T802
MSc in Engineering

The application of thermo electrical generators to use waste heat as a source to increase the overall efficiency of a cooling unit

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Abstract:

The following work analyses the usage of a thermo electrical generator to use the waste heat from an air conditioning system cooler. The cooler from a large air conditioning system emits great amounts of energy to the environment. This energy is a great amount of waste heat but at low temperature.

To use this energy to increase the overall efficiency of the cooling unit and to lower the ecological footprint some options are possible. One possibility is the usage of a thermo electrical generator. A thermo electrical generator generates electrical power out of temperature differences. The overall efficiency of such a TEG is at the low end of the efficiency scale. With new materials like skutterudites the efficiency can be raised. To look at the power scale, this work analyses the power production of a commercial TEGs at the low efficiency scale, the amount of waste energy and out of that the overall efficiency of such a combination between a TEG and an air conditioning system roof cooler.

The analysis includes also a theoretical outlook on the energy production of a nano material based TEG with a theoretical efficiency five times of the one of a commercial available TEG. The research is based on a case study using historical data from a roof cooler of a big building in Vienna. The data will be combined with the theory to produce results.

In an experiment the behaviour of a commercial TEG will be analysed and the occurring problems are shown.

To support the results of the analysis and to check the acceptance and the possibility of a commercial usage of such a system, a small amount of experts were asked for their opinion. The results of the survey are a base for the further commercial development of the system, and it shows the problems, which can occur by an installation of such a system.

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Glossary

Adsorber machine
A cooling unit which has a small amount of moving parts and which needs heat to produce chill. The heat can be waste heat from an industrial process.

Carnot Cycle A circle process, with special importance in thermodynamics.

Cooling unit A thermodynamic machine, which produces chill for several purposes.

Efficiency A term, which describes the conversion rate from one energy form to another energy form; e.g the efficiency of a gasoline motor lies of about 30%.

Legionella bacteria
A bacteria which elicit the legionella disease, a respiratory system illness.

Peltier effect A thermoelectric effect, the Peltier effect is the reverse effect of the Seebeck effect. The effect is directly proportional to the attached current.

Practical efficiency
The efficiency, which can use in a practical usage it is lower than a calculated theoretical efficiency.

TEG Thermo electrical generator, a semiconductor based electrical generator, which produces energy out of a temperature differences, it has a low efficiency with <4%.

Return line The line which transports the cooled down water from the roof cooler and goes down the cooling machine.

Roof cooler A cooler of a cooling unit on the roof, to emit heat to the environment.

RTEG Radionuclide thermo electrical generator, like a TEG, but it uses a radionuclide to produce the power and the temperature difference, e.g. a plutonium pellet.

Seebeck effect A thermoelectric effect, which occurs a circuit which is constructed out of two different homogenous conductors produces a electrical current when the junctions are at different temperatures.

Skutterudites A group of cobalt arsenide materials, which has variable amounts of the elements nickel and iron. The cobalt can be substituted by the two elements. The material has interesting characteristics for thermoelectric elements.

Supply line The line which comes from the cooling unit and goes to the roof cooler to cools down to a lower temperature by the fans of the cooler.

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1 Introduction

1.1 Background to the problem

In a time of lacking conventional energy sources, increasing environmental pollution, increasing energy demand and rising energy prices, it is very important to search for alternative energy sources or to increase the efficiency of existing energy forms.

Alternative energy sources are for example photovoltaic solar cells or wind power stations.
Possibilities to increase the overall efficiency of an existing energy form are the usage of the waste heat from a car combustion engine or the usage of the waste heat of a roof cooler from a cooling unit. (Faninger, 2006).

For several industrial and scientific purposes a cooling machine is needed.
The usage of such a cooling machine is various, many industrial productions and also scientific processes need constant temperature in the production process or in the research process, so that an air conditioning system is necessary to hold the temperature constant. The air conditioning system contains a cooling unit, a heat unit and sometimes a humidifier. (Recknagel, 1997).

A normal, standard cooling machine, which is produced by the industry is in the range from some kilowatts to some megawatts, it also produces waste energy, which is given to the environment as waste heat. (Toshiba, 2012) (York, 2012)

Most of the nowadays used conventional energy (e.g. fossil energy sources) produces heat, this heat is mostly the biggest part from the so produced energy. One usage from this waste heat energy is for heating purposes, like a power-heat coupling, which is used e.g. in the Netherlands to heat greenhouses (E-control.at, 2012).

Another possibility is to produce chill out of waste heat with an adsorber machine. These technologies need relative complex hydraulic and mechanical installations and they can only be used at one or two seasons of the year. The maintenance costs of such a complex system are relatively high, and in case of complex maintenance the non-operations periods are also relatively high (Agentur für erneuerbare Energien, 2012). The minimum temperature for that purpose is about 95°C, below this temperature the LiBr chill liquid crystallizes. Therefor the usage of an adsorber machines for low temperature does not look possible at the moment (Recknagel, 1997).

