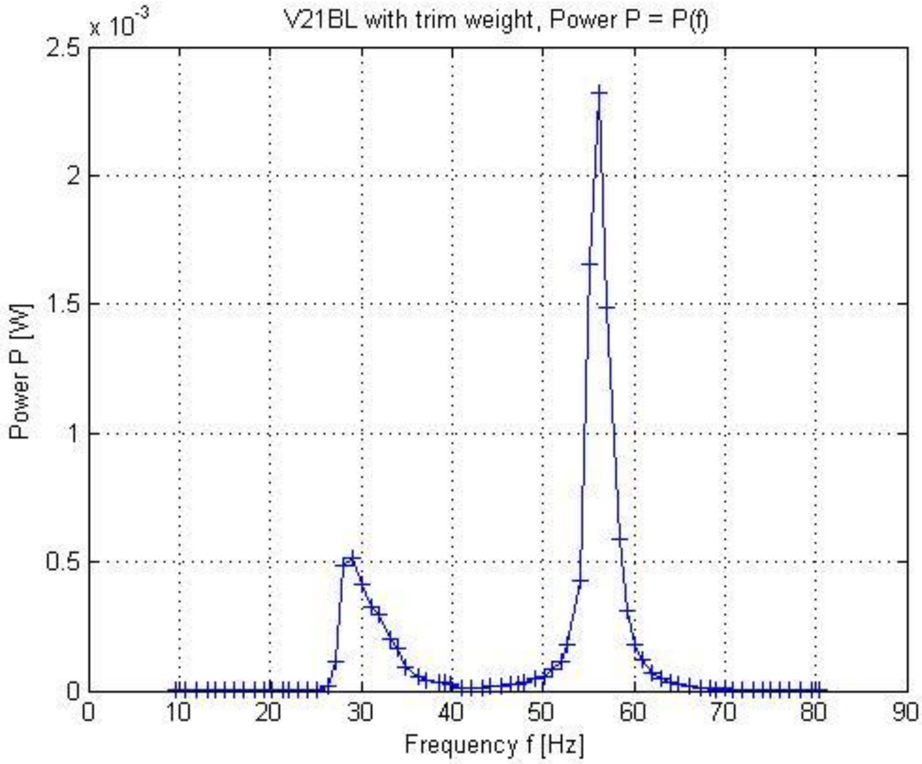

Figure 18: Plot of V21BL with an additional weight of 1.85 g with power as a function of frequency.

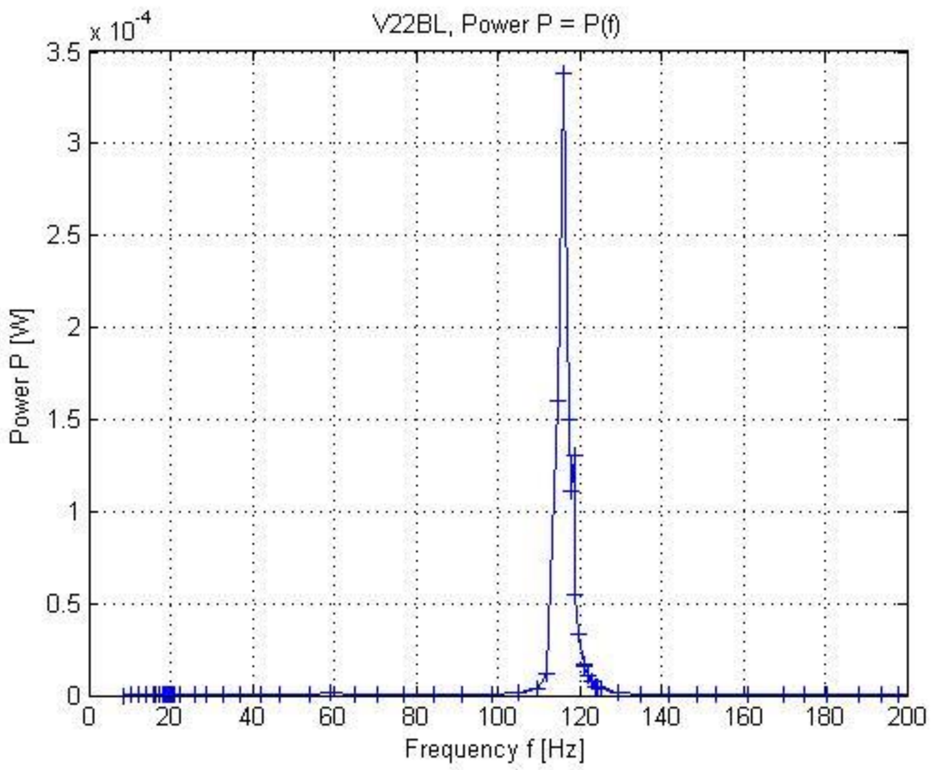

Figure 19: Plot of V22BL with no additional weight with power as a function of frequency.

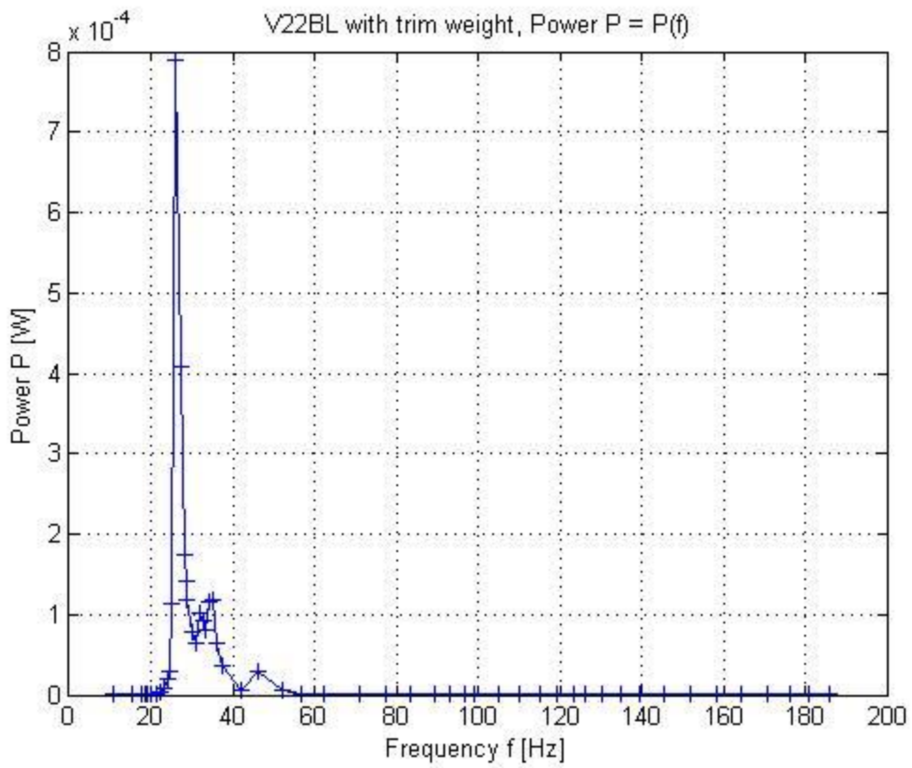

Figure 20: Plot of V22BL with an additional weight of 1.85 g with power as a function of frequency.

4.3.3 Peak power densities

The different micro generators peak power density with respect to the active area used. For the TEG:s, the peak occurs at 20°C temperature differential, for the PEG:s it is at their resonant frequency. The active area is the area that produces electric current, 30x30 mm^2 for the TEG:s. The oscillating area is the active area for the PEG:s, since the entire oscillating length is needed for its motion and not just the wafer. Below is a table with peak power and peak power densities at different loads.

Table 4.3.3: Peak powers and peak power densities at different loads.

Model	Load [Ω]	Peak power [µW]	Power density [$\mu W/mm^2 = W/m^2$]
UT	10	750	0.83
UT	100	697	0.77
UT	565	120	0.13
HT*	10	854	0.95
HT*	100	507	0.56
HT*	565	73	0.08
HT	565	261	0.29
PT	10	2670	2.97
PT	100	1552	1.72
PT	565	301	0.33
V21BL	565	565 (119.2 Hz)	0.60
V21BL+trim	565	2320 (56.1 Hz)	2.44
V22BL	565	339 (116.0 Hz)	1.04
V22BL+trim	565	790 (25.9 Hz)	2.43

4.4 Analysis

4.4.1 Power output and characteristics

The thermoelectric generators function continuously with no sudden changes while the piezoelectric vibration harvesters is nearly the opposite with abrupt changes. The two generator types have similar peak power outputs above 2 mW for the best models. The PEG:s have small or minute peaks at frequencies apart from the resonant frequency.
The main factors for power output of the PEG:s are resonant frequency and vibration amplitude. These factors are a measure of how much the piezocrystal is deflected over time and thus a measure of its power. The resonant frequency can be lowered and the amplitude increased by adding a trim weight to the PEG.

The power output for the TEG is dependent on the temperature differential across its thermal plates. The amount of electrical power extracted depends on how much of the heat flow through the entire TEG that passes through the thermocouple legs.

4.4.2 Size

The physical dimensions of the TEG and the PEG strip are of the same order of magnitude. They are thin, flat and rectangular shapes; the TEG:s are thicker but the PEG require space for vibrations.
The TEG:s occupy a flat surface of 30x34 mm^2, where the active area is 30x30 mm^2 and the extra 4 mm are for electrical connections. They are of different thicknesses: the UT11 model is 2.45 mm, the HT4 4.14 mm and the PT4 3.23 mm.

The PEG:s are of similar length, V21BL is 56.52 mm long active area with an additional 27.56 mm for mounting and electrical connection. The V22BL is 53.16 mm long with 32.77 mm for mounting and electrical connection. The active width differ, V21BL is 16.8 mm broad whereas V22BL is 6.1 mm.

The surface power density of the various micro generators varies but under good conditions they are comparable and in the same range.

4.4.3 Robustness

The PEG is a moving part in that it has to vibrate. There are no moving parts inside it to create the electric output. The TEG is completely stationary and need no movement at all to operate.
The tested PEG:s are quite flexible and apart from electrical connections are completely sealed from the environment. The TEG are susceptible for electrical and thermal short circuits since the thermocouple legs are exposed to surrounding air, the air acting as thermal and electrical insulant. The material that the investigated TEGs are made from is brittle. Both micro generators can be sealed inside a dust and waterproof enclosure without decrease in performance.

5. Conclusion and the next step

5.1 Conclusion and design guidelines

Electronic devices can harvest energy from their environment to power on board circuitry. Knowledge of the energy content and behaviour of the energy source is important for optimization and choice of micro generator.

The micro generators work on different principles and draw their power from different sources. Their power output is similar in magnitude and density but the conditions to be met differ greatly. This prevents decisions solely made by power output or size, but it does however grant the possibility to use both simultaneously; the technologies do not compete for resources.

In some cases the electric load characteristics could favour one micro generator over the other. The amount of electric conditioning circuitry needed could be lowered if matched with the right generator.

In any device incorporating micro generators the entire volume geometry need consideration. The PEG needs space to vibrate in and there is an ideal thickness for a certain TEG surface.

Since the PEG:s need to vibrate during operation, the material will break after some time. The TEG:s being rigid and stationary have only chemical reactions to affect its performance over time. If however the TEG:s are put in a vibrating or moving environment its brittleness could make it crack easier than the flexible PEG. Thermal stresses also affect the life time of the micro generators.

5.2 Further investigations and improvements

5.2.1 TEG

The investigated thermo electrical generators have a few drawbacks. They are brittle, expensive, subject to moist and thermal side flows. If made flexible it is possible that the generator could withstand vibrations and shocks better and be included in a wider field of applications. The way heat flows through the TEG is what ultimately decides its performance. Increasing the number of legs per unit surface is the most obvious improvement. More efficient heat insulating is needed to contain the heat flow to the legs. The models investigated here have simple air gaps.

Investigations have not taken into account that the heat source may deplete. The electrical currents impact on the TEG:s thermal conductivity has not been investigated. How big is the difference in thermal conductivity when the circuit is open compared with a short circuit?

The impact of the shape and proportions of the components have not been investigated.

5.2.2 PEG

The major drawback of the investigated piezoelectric generators is the narrow peak of the resonance frequency. In some situations, the fact that it only vibrates in one direction could also be a problem since a lot of vibrations could be along other directions and would therefore not be harvested. There are two ways to improve on the resonance problem, increasing the efficiency of the crystal or making it accept a broader range of frequencies. Different crystals could have different optimal vibration ranges. The added trim weight in this investigation increased the height of a secondary peak, perhaps this could be utilized in a future device. The geometry and shape of the wafers and the encasing material all affect the total behaviour. The effects of other mounting points are unknown.

Since piezocrystals is used as actuators, the resonant frequency could be affected by the electrical circuit and load characteristics. The PEG: s behaviour at larger amplitudes and shocks needs to be investigated since these are common.

6. Tables

6.1 PEG

6.1.1 PEG, V21BL

Measurement data on the V21BL piezo strip. The driving frequency is f, V_c is the voltage across the capacitor, Δt is the charging time of the capacitor and P is the power output.

V21BL **f [Hz]**	**V_c [V]**	**Δt [s]**	**P [W]**
8.3	0.000	10.6	$1.49 \cdot 10^{-12}$
10.6	0.000	10.2	$1.49 \cdot 10^{-12}$
12.4	0.000	10.4	$2.64 \cdot 10^{-12}$
14.1	0.001	10.5	$5.94 \cdot 10^{-12}$
17.9	0.002	11.0	$4.77 \cdot 10^{-10}$
19.5	0.002	10.2	$5.35 \cdot 10^{-11}$
21.3	0.002	10.5	$9.50 \cdot 10^{-11}$
24.5	0.008	10.4	$1.14 \cdot 10^{-9}$
26.9	0.034	10.7	$1.95 \cdot 10^{-8}$
27.4	0.051	10.2	$4.26 \cdot 10^{-8}$
28.3	0.078	10.2	$1.00 \cdot 10^{-7}$
29.3	0.195	10.3	$6.25 \cdot 10^{-7}$
30.2	0.342	10.3	$1.93 \cdot 10^{-6}$
30.4	0.451	10.5	$3.36 \cdot 10^{-6}$
31.0	0.539	10.3	$4.79 \cdot 10^{-6}$
32.0	0.459	10.5	$3.48 \cdot 10^{-6}$
33.3	0.348	10.3	$2.00 \cdot 10^{-6}$
33.7	0.359	10.3	$2.13 \cdot 10^{-6}$
34.0	0.321	10.2	$1.70 \cdot 10^{-6}$
35.3	0.337	10.2	$1.87 \cdot 10^{-6}$
38.6	0.214	10.5	$7.56 \cdot 10^{-7}$
44.4	0.089	10.0	$1.32 \cdot 10^{-7}$
50.7	0.036	10.3	$2.13 \cdot 10^{-8}$
55.0	0.028	10.3	$1.32 \cdot 10^{-8}$
55.1	0.028	10.2	$1.25 \cdot 10^{-8}$
56.2	0.026	10.0	$1.10 \cdot 10^{-8}$
57.0	0.026	9.9	$1.11 \cdot 10^{-8}$
57.8	0.028	10.2	$1.28 \cdot 10^{-8}$
59.4	0.034	10.3	$1.91 \cdot 10^{-8}$
60.3	0.054	10.2	$4.83 \cdot 10^{-8}$
60.8	0.134	10.2	$2.97 \cdot 10^{-7}$
61.2	0.165	10.1	$4.46 \cdot 10^{-7}$
61.9	0.467	10.3	$3.60 \cdot 10^{-6}$
63.0	0.168	10.3	$4.63 \cdot 10^{-7}$

V21BL

f [Hz]	V_c [V]	Δt [s]	P [W]
64.0	0.059	10.2	$5.72 \cdot 10^{-8}$
65.2	0.039	10.2	$2.46 \cdot 10^{-8}$
70.7	0.035	10.1	$2.06 \cdot 10^{-8}$
77.1	0.037	10.7	$2.30 \cdot 10^{-8}$
80.8	0.043	10.4	$3.05 \cdot 10^{-8}$
86.8	0.060	10.2	$5.90 \cdot 10^{-8}$
89.9	0.048	10.2	$3.77 \cdot 10^{-8}$
91.0	0.056	10.0	$5.10 \cdot 10^{-8}$
92.1	0.063	10.1	$6.57 \cdot 10^{-8}$
92.9	0.073	10.2	$8.74 \cdot 10^{-8}$
94.1	0.082	10.4	$1.10 \cdot 10^{-7}$
95.0	0.069	10.1	$7.86 \cdot 10^{-8}$
96.3	0.077	10.1	$9.66 \cdot 10^{-8}$
97.2	0.083	10.1	$1.13 \cdot 10^{-7}$
98.2	0.082	10.2	$1.12 \cdot 10^{-7}$
99.1	0.078	10.0	$1.01 \cdot 10^{-7}$
99.9	0.085	10.2	$1.20 \cdot 10^{-7}$
100.5	0.077	10.1	$9.66 \cdot 10^{-8}$
105.9	0.183	10.0	$5.52 \cdot 10^{-7}$
111.5	0.421	10.2	$2.92 \cdot 10^{-6}$
115.1	0.895	10.2	$1.32 \cdot 10^{-5}$
116.2	1.197	10.1	$2.36 \cdot 10^{-5}$
117.0	1.619	11.1	$4.32 \cdot 10^{-5}$
118.2	2.540	10.2	$1.06 \cdot 10^{-4}$
118.7	3.510	10.1	$2.03 \cdot 10^{-4}$
119.2	5.850	10.3	$5.65 \cdot 10^{-4}$
120.1	5.630	10.3	$5.23 \cdot 10^{-4}$
120.7	5.000	10.2	$4.13 \cdot 10^{-4}$
121.3	4.870	10.2	$3.91 \cdot 10^{-4}$
122.1	4.190	10.1	$2.90 \cdot 10^{-4}$
122.6	3.570	10.3	$2.10 \cdot 10^{-4}$
123.1	3.140	10.1	$1.63 \cdot 10^{-4}$
124.4	2.080	10.5	$7.14 \cdot 10^{-5}$
125.1	1.784	10.2	$5.25 \cdot 10^{-5}$
129.4	0.905	10.3	$1.35 \cdot 10^{-5}$
134.8	1.136	10.8	$2.13 \cdot 10^{-5}$
141.1	0.379	10.1	$2.37 \cdot 10^{-6}$
150.1	0.104	10.1	$1.78 \cdot 10^{-7}$
160.8	0.025	10.4	$1.06 \cdot 10^{-8}$
168.0	0.014	10.6	$3.33 \cdot 10^{-9}$
175.2	0.008	10.1	$1.16 \cdot 10^{-9}$
181.3	0.006	10.3	$5.36 \cdot 10^{-10}$
188.6	0.004	10.1	$3.19 \cdot 10^{-10}$
194.0	0.004	10.4	$2.64 \cdot 10^{-10}$