These above described technologies can be used in relative heavy power plant, but are difficult to transpose for the usage in a car or in a home power plant, also the costs of a small energy plant and the payback period are at the moment not in an acceptable range.

The produced waste heat energy from an air conditioning system can be used in several ways, one of the possibilities, but with low efficiency, is to heat the warm water circuit of a building. The efficiency is low (an exact value is not available), because the waste heat is in the low temperature range (30°C to 50°C). The low efficiency results in the additional energy, which is needed to warm up the water for heating and warm water purposes. The next problem occurs during the heat transfer from the additional heating source to the temperate water. The temperature for low temperature heating purposes should be in the range of about 30°C and more, but in the heating season normally no chill is needed. The next possibility is to heat warm water with that waste energy, but on hygienic reason the temperature should reach 65°C (legionella bacteria), so that again additional heat energy is needed to reach this temperature. This raises the efficiency of the heating process, but less warm water will be used than energy is available.

To use the waste heat to produce electrical energy is also possible by using a thermoelectric generator. A thermoelectric element (TEG) is based on semiconductor materials and uses temperature differences to produce an electrical current. The effect which is used by a TEG is called "Seebeck effect". This effect occurs in principle at every junction between two different materials. The overall efficiency of such a TEG is not very high it is just of about 4%. To use the waste heat from a roof cooler to produce electrical energy is a new idea and a new research issue which is after the initial review not researched by anyone till today.

1.2 Justification for the research

In times, in which energy will be a rare resource, especially for energy which is produced out of fossil sources (oil, coal etc.), alternative energy sources or technologies which can increase the efficiency of a fossil energy source, the justification of research on such technologies is very high. Most of the input energy by the usage of fossil energy will be heat (up to 70%), this energy is blown to the environment and cannot be used for the original purpose.

A modern power plant with the possibility of power - heat cogeneration has an efficiency of about 70%, but 30% of this energy goes still to the environment. To know this is necessary for the ecological footprint, because the electrical energy which is produced by such a power plant drives the described cooling unit. To raise the efficiency of the examined cooling unit to an optimum, and to reduce the production of greenhouse gases (CO_2, H_2O, CH_4, NOX, O_3) (Forster et.al, 2007) new technologies should be used. One of these technologies, which exists over 100 years is the usage of TEG´s, till 2010 the efficiencies of such TEG´s were very low (<5%). (Recknagel, 1997, p.1753)(Schubert, 1984, p. 86)

Since 2010, when new materials can raise, based on ceramics and on nanotechnologies were invented, the efficiency of a TEG can be raised up to 20% and perhaps more (Wölfing, 2001) (Yang et.al, 2006).

For modern industry production, laboratory research and for the comfort of persons cooling units were developed and used to hold a specific temperature constant.

A modern building cooling unit has a connected wattage of about 150 kW and a cooling wattage of about 600kW under full load (York, 2012). The waste energy from one cooling unit which blasts through the roof cooler to the environment is after some calculations in average 148kWh (532.8MJ), the peak energy is of about 439kWh (1,580.4MJ). This energy is the energy which the cool water contains in an hour.

With a TEG, based on existing materials with an average efficiency of about 4% theoretically 6kWh per cooling unit can be generated. This is about the energy which the pumps, for the cool water circuit need for transportation of the hot water from the air conditioning system to the roof cooler.

With TEG materials, based on nanotechnologies, the theoretical energy output of a combination a roof cooler and a TEG can reach acceptable values in the range of about 15kWh up to 30kWh.

By an estimated duty cycle of the cooling machine of about 4,000 hours a year (50%), ~24,000 kWh can be produced theoretically per cooling machine and per year with a commercial available TEG.
The price of one kilowatt hour is about 13 Eurocent, so that with such a system 3,120 Euro/year can be saved. Vienna has of about 300 roof cooling systems in that dimension, so that only in Vienna (1.7 million inhabitants) an energy consumption of 7.2 GWh/year can be saved, which is about 0.01% of the whole yearly electrical energy production of Austria (71 TWh).

After a literature review and some internet research it was discovered that no one has extended a cooling unit cooler with a TEG, to increase the overall efficiency of this system. The research in the nanotechnology TEG (> 4% efficiency) issue is relatively new and most of the existing TEG (4% to 6% efficiency) will be used only in exotic applications, like energy production in a space probe in combination with a radionuclide. These are so called radioisotope TEG or short RTG.

As a first short result it can be said that a combination between a roof cooler and a TEG is a new idea.

With new TEG materials and on lacking resources in the future this technology has potential. Research at the moment is based on generating power with TEG in cars, to use the waste heat to supply the electrical consumers of a car.

1.3 Aims and objectives

The aim of this research was to make recommendations on how a TEG can use the waste energy which a roof cooler emits to the environment and to increase in consequence the efficiency of the complete cooling unit. This includes existing TEG based on materials like bismuth telluride and also TEG based on new experimental materials like Skutterudites, and

the behaviour of these TEG´s in a low temperature difference environment.
The objectives of this work should be:

* Calculate the energy produced by a TEG roof cooler combination, based on real world data from 2008, 2010 and 2012.