6.1.2 PEG, V22BL

Measurement data on the V22BL piezo strip. The driving frequency is f, V_c is the voltage across the capacitor, Δt is the charging time of the capacitor and P is the power output.

V22BL

f [Hz]	**V_c [V]**	**Δt [s]**	**P [W]**
8.5	0.000	10.1	$2.64 \cdot 10^{-12}$
10.2	0.001	10.4	$4.13 \cdot 10^{-12}$
12.3	0.001	10.3	$8.09 \cdot 10^{-12}$
14.2	0.001	10.2	$5.94 \cdot 10^{-12}$
15.8	0.001	10.4	$1.65 \cdot 10^{-11}$
16.3	0.001	9.2	$2.38 \cdot 10^{-11}$
17.1	0.006	10.1	$5.17 \cdot 10^{-10}$
18.0	0.004	10.4	$2.77 \cdot 10^{-10}$
18.4	0.004	10.1	$2.51 \cdot 10^{-10}$
19.0	0.003	10.4	$1.39 \cdot 10^{-10}$
19.5	0.002	10.1	$7.28 \cdot 10^{-11}$
19.9	0.002	10.3	$6.60 \cdot 10^{-11}$
20.4	0.002	10.2	$3.71 \cdot 10^{-11}$
21.1	0.002	10.2	$5.35 \cdot 10^{-11}$
22.5	0.003	10.3	$1.20 \cdot 10^{-10}$
25.9	0.009	10.5	$1.19 \cdot 10^{-9}$
28.8	0.047	10.1	$3.60 \cdot 10^{-8}$
32.9	0.136	10.1	$3.06 \cdot 10^{-7}$
37.2	0.132	10.2	$2.87 \cdot 10^{-7}$
41.9	0.047	10.2	$3.61 \cdot 10^{-8}$
46.7	0.068	10.1	$7.65 \cdot 10^{-8}$
53.8	0.043	10.2	$3.11 \cdot 10^{-8}$
58.9	0.292	10.3	$1.41 \cdot 10^{-6}$
65.1	0.045	10.2	$3.37 \cdot 10^{-8}$
70.6	0.030	10.1	$1.51 \cdot 10^{-8}$
76.9	0.041	10.2	$2.73 \cdot 10^{-8}$
84.2	0.053	10.1	$4.65 \cdot 10^{-8}$
91.3	0.100	10.3	$1.66 \cdot 10^{-7}$
98.6	0.090	10.2	$1.33 \cdot 10^{-7}$
105.0	0.263	10.2	$1.14 \cdot 10^{-6}$
109.5	0.469	9.0	$3.63 \cdot 10^{-6}$
111.9	0.834	10.2	$1.15 \cdot 10^{-5}$
114.9	3.120	10.1	$1.61 \cdot 10^{-4}$
116.0	4.530	10.0	$3.39 \cdot 10^{-4}$
117.4	3.010	10.1	$1.49 \cdot 10^{-4}$
118.0	2.600	10.1	$1.12 \cdot 10^{-4}$
118.8	2.810	10.0	$1.30 \cdot 10^{-4}$
118.9	1.815	10.0	$5.44 \cdot 10^{-5}$
119.8	1.416	10.2	$3.31 \cdot 10^{-5}$

V22BL			
f [Hz]	V_c [V]	Δt [s]	P [W]
121.0	1.009	10.1	$1.68\cdot 10^{-5}$
121.1	0.991	10.3	$1.62\cdot 10^{-5}$
122.1	0.790	10.2	$1.03\cdot 10^{-5}$
123.0	0.662	10.2	$7.23\cdot 10^{-6}$
124.1	0.550	10.2	$4.99\cdot 10^{-6}$
124.5	0.535	10.4	$4.72\cdot 10^{-6}$
125.1	0.442	10.2	$3.22\cdot 10^{-6}$
129.5	0.252	10.5	$1.05\cdot 10^{-6}$
135.0	0.245	10.2	$9.90\cdot 10^{-7}$
141.7	0.106	10.2	$1.84\cdot 10^{-7}$
148.8	0.038	10.3	$2.35\cdot 10^{-8}$
153.4	0.020	10.0	$6.80\cdot 10^{-9}$
161.1	0.011	10.3	$1.96\cdot 10^{-9}$
169.7	0.007	10.3	$9.04\cdot 10^{-10}$
174.8	0.006	10.1	$5.36\cdot 10^{-10}$
180.5	0.004	9.4	$2.51\cdot 10^{-10}$
188.5	0.003	10.2	$1.49\cdot 10^{-10}$
193.6	0.003	10.3	$1.03\cdot 10^{-10}$
198.0	0.003	12.1	$1.12\cdot 10^{-10}$

6.1.3 PEG, V21BL + trim weight

Measurement data on the V21BL piezo strip with attached trim weight of 1.85 grams. The driving frequency is f, V_c is the voltage across the capacitor, Δt is the charging time of the capacitor and P is the power output.

V21BL	+ trim: 1.85 g		
f [Hz]	V_c [V]	Δt [s]	P [W]
9.6	0.013	10.2	$2.79\cdot 10^{-9}$
10.7	0.022	10.3	$7.99\cdot 10^{-9}$
11.9	0.013	10.1	$2.79\cdot 10^{-9}$
13.2	0.020	10.2	$6.60\cdot 10^{-9}$
14.0	0.065	10.3	$6.97\cdot 10^{-8}$
15.1	0.206	10.2	$7.00\cdot 10^{-7}$
16.0	0.335	10.1	$1.85\cdot 10^{-6}$
17.1	0.239	10.4	$9.42\cdot 10^{-7}$
18.4	0.312	10.1	$1.61\cdot 10^{-6}$
19.4	0.382	10.2	$2.41\cdot 10^{-6}$
20.1	0.146	10.2	$3.52\cdot 10^{-7}$
21.4	0.102	10.3	$1.72\cdot 10^{-7}$
22.0	0.133	10.1	$2.92\cdot 10^{-7}$
23.1	0.224	11.0	$8.28\cdot 10^{-7}$
24.0	0.306	10.1	$1.54\cdot 10^{-6}$
25.2	0.528	10.3	$4.60\cdot 10^{-6}$
26.4	1.037	10.1	$1.77\cdot 10^{-5}$
27.3	2.579	10.2	$1.10\cdot 10^{-4}$
28.0	5.420	10.2	$4.85\cdot 10^{-4}$

V21BL	**+ trim: 1.85 g**		
f [Hz]	**V_c [V]**	**Δt [s]**	**P [W]**
29.1	5.580	10.2	$5.14\cdot 10^{-4}$
30.2	5.010	10.4	$4.14\cdot 10^{-4}$
31.1	4.450	10.2	$3.27\cdot 10^{-4}$
32.0	4.220	10.9	$2.94\cdot 10^{-4}$
33.2	3.510	10.1	$2.03\cdot 10^{-4}$
34.0	3.140	10.3	$1.63\cdot 10^{-4}$
34.9	2.350	10.1	$9.11\cdot 10^{-5}$
36.3	1.770	10.8	$5.17\cdot 10^{-5}$
37.1	1.630	10.0	$4.38\cdot 10^{-5}$
38.5	1.470	10.1	$3.57\cdot 10^{-5}$
39.2	1.470	10.1	$3.57\cdot 10^{-5}$
39.9	1.270	9.3	$2.66\cdot 10^{-5}$
41.0	0.910	10.3	$1.37\cdot 10^{-5}$
42.2	0.790	10.0	$1.03\cdot 10^{-5}$
43.3	0.860	10.3	$1.22\cdot 10^{-5}$
44.2	0.960	10.4	$1.52\cdot 10^{-5}$
45.4	1.070	10.5	$1.89\cdot 10^{-5}$
46.4	1.180	10.1	$2.30\cdot 10^{-5}$
47.3	1.320	10.0	$2.87\cdot 10^{-5}$
47.9	1.430	10.3	$3.37\cdot 10^{-5}$
49.1	1.690	10.3	$4.71\cdot 10^{-5}$
50.1	1.880	10.2	$5.83\cdot 10^{-5}$
51.1	2.250	10.2	$8.35\cdot 10^{-5}$
52.0	2.630	10.1	$1.14\cdot 10^{-4}$
52.7	3.270	10.4	$1.76\cdot 10^{-4}$
54.0	5.080	10.7	$4.26\cdot 10^{-4}$
55.2	10.020	10.4	$1.66\cdot 10^{-3}$
56.1	11.860	10.3	$2.32\cdot 10^{-3}$
56.9	9.490	10.4	$1.49\cdot 10^{-3}$
58.4	5.970	11.4	$5.88\cdot 10^{-4}$
59.3	4.320	10.2	$3.08\cdot 10^{-4}$
60.2	3.320	10.2	$1.82\cdot 10^{-4}$
60.9	2.680	10.1	$1.19\cdot 10^{-4}$
62.0	2.040	10.6	$6.87\cdot 10^{-5}$
63.0	1.650	10.4	$4.49\cdot 10^{-5}$
64.1	1.350	10.6	$3.01\cdot 10^{-5}$
64.9	1.300	10.2	$2.79\cdot 10^{-5}$
66.0	1.150	10.4	$2.18\cdot 10^{-5}$
67.4	0.900	10.3	$1.34\cdot 10^{-5}$
68.4	0.740	10.1	$9.04\cdot 10^{-6}$
69.0	0.660	10.1	$7.19\cdot 10^{-6}$
70.0	0.690	10.3	$7.86\cdot 10^{-6}$
70.8	0.660	10.1	$7.19\cdot 10^{-6}$
71.8	0.600	10.4	$5.94\cdot 10^{-6}$
73.2	0.470	9.9	$3.64\cdot 10^{-6}$
74.1	0.430	10.7	$3.05\cdot 10^{-6}$

V21BL	+ trim: 1.85 g		
f [Hz]	V_c [V]	Δt [s]	P [W]
75.1	0.370	10.1	$2.26 \cdot 10^{-6}$
76.0	0.330	10.1	$1.80 \cdot 10^{-6}$
77.0	0.280	10.2	$1.29 \cdot 10^{-6}$
78.3	0.240	10.2	$9.50 \cdot 10^{-7}$
79.5	0.210	10.3	$7.28 \cdot 10^{-7}$
80.4	0.180	10.3	$5.35 \cdot 10^{-7}$

6.1.4 PEG, V22BL + trim weight

Measurement data on the V22BL piezo strip with attached trim weight of 1.85 grams. The driving frequency is f. V_c is the voltage across the capacitor. Δt is the charging time of the capacitor and P is the power output.

V22BL	+ trim: 1.85 g		
f [Hz]	Vc [V]	Δt [s]	P [W]
11.0	0.027	10.2	$1.17 \cdot 10^{-8}$
15.2	0.118	10.1	$2.28 \cdot 10^{-7}$
17.9	0.209	10.3	$7.21 \cdot 10^{-7}$
18.5	0.270	10.0	$1.20 \cdot 10^{-6}$
19.2	0.236	10.1	$9.19 \cdot 10^{-7}$
20.1	0.340	10.4	$1.91 \cdot 10^{-6}$
21.3	0.293	10.1	$1.42 \cdot 10^{-6}$
22.1	0.393	10.1	$2.55 \cdot 10^{-6}$
22.1	0.381	10.0	$2.40 \cdot 10^{-6}$
23.1	0.655	10.3	$7.08 \cdot 10^{-6}$
24.1	1.105	10.2	$2.01 \cdot 10^{-5}$
24.5	1.353	10.1	$3.02 \cdot 10^{-5}$
25.1	2.610	10.4	$1.12 \cdot 10^{-4}$
25.9	6.920	10.2	$7.90 \cdot 10^{-4}$
27.2	4.970	10.4	$4.08 \cdot 10^{-4}$
28.2	3.250	10.2	$1.74 \cdot 10^{-4}$
28.6	2.930	10.4	$1.42 \cdot 10^{-4}$
28.9	2.680	10.1	$1.19 \cdot 10^{-4}$
30.3	2.180	11.1	$7.84 \cdot 10^{-5}$
31.2	1.964	10.2	$6.36 \cdot 10^{-5}$
32.0	2.470	10.1	$1.01 \cdot 10^{-4}$
33.0	2.370	10.3	$9.27 \cdot 10^{-5}$
33.4	2.220	10.2	$8.13 \cdot 10^{-5}$
34.4	2.640	10.0	$1.15 \cdot 10^{-4}$
35.0	2.680	10.0	$1.19 \cdot 10^{-4}$
36.0	1.99	10.0	$6.50 \cdot 10^{-5}$
37.3	1.487	10.4	$3.65 \cdot 10^{-5}$
41.9	0.650	10.1	$6.97 \cdot 10^{-6}$
46.4	1.349	10.5	$3.00 \cdot 10^{-5}$
52.0	0.577	10.2	$5.49 \cdot 10^{-6}$

V22BL	+ trim: 1.85 g		
f [Hz]	Vc [V]	Δt [s]	P [W]
56.8	0.342	10.2	$1.93 \cdot 10^{-6}$
62.2	0.185	10.3	$5.63 \cdot 10^{-7}$
71.0	0.115	12.0	$2.19 \cdot 10^{-7}$
77.6	0.043	10.2	$3.01 \cdot 10^{-8}$
83.4	0.025	10.1	$1.01 \cdot 10^{-8}$
89.4	0.013	10.2	$2.96 \cdot 10^{-9}$
93.2	0.012	10.3	$2.42 \cdot 10^{-9}$
96.8	0.008	10.7	$9.53 \cdot 10^{-10}$
99.3	0.003	10.2	$1.91 \cdot 10^{-10}$
104.9	0.004	10.4	$3.19 \cdot 10^{-10}$
109.9	0.002	9.4	$9.50 \cdot 10^{-11}$
115.2	0.003	10.1	$1.12 \cdot 10^{-10}$
119.5	0.003	10.2	$1.39 \cdot 10^{-10}$
123.3	0.002	10.3	$4.77 \cdot 10^{-11}$
126.3	0.002	10.2	$7.28 \cdot 10^{-11}$
130.2	0.002	10.3	$5.35 \cdot 10^{-11}$
135.0	0.002	10.4	$7.28 \cdot 10^{-11}$
139.7	0.002	11.8	$9.50 \cdot 10^{-11}$
145.3	0.002	10.1	$4.22 \cdot 10^{-11}$
151.8	0.002	10.1	$6.60 \cdot 10^{-11}$
158.3	0.002	10.1	$4.22 \cdot 10^{-11}$
164.2	0.002	10.3	$7.99 \cdot 10^{-11}$
170.9	0.002	10.3	$3.71 \cdot 10^{-11}$
176.5	0.001	10.1	$2.38 \cdot 10^{-11}$
180.9	0.001	10.1	$1.34 \cdot 10^{-11}$
185.9	0.001	10.1	$1.65 \cdot 10^{-11}$

6.2 TEG

6.2.1 TEG, UT11 model, measurement 1

Measurement data on the UT11 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, ΔT – temperature difference between *T1* and *T2*, *I* – load current and *P* – power output in the load. Load resistance: 10 Ω.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [µW]
5.3	15.0	9.7	5.93	351.65
5.8	15.0	9.2	5.56	309.14
6.0	15.0	9.0	5.43	294.85
6.3	15.0	8.7	5.27	277.73
6.8	15.3	8.4	5.07	257.05
7.1	15.3	8.2	4.89	239.12
7.4	15.3	7.9	4.75	225.63
7.6	15.3	7.6	4.64	215.30
7.9	15.3	7.4	4.56	207.94
8.1	15.3	7.1	4.41	194.48
8.4	15.3	6.8	4.28	183.18

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [µW]
8.7	15.5	6.8	4.15	172.23
8.9	15.5	6.6	4.03	162.41
9.2	15.5	6.3	3.85	148.23
9.5	15.5	6.1	3.75	140.63
9.7	15.5	5.8	3.64	132.50
10.0	15.8	5.8	3.51	123.20
10.3	15.8	5.5	3.38	114.24
10.5	15.8	5.3	3.28	107.58
10.8	15.8	5.0	3.11	96.72
11.6	16.1	4.5	2.72	73.98
11.8	16.1	4.2	2.60	67.60
12.1	16.1	4.0	2.51	63.00
12.4	16.3	4.0	2.27	51.53
12.6	16.3	3.7	2.22	49.28
13.2	16.3	3.2	2.00	40.00
13.4	16.3	2.9	1.87	34.97
13.7	16.6	2.9	1.73	29.93
13.9	16.6	2.6	1.65	27.23
14.2	16.6	2.4	1.50	22.50
14.5	16.8	2.4	1.39	19.32
14.7	16.8	2.1	1.29	16.64
15.0	16.8	1.8	1.15	13.23
15.3	16.8	1.6	1.04	10.82
15.5	17.1	1.6	0.87	7.57
15.8	17.1	1.3	0.80	6.40

6.2.2 TEG, UT11 model, measurement 2

Measurement data on the UT11 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, Δ*T* – temperature difference between *T1* and *T2*, *I* – load current and *P* – power output in the load. Load resistance: 100 Ω.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [µW]
-7.6	13.9	21.5	2.85	812.25
-7.3	13.9	21.3	2.80	784.00
-7.1	13.9	21.0	2.75	756.25
-6.6	13.9	20.5	2.69	723.61
-5.8	13.9	19.7	2.59	670.81
-5.2	13.9	19.2	2.52	635.04
-3.9	13.9	17.9	2.40	576.00
-3.4	13.9	17.4	2.34	547.56
-3.1	13.9	17.1	2.30	529.00
-2.9	14.2	17.1	2.27	515.29
-2.6	14.2	16.8	2.24	501.76
-2.4	14.2	16.6	2.21	488.41
-1.3	14.2	15.5	2.08	432.64

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
-1.0	14.2	15.3	2.05	420.25
-0.5	14.5	15.0	2.02	408.04
-0.3	14.5	14.7	1.98	392.04
0.3	14.5	14.2	1.93	372.49
0.5	14.5	13.9	1.89	357.21
0.8	14.5	13.7	1.87	349.69
1.1	14.5	13.4	1.83	334.89
2.6	14.7	12.1	1.66	275.56
2.9	14.7	11.8	1.62	262.44
3.2	15.0	11.8	1.59	252.81
3.7	15.0	11.3	1.53	234.09
3.9	15.0	11.1	1.50	225.00
4.2	15.0	10.8	1.47	216.09
4.5	15.0	10.5	1.45	210.25
4.5	15.0	10.5	1.43	204.49
4.7	15.0	10.3	1.41	198.81
5.0	15.3	10.3	1.39	193.21
5.8	15.3	9.5	1.28	163.84
6.0	15.3	9.2	1.27	161.29
6.3	15.3	9.0	1.24	153.76
6.6	15.5	9.0	1.20	144.00
7.6	15.5	7.9	1.08	116.64
7.9	15.5	7.6	1.06	112.36
8.9	15.8	6.9	0.92	84.64
9.2	15.8	6.6	0.89	79.21
10.0	16.1	6.1	0.82	67.24
10.3	16.1	5.8	0.79	62.41
10.5	16.1	5.5	0.76	57.76
11.0	16.3	5.3	0.70	49.00
11.3	16.3	5.0	0.68	46.24
11.6	16.3	4.7	0.65	42.25
11.8	16.3	4.5	0.62	38.44
12.1	16.3	4.2	0.60	36.00
12.4	16.6	4.2	0.55	30.25
12.6	16.6	4.0	0.54	29.16
12.9	16.6	3.7	0.51	26.01
13.2	16.6	3.4	0.48	23.04
13.4	16.8	3.4	0.45	20.25
13.7	16.8	3.2	0.43	18.49
13.9	16.8	2.9	0.40	16.00
14.2	16.8	2.6	0.37	13.69
14.5	16.8	2.4	0.35	12.25
14.7	17.1	2.4	0.32	10.24
15.0	17.1	2.1	0.29	8.41

6.2.3 TEG, UT11 model, measurement 3

Measurement data on the UT11 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, Δ*T* – temperature difference between *T1* and *T2*, *I* – load current and *P* – power output in the load. Load resistance: 565 Ω.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
-2.9	16.6	19.5	0.46	119.55
-2.4	16.6	18.9	0.44	109.38
-0.5	16.8	17.4	0.41	94.98
0.3	16.8	16.6	0.39	85.94
0.8	16.8	16.1	0.38	81.59
1.3	16.8	15.5	0.37	77.35
1.6	17.1	15.5	0.37	77.35
1.8	17.1	15.3	0.36	73.22
2.4	17.1	14.7	0.35	69.21
3.2	17.1	14.0	0.34	65.31
3.7	17.4	13.7	0.33	61.53
4.2	17.4	13.2	0.32	57.86
4.5	17.4	12.9	0.31	54.30
4.7	17.4	12.6	0.31	54.30
5.3	17.6	12.4	0.30	50.85
5.5	17.6	12.1	0.29	47.52
5.8	17.6	11.9	0.29	47.52
6.0	17.6	11.6	0.28	44.30
6.8	17.9	11.1	0.26	38.19
7.4	17.9	10.5	0.26	38.19
7.6	17.9	10.3	0.25	35.31
7.9	17.9	10.0	0.25	35.31
8.1	17.9	9.8	0.24	32.54
8.7	18.2	9.5	0.23	29.89
8.9	18.2	9.2	0.22	27.35
9.2	18.2	9.0	0.22	27.35
9.5	18.2	8.7	0.22	27.35
9.7	18.2	8.4	0.21	24.92
10.0	18.2	8.2	0.20	22.60
10.0	18.4	8.4	0.20	22.60
10.5	18.4	7.9	0.19	20.40
10.8	18.4	7.6	0.19	20.40
11.0	18.4	7.4	0.18	18.31
11.3	18.4	7.1	0.18	18.31
11.6	18.7	7.1	0.17	16.33
12.1	18.7	6.6	0.16	14.46
12.4	18.7	6.3	0.15	12.71
12.6	18.7	6.1	0.15	12.71
12.9	19.0	6.1	0.14	11.07
13.2	19.0	5.8	0.14	11.07
13.4	19.0	5.5	0.13	9.55

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
13.7	19.0	5.3	0.13	9.55
13.9	19.0	5.0	0.12	8.14
14.2	19.0	4.7	0.12	8.14
14.5	19.2	4.7	0.11	6.84
14.7	19.2	4.5	0.11	6.84
15.0	19.2	4.2	0.10	5.65
15.3	19.2	4.0	0.10	5.65
15.5	19.2	3.7	0.09	4.58
15.8	19.5	3.7	0.08	3.62
16.1	19.5	3.4	0.08	3.62
16.3	19.5	3.2	0.07	2.77
16.8	19.5	2.6	0.07	2.77
17.1	19.7	2.6	0.06	2.03
17.6	19.7	2.1	0.05	1.41

6.2.4 TEG, HT4 model, measurement 1

Measurement data on the HT4 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, ΔT – temperature difference between *T1* and *T2*, *I* – load current and *P* – power output in the load. Load resistance: 10 Ω.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
-5.2	19.2	24.5	11.52	1327.10
-7.6	16.3	23.9	11.09	1229.88
-7.6	15.8	23.4	10.75	1155.63
-6.8	15.5	22.3	10.34	1069.16
-6.3	15.3	21.6	9.81	962.36
-4.5	15.5	20.0	9.24	853.78
-3.7	15.8	19.5	8.88	788.54
-2.9	15.8	18.7	8.62	743.04
-2.1	16.1	18.1	8.32	692.22
-1.3	16.3	17.6	7.92	627.26
-0.3	16.3	16.6	7.71	594.44
0.3	16.3	16.1	7.50	562.50
0.8	16.6	15.8	7.30	532.90
1.3	16.6	15.3	7.10	504.10
1.8	16.8	15.0	6.92	478.86
2.1	16.8	14.7	6.68	446.22
3.2	17.1	14.0	6.52	425.10
3.7	17.1	13.4	6.38	407.04
3.9	17.4	13.4	6.30	396.90
4.2	17.4	13.2	6.18	381.92
4.7	17.4	12.6	5.99	358.80
5.3	17.6	12.4	5.86	343.40
5.8	17.6	11.9	5.75	330.63
6.0	17.6	11.6	5.64	318.10
6.3	17.9	11.6	5.44	295.94

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
6.8	17.9	11.1	5.32	283.02
7.1	17.9	10.8	5.20	270.40
8.1	17.9	9.8	4.85	235.23
8.7	18.2	9.5	4.68	219.02
8.9	18.2	9.2	4.58	209.76
9.2	18.2	9.0	4.49	201.60
9.5	18.4	9.0	4.33	187.49
9.7	18.4	8.7	4.25	180.63
10.0	18.4	8.4	4.09	167.28
10.5	18.7	8.2	4.00	160.00
10.8	18.7	7.9	3.93	154.45
11.0	18.7	7.6	3.78	142.88
11.3	18.7	7.4	3.72	138.38
11.6	18.7	7.1	3.67	134.69
11.6	19.0	7.4	3.61	130.32
11.8	19.0	7.1	3.54	125.32
12.1	19.0	6.9	3.43	117.65
12.4	19.0	6.6	3.27	106.93
12.6	19.2	6.6	3.18	101.12
12.9	19.2	6.3	3.13	97.97
13.2	19.2	6.1	3.03	91.81
13.4	19.2	5.8	2.92	85.26
13.7	19.2	5.5	2.90	84.10
13.9	19.5	5.5	2.80	78.40
14.2	19.5	5.3	2.70	72.90
14.5	19.5	5.0	2.63	69.17
14.7	19.5	4.7	2.61	68.12
14.7	19.5	4.7	2.44	59.54
15.0	19.7	4.7	2.35	55.23
15.3	19.7	4.5	2.32	53.82
15.8	19.7	4.0	2.18	47.52
16.1	19.7	3.7	2.11	44.52
16.1	20.0	4.0	2.08	43.26
16.3	20.0	3.7	2.00	40.00
16.6	20.0	3.4	1.94	37.64
16.8	20.0	3.2	1.85	34.23
17.1	20.0	2.9	1.73	29.93
17.1	20.3	3.2	1.70	28.90
17.4	20.3	2.9	1.66	27.56
17.6	20.3	2.6	1.56	24.34
17.9	20.3	2.4	1.40	19.60
17.9	20.5	2.6	1.36	18.50
18.4	20.5	2.1	1.27	16.13
18.7	20.8	2.1	1.15	13.23
19.0	20.5	1.6	1.06	11.24
19.5	20.8	1.3	0.88	7.74
21.1	21.3	0.3	0.29	0.84

6.2.5 TEG, HT4 model, measurement 2

Measurement data on the HT4 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, Δ*T* – temperature difference between *T1* and *T2*, *I* – load current and *P* – power output in the load. Load resistance: 100 Ω.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
-5.2	19.5	24.7	2.89	835.21
-8.4	17.1	25.5	2.91	846.81
-9.4	16.1	25.5	2.87	823.69
-10.0	15.3	25.2	2.81	789.61
-10.0	15.0	25.0	2.76	761.76
-9.7	14.7	24.4	2.69	723.61
-9.2	14.7	23.9	2.62	686.44
-8.6	15.0	23.6	2.57	660.49
-8.1	15.0	23.1	2.52	635.04
-7.1	15.0	22.1	2.45	600.25
-6.8	15.0	21.8	2.41	580.81
-6.3	15.3	21.6	2.37	561.69
-6.0	15.3	21.3	2.33	542.89
-5.8	15.3	21.0	2.31	533.61
-4.2	15.5	19.7	2.19	479.61
-3.7	15.5	19.2	2.16	466.56
-3.1	15.8	18.9	2.06	424.36
-2.6	15.8	18.4	2.06	424.36
-2.1	15.8	17.9	2.02	408.04
-1.6	16.1	17.6	1.98	392.04
-1.3	16.1	17.4	1.95	380.25
-0.8	16.1	16.8	1.90	361.00
-0.5	16.3	16.8	1.85	342.25
0.5	16.3	15.8	1.79	320.41
1.1	16.6	15.5	1.74	302.76
1.6	16.6	15.0	1.71	292.41
2.1	16.8	14.7	1.65	272.25
2.6	16.8	14.2	1.62	262.44
2.9	16.8	14.0	1.59	252.81
3.4	16.8	13.4	1.56	243.36
3.7	17.1	13.4	1.54	237.16
3.9	17.1	13.2	1.51	228.01
4.2	17.1	12.9	1.49	222.01
4.5	17.1	12.6	1.47	216.09
4.7	17.1	12.4	1.45	210.25
4.5	17.4	12.9	1.44	207.36
5.0	17.4	12.4	1.38	190.44
5.3	17.4	12.1	1.36	184.96
5.8	17.4	11.6	1.33	176.89
6.3	17.6	11.3	1.31	171.61
6.6	17.6	11.1	1.28	163.84
6.8	17.6	10.8	1.27	161.29

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
7.1	17.6	10.5	1.25	156.25
7.9	17.6	9.7	1.18	139.24
8.1	17.9	9.8	1.16	134.56
8.4	17.9	9.5	1.12	125.44
8.9	17.9	9.0	1.09	118.81
9.2	17.9	8.7	1.07	114.49
9.5	18.2	8.7	1.05	110.25
9.7	18.2	8.4	1.03	106.09
10.0	18.2	8.2	0.99	98.01
10.5	18.2	7.6	0.97	94.09
10.8	18.4	7.6	0.96	92.16
11.0	18.4	7.4	0.94	88.36
11.3	18.4	7.1	0.93	86.49
11.6	18.4	6.9	0.92	84.64
11.8	18.4	6.6	0.89	79.21
12.1	18.4	6.3	0.88	77.44
12.4	18.4	6.1	0.86	73.96
12.6	18.7	6.1	0.81	65.61
13.2	18.7	5.5	0.80	64.00
13.4	18.7	5.3	0.78	60.84
13.7	18.7	5.0	0.76	57.76
13.9	19.0	5.0	0.72	51.84
14.2	19.0	4.7	0.70	49.00
14.5	19.0	4.5	0.68	46.24
14.7	19.0	4.2	0.64	40.96
15.0	19.2	4.2	0.61	37.21
15.8	19.2	3.4	0.54	29.16
16.3	19.5	3.2	0.49	24.01
16.6	19.5	2.9	0.45	20.25
16.8	19.5	2.6	0.43	18.49
17.1	19.7	2.6	0.42	17.64
17.6	19.7	2.1	0.36	12.96
17.9	20.0	2.1	0.32	10.24
18.4	20.0	1.6	0.27	7.29
18.7	20.3	1.6	0.25	6.25
19.0	20.3	1.3	0.21	4.41
19.2	20.3	1.1	0.21	4.41
19.5	20.3	0.8	0.19	3.61
19.7	20.5	0.8	0.17	2.89

6.2.6 TEG, HT4 model, measurement 3

Measurement data on the HT4 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, Δ*T* – temperature difference between *T1* and *T2, I* – load current and *P* – power output in the load. Load resistance: 565 Ω. No heat conducting paste applied.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
-5.2	20.5	25.8	0.48	130.18
-7.1	19.0	26.0	0.48	130.18
-7.6	18.2	25.8	0.47	124.81
-7.9	17.9	25.8	0.46	119.55
-7.3	17.4	24.7	0.45	114.41
-6.6	17.4	23.9	0.43	104.47
-6.0	17.4	23.4	0.42	99.67
-5.2	17.4	22.6	0.41	94.98
-4.5	17.4	21.8	0.40	90.40
-3.9	17.6	21.6	0.39	85.94
-3.4	17.6	21.0	0.38	81.59
-2.9	17.6	20.5	0.37	77.35
-2.4	17.6	20.0	0.36	73.22
-1.8	17.9	19.7	0.35	69.21
-1.6	17.9	19.5	0.35	69.21
-1.0	17.9	18.9	0.34	65.31
-0.5	17.9	18.4	0.33	61.53
0.5	18.2	17.6	0.32	57.86
0.8	18.2	17.4	0.32	57.86
1.3	18.4	17.1	0.31	54.30
2.1	18.4	16.3	0.30	50.85
2.4	18.4	16.1	0.29	47.52
2.6	18.4	15.8	0.29	47.52
3.2	18.7	15.5	0.28	44.30
3.4	18.7	15.3	0.28	44.30
3.7	18.7	15.0	0.27	41.19
3.9	18.7	14.8	0.27	41.19
4.2	18.7	14.5	0.27	41.19
4.5	19.0	14.5	0.26	38.19
4.7	19.0	14.2	0.26	38.19
5.0	19.0	14.0	0.25	35.31
5.3	19.0	13.7	0.25	35.31
5.5	19.0	13.4	0.25	35.31
5.8	19.0	13.2	0.24	32.54
6.0	19.2	13.2	0.24	32.54
6.3	19.2	12.9	0.23	29.89
6.6	19.2	12.6	0.23	29.89
6.8	19.2	12.4	0.23	29.89
7.1	19.2	12.1	0.22	27.35
5.3	19.2	14.0	0.22	27.35

T1 [°C]	T2 [°C]	∆T [°C]	I [mA]	P [μW]
7.6	19.5	11.9	0.21	24.92
7.9	19.5	11.6	0.21	24.92
8.1	19.5	11.3	0.21	24.92
8.4	19.5	11.1	0.20	22.60
8.7	19.5	10.8	0.20	22.60
8.7	19.5	10.8	0.20	22.60
9.2	19.5	10.3	0.19	20.40
9.5	19.7	10.3	0.19	20.40
9.7	19.7	10.0	0.18	18.31
10.0	19.7	9.8	0.18	18.31
10.3	19.7	9.5	0.18	18.31
10.5	19.7	9.2	0.17	16.33
10.8	19.7	9.0	0.17	16.33
11.0	20.0	9.0	0.16	14.46
11.3	20.0	8.7	0.16	14.46
11.6	20.0	8.4	0.16	14.46
11.8	20.0	8.2	0.15	12.71
12.1	20.0	7.9	0.15	12.71
12.4	20.0	7.6	0.14	11.07
12.6	20.3	7.7	0.14	11.07
12.9	20.3	7.4	0.14	11.07
13.2	20.3	7.1	0.13	9.55
13.4	20.3	6.9	0.13	9.55
13.7	20.3	6.6	0.12	8.14
13.9	20.5	6.6	0.12	8.14
14.2	20.5	6.3	0.11	6.84
14.5	20.5	6.1	0.11	6.84
14.7	20.5	5.8	0.11	6.84
15.0	20.5	5.5	0.10	5.65
15.3	20.5	5.3	0.10	5.65
15.5	20.5	5.0	0.09	4.58
15.8	20.8	5.0	0.09	4.58
16.1	20.8	4.8	0.09	4.58
16.8	21.1	4.2	0.07	2.77
17.1	21.1	4.0	0.07	2.77
17.4	21.1	3.7	0.07	2.77
17.9	21.1	3.2	0.06	2.03
18.2	21.1	2.9	0.05	1.41
18.2	21.3	3.2	0.05	1.41
18.4	21.3	2.9	0.05	1.41
18.7	21.3	2.6	0.05	1.41
19.0	21.3	2.4	0.04	0.90
19.2	21.3	2.1	0.04	0.90
19.5	21.6	2.1	0.04	0.90
20.0	21.6	1.6	0.03	0.51
20.3	21.6	1.3	0.02	0.23

6.2.7 TEG, HT4 model, measurement 4

Measurement data on the HT4 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, ΔT – temperature difference between *T1* and *T2*, *I* – load current and *P* – power output in the load. Load resistance: 565 Ω. Heat conducting paste applied.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [µW]
-10.2	18.1	28.4	0.99	98.01
-11.3	17.6	28.9	0.98	96.04
-11.3	17.1	28.4	0.96	92.16
-11.0	17.1	28.1	0.95	90.25
-10.7	17.1	27.8	0.93	86.49
-9.7	17.1	26.8	0.90	81.00
-9.4	17.1	26.5	0.89	79.21
-8.9	17.1	26.0	0.88	77.44
-8.4	17.1	25.5	0.86	73.96
-7.9	17.4	25.2	0.85	72.25
-7.3	17.4	24.7	0.83	68.89
-6.6	17.4	23.9	0.81	65.61
-6.0	17.4	23.4	0.80	64.00
-5.5	17.4	22.9	0.78	60.84
-4.5	17.6	22.1	0.74	309.39
-3.9	17.6	21.6	0.73	301.09
-3.1	17.6	20.8	0.71	284.82
-2.9	17.6	20.5	0.69	269.00
-2.4	17.6	20.0	0.68	261.26
-2.1	17.6	19.7	0.67	253.63
-1.3	17.9	19.2	0.64	231.42
-0.5	17.9	18.4	0.63	224.25
-0.3	17.9	18.2	0.62	217.19
0.3	18.2	17.9	0.61	210.24
0.5	18.2	17.6	0.60	203.40
2.1	18.2	16.1	0.55	170.91
2.4	18.2	15.8	0.54	164.75
2.9	18.4	15.5	0.53	158.71
4.2	18.4	14.2	0.49	135.66
4.5	18.4	14.0	0.48	130.18
5.0	18.4	13.4	0.47	124.81
5.5	18.7	13.2	0.45	114.41
5.8	18.7	12.9	0.44	109.38
6.0	18.7	12.6	0.43	104.47
6.3	18.7	12.4	0.42	99.67
6.6	18.7	12.1	0.41	94.98
6.8	18.7	11.9	0.40	90.40
7.1	18.7	11.6	0.40	90.40
7.4	18.7	11.3	0.39	85.94
7.6	18.7	11.1	0.38	81.59
7.9	18.7	10.8	0.37	77.35

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
8.1	18.7	10.5	0.36	73.22
8.7	19.0	10.3	0.35	69.21
8.9	19.0	10.0	0.34	65.31
9.2	19.0	9.8	0.32	57.86
9.7	19.0	9.2	0.31	54.30
10.0	19.0	9.0	0.30	50.85
10.3	19.0	8.7	0.30	50.85
10.5	19.0	8.4	0.29	47.52
11.0	19.2	8.2	0.27	41.19
11.3	19.2	7.9	0.27	41.19
11.8	19.2	7.4	0.25	35.31
12.1	19.2	7.1	0.24	32.54
12.6	19.5	6.9	0.23	29.89
12.9	19.5	6.6	0.22	27.35
13.9	19.5	5.5	0.19	20.40
14.2	19.7	5.5	0.19	20.40
14.5	19.7	5.3	0.17	16.33
15.3	19.7	4.5	0.16	14.46
15.5	20.0	4.5	0.15	12.71
15.8	20.0	4.2	0.14	11.07
16.1	20.0	4.0	0.14	11.07
16.3	20.0	3.7	0.12	8.14
16.6	20.0	3.4	0.12	8.14
16.8	20.0	3.2	0.11	6.84
17.4	20.3	2.9	0.09	4.58

6.2.8 TEG, PT4 model, measurement 1

Measurement data on the HT4 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, Δ*T* – temperature difference between *T1* and *T2*, *I* – load current and *P* – power output in the load. Load resistance: 10 Ω. Heat conducting paste applied.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
-6.3	17.4	23.7	19.25	3705.63
-5.8	17.4	23.1	18.82	3541.92
-5.2	17.4	22.6	18.33	3359.89
-4.7	17.4	22.1	17.93	3214.85
-4.2	17.6	21.8	17.58	3090.56
-3.7	17.6	21.3	17.29	2989.44
-3.1	17.6	20.8	16.95	2873.03
-2.9	17.6	20.5	16.63	2765.57
-2.4	17.6	20.0	16.34	2669.96

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [µW]
-1.8	17.6	19.5	16.04	2572.82
-1.6	17.6	19.2	15.73	2474.33
-1.0	17.9	18.9	15.42	2377.76
-0.5	17.9	18.4	15.15	2295.23
-0.3	17.9	18.2	14.84	2202.26
0.5	17.9	17.4	14.42	2079.36
0.8	17.9	17.1	14.14	1999.40
1.1	18.2	17.1	13.85	1918.23
2.1	18.2	16.1	13.19	1739.76
2.6	18.2	15.5	12.80	1638.40
3.2	18.2	15.0	12.38	1532.64
3.7	18.4	14.7	12.11	1466.52
5.0	18.4	13.4	11.24	1263.38
5.3	18.4	13.2	11.10	1232.10
5.5	18.4	12.9	10.85	1177.23
5.8	18.7	12.9	10.66	1136.36
6.0	18.7	12.6	10.51	1104.60
6.3	18.7	12.4	10.28	1056.78
6.6	18.7	12.1	10.09	1018.08
6.8	18.7	11.9	9.93	986.05
7.1	18.7	11.6	9.70	940.90
7.4	18.7	11.3	9.53	908.21
8.1	19.0	10.8	8.94	799.24
8.4	19.0	10.5	8.77	769.13
8.7	19.0	10.3	8.64	746.50
8.9	19.0	10.0	8.50	722.50
9.5	19.0	9.5	7.95	632.03
10.0	19.0	9.0	7.67	588.29
10.0	19.2	9.2	7.50	562.50
10.3	19.2	9.0	7.36	541.70
10.5	19.2	8.7	7.21	519.84
10.8	19.2	8.4	7.09	502.68
11.0	19.2	8.2	6.88	473.34
11.3	19.2	7.9	6.72	451.58
11.6	19.2	7.6	6.51	423.80
11.8	19.2	7.4	6.36	404.50

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [µW]
12.1	19.2	7.1	6.16	379.46
12.6	19.5	6.9	5.71	326.04
12.9	19.5	6.6	5.58	311.36
13.4	19.5	6.1	5.15	265.23
13.7	19.5	5.8	5.02	252.00
13.9	19.5	5.5	4.82	232.32
14.2	19.7	5.5	4.62	213.44
14.5	19.7	5.3	4.44	197.14
14.7	19.7	5.0	4.22	178.08
15.0	19.7	4.7	4.06	164.84
15.3	19.7	4.5	3.86	149.00
15.5	19.7	4.2	3.68	135.42
15.8	19.7	4.0	3.47	120.41
16.1	20.0	4.0	3.31	109.56
16.3	20.0	3.7	3.11	96.72
16.6	20.0	3.4	2.90	84.10
16.8	20.0	3.2	2.73	74.53
17.1	20.0	2.9	2.48	61.50
17.4	20.0	2.6	2.36	55.70
17.6	20.3	2.6	2.18	47.52
17.9	20.3	2.4	1.99	39.60
18.2	20.3	2.1	1.81	32.76
18.4	20.3	1.8	1.64	26,90

6.2.9 TEG, PT4 model, measurement 2

Measurement data on the HT4 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, Δ*T* – temperature difference between *T1* and *T2*, *I* – load current and *P* – power output in the load. Load resistance: 100 Ω. Heat conducting paste applied.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [µW]
-8.9	15.5	24.4	4.80	2304.00
-8.6	15.5	24.2	4.73	2237.29
-8.1	15.5	23.6	4.65	2162.25
-7.9	15.5	23.4	4.59	2106.81
-6.6	15.5	22.1	4.36	1900.96

T1 [°C]	T2 [°C]	∆T [°C]	I [mA]	P [µW]
-6.0	15.5	21.6	4.29	1840.41
-5.8	15.5	21.3	4.21	1772.41
-5.2	15.5	20.8	4.14	1713.96
-5.0	15.5	20.5	4.09	1672.81
-4.7	15.8	20.5	4.04	1632.16
-4.5	15.8	20.2	3.99	1592.01
-4.2	15.8	20.0	3.94	1552.36
-3.9	15.8	19.7	3.88	1505.44
-3.4	15.8	19.2	3.80	1444.00
-2.9	15.8	18.7	3.73	1391.29
-2.6	15.8	18.4	3.66	1339.56
-2.4	15.8	18.1	3.62	1310.44
-2.1	15.8	17.9	3.56	1267.36
-1.6	15.8	17.4	3.50	1225.00
-0.8	16.1	16.8	3.35	1122.25
-0.5	16.1	16.6	3.31	1095.61
-0.3	16.1	16.3	3.27	1069.29
0.3	16.1	15.8	3.18	1011.24
1.3	16.3	15.0	2.97	882.09
1.6	16.3	14.7	2.93	858.49
1.8	16.3	14.5	2.89	835.21
2.1	16.3	14.2	2.85	812.25
2.6	16.3	13.7	2.75	756.25
2.9	16.3	13.4	2.72	739.84
3.2	16.3	13.2	2.67	712.89
3.7	16.6	12.9	2.56	655.36
3.9	16.6	12.6	2.53	640.09
4.2	16.6	12.4	2.45	600.25
4.5	16.6	12.1	2.43	590.49
4.7	16.6	11.9	2.40	576.00
5.0	16.6	11.6	2.36	556.96
5.3	16.6	11.3	2.31	533.61
5.5	16.6	11.1	2.25	506.25
5.8	16.6	10.8	2.21	488.41
7.9	16.8	9.0	1.82	331.24
8.1	16.8	8.7	1.79	320.41

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
8.4	17.1	8.7	1.75	306.25
8.7	17.1	8.4	1.70	289.00
8.9	17.1	8.2	1.66	275.56
9.2	17.1	7.9	1.59	252.81
9.5	17.1	7.6	1.56	243.36
9.7	17.1	7.4	1.53	234.09
10.0	17.1	7.1	1.46	213.16
10.3	17.4	7.1	1.42	201.64
10.5	17.4	6.9	1.39	193.21
10.8	17.4	6.6	1.33	176.89
11.0	17.4	6.3	1.30	169.00
11.3	17.4	6.1	1.24	153.76
11.6	17.4	5.8	1.19	141.61
11.8	17.6	5.8	1.15	132.25
12.1	17.6	5.5	1.11	123.21
12.4	17.6	5.3	1.07	114.49
12.6	17.6	5.0	1.02	104.04
12.9	17.6	4.7	0.97	94.09
13.9	17.9	4.0	0.80	64.00
14.5	17.9	3.4	0.71	50.41
15.0	18.2	3.2	0.61	37.21
15.3	18.2	2.9	0.57	32.49
15.8	18.2	2.4	0.50	25.00
16.1	18.4	2.4	0.45	20.25
16.3	18.4	2.1	0.41	16.81
16.6	18.4	1.8	0.38	14.44
16.8	18.4	1.6	0.35	12.25
17.6	19.0	1.3	0.25	6,25

6.2.10 TEG, PT4 model, measurement 3

Measurement data on the HT4 peltier cooler used as TEG. *T1* is temperature on the cold side, *T2* on the warm, Δ*T* – temperature difference between *T1* and *T2*, *I* – load current and *P* – power output in the load. Load resistance: 565 Ω. Heat conducting paste applied.

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
-9.2	17.1	26.3	0.95	509.91
-8.9	17.1	26.0	0.92	478.22
-8.4	16.8	25.2	0.91	467.88
-7.9	16.8	24.7	0.90	457.65
-7.6	17.1	24.7	0.88	437.54
-7.1	17.1	24.2	0.87	427.65
-6.6	17.1	23.7	0.85	408.21
-6.0	17.1	23.1	0.83	389.23
-5.5	17.1	22.6	0.82	379.91
-5.0	17.1	22.1	0.80	361.60
-4.5	17.4	21.8	0.79	352.62
-4.2	17.4	21.6	0.77	334.99
-3.7	17.4	21.0	0.76	326.34
-3.4	17.4	20.8	0.75	317.81
-2.9	17.4	20.3	0.74	309.39
-2.6	17.4	20.0	0.73	301.09
-2.1	17.6	19.7	0.72	292.90
-1.8	17.6	19.5	0.71	284.82
-1.3	17.6	18.9	0.69	269.00
-0.8	17.6	18.4	0.67	253.63
-0.3	17.6	17.9	0.66	246.11
0.3	17.9	17.6	0.64	231.42
0.5	17.9	17.4	0.63	224.25
1.1	17.9	16.8	0.61	210.24
1.6	17.9	16.3	0.60	203.40
1.8	17.9	16.1	0.59	196.68
2.1	18.2	16.1	0.58	190.07
2.4	18.2	15.8	0.57	183.57
2.9	18.2	15.3	0.56	177.18
3.2	18.2	15.0	0.55	170.91

T1 [°C]	T2 [°C]	ΔT [°C]	I [mA]	P [μW]
3.7	18.2	14.5	0.53	158.71
4.2	18.4	14.2	0.52	152.78
4.5	18.4	14.0	0.51	146.96
4.7	18.4	13.7	0.51	146.96
5.0	18.4	13.4	0.50	141.25
5.3	18.4	13.2	0.49	135.66
5.8	18.4	12.6	0.47	124.81
6.0	18.4	12.4	0.45	114.41
6.6	18.4	11.9	0.44	109.38
6.8	18.7	11.9	0.44	109.38
7.1	18.7	11.6	0.43	104.47
7.4	18.7	11.3	0.42	99.67
7.4	18.7	11.3	0.41	94.98
7.6	18.7	11.1	0.40	90.40
7.9	18.7	10.8	0.40	90.40
8.4	19.0	10.5	0.39	85.94
8.7	19.0	10.3	0.38	81.59
9.2	19.0	9.8	0.36	73.22
9.5	19.0	9.5	0.35	69.21
9.7	19.0	9.2	0.34	65.31
10.0	19.0	9.0	0.34	65.31
10.3	19.0	8.7	0.33	61.53
10.5	19.2	8.7	0.32	57.86
10.8	19.2	8.4	0.31	54.30
11.0	19.2	8.2	0.30	50.85
11.6	19.2	7.6	0.29	47.52
11.8	19.2	7.4	0.28	44.30
12.1	19.2	7.1	0.27	41.19
12.4	19.5	7.1	0.26	38.19
12.6	19.5	6.9	0.25	35.31
12.9	19.5	6.6	0.24	32.54
13.2	19.5	6.3	0.24	32.54
13.4	19.5	6.1	0.23	29.89
13.7	19.5	5.8	0.22	27.35
13.9	19.5	5.5	0.21	24.92
14.2	19.7	5.5	0.20	22.60

T1 [°C]	T2 [°C]	∆T [°C]	I [mA]	P [µW]
14.5	19.7	5.3	0.19	20.40
14.7	19.7	5.0	0.18	18.31
15.0	19.7	4.7	0.18	18.31
15.5	19.7	4.2	0.16	14.46
15.8	19.7	4.0	0.15	12.71
16.1	20.0	4.0	0.14	11.07

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