* Calculate an estimate of possible energy production with other TEG materials, like Skutterudites with an efficiency of about 20 % under the same assumptions like the existing BiTe materials.

* Identify the problems which can occur by the usage of TEG´s in a roof cooler of a cooler unit e.g. the behaviour of the cooling machines cooling efficiency.

* Calculate the payback period and the costs of the TEG installation in an existing roof cooler of a cooler unit.

* Identify the views of experts (<10) about this application of TEG´s and issues arising.

1.4 Scope of the research

The scope of this research was to examine the possibility to use the waste heat from a roof cooler from a cooling machine as energy source for a TEG, based on a case study. The case study itself was based on real world data from the years 2008, 2010 and 2012. The research analysed the behaviour of a commercial available BiTe TEG in a case study. The research analysed also based on literature data the possible usage of a TEG which consist of new materials, like PbTe doped with PbI_2.

The case study as primary research in that work can give recommendations for the usage of a TEG - roof cooler combination to increase the overall efficiency of the complete cooling unit. It looks also to the commercial background, like payback period. The research includes also an experiment with a commercial available BiT_2 TEG to support the results of the case study and a survey from a small group of experts. The experiment had the function to look at the temperature behaviour of a TEG, to find out if a TEG will have an optimal working point and to look on the heat transfer problematic. In the survey itself experts were asked about their opinion in technical and commercial issues to use a TEG with a roof cooler.

After literature and internet research no one it was found out that nobody had worked on this problem before. The research itself, can also give recommendations and suggestions for further research and innovations in that issue with more research resources than my "kitchen table lab".

1.5 Outline of the dissertation

Chapter 1 introduces the practical problem and defines the aims and objectives of that dissertation. It introduces the waste energy emitting of a cooling machine as a part of the cooling machine process, but it also looks on the usage of that waste energy with a thermo electrical generator. It also shows on the justification of that dissertation and describes that this energy will go unused to the environment.

Chapter 2 shows at the wider context of the issue and identifies the existing available literature knowledge. The literature was critically reviewed to use it in the context of that dissertation. With the existing knowledge the research question could be defined and written down.

Chapter 3 identifies as a primary research a case study, which is supported by an experiment and a survey. The survey supports the research issue and the usage of a TEG in a roof cooler. The experiment shows the behaviour of a TEG and supports any speculative assumptions. The view of the experts supports the practical application and commercial appropriateness.

Chapter 4 includes the results and the analysis of the primary research. The results are recommendations for the usage of a TEG in a roof cooler, or in a cooling machine to generate electrical power to increase the overall performance of the cooling machine and to reduce the ecological footprint of that cooling machine. Further it identifies the usage of new materials to increase the efficiency of the used theoretical TEG into a commercial usable range.

Chapter 5 provides the conclusions which are found in the research in terms of the research questions and the research aim. The conclusions show the commercial as well as the ecological aspect of the research. And finally it gives recommendations to further research in that issue.

2 Research definition:

2.1 The practical problem

The practical problem is how to use the waste energy, which can be in the range of several hundred of kilowatts per hour, which is produced by an average cooling machine. The energy is transported with a cool water circuit to a roof cooler and the energy is emitted to the environment. In some special purposes but with energy transport problems (and with low efficiency) the waste energy is used to increase the water for warm water purposes and sometimes for heating purposes. In normally the low temperature, heat energy (30°C to 50°C) of such a roof cooler is given to environment with no usage. To use this heat energy and to produce direct electrical energy in combination with a TEG and a roof cooler, to increase the overall performance of a cooling machine, is the aim of this work. The cooling machine itself is not inefficient, but a combination with a TEG will produce additional electrical power, out of the produced waste heat. The produced waste heat normally will go unused to the environment with that combination parts of the waste heat will be used.

To understand the principles of a cooling unit and the radiated waste heat, this section explains a cooling machine and how it works.
Today air conditioners (Recknagel, 1997) (Toshiba, 2012) consist mostly of an inner part with a radiator combined with a ventilator (this is called "fan coil") and an outer part which has also a fan and a radiator. Simply explained the air condition transports the temperature and the energy which occurs at the inner part to the outer part. The air condition is also an energy pump system and reduces the energy level of a closed environment, e.g. a laboratory room. A refrigerator works on a similar base.

This is the simplest construction of an air condition it is used in many purposes complex systems have a central cooling machine a radiator on the roof of a building and two water circuits. One is the cold water circuit with a supply line with normally 6°C and the return line with 12°C, this is the cooling circuit to the consumers.

The cool water is produced in the cooling machine, which consists of a compressor which works with a coolant and a cooling circuit which is transported to the roof of a building. On the roof a heat exchanger is situated, this heat exchanger gives the produced energy in case of the so called "Carnot cycle process" (Recknagel, 1997) to the environment. The heat exchanger consists of the heat exchanger and some fans. The energy which is given to environment is waste heat. Figure 2.1 shows the principle of a cooling unit. In the schematics the cool water circuit is not shown.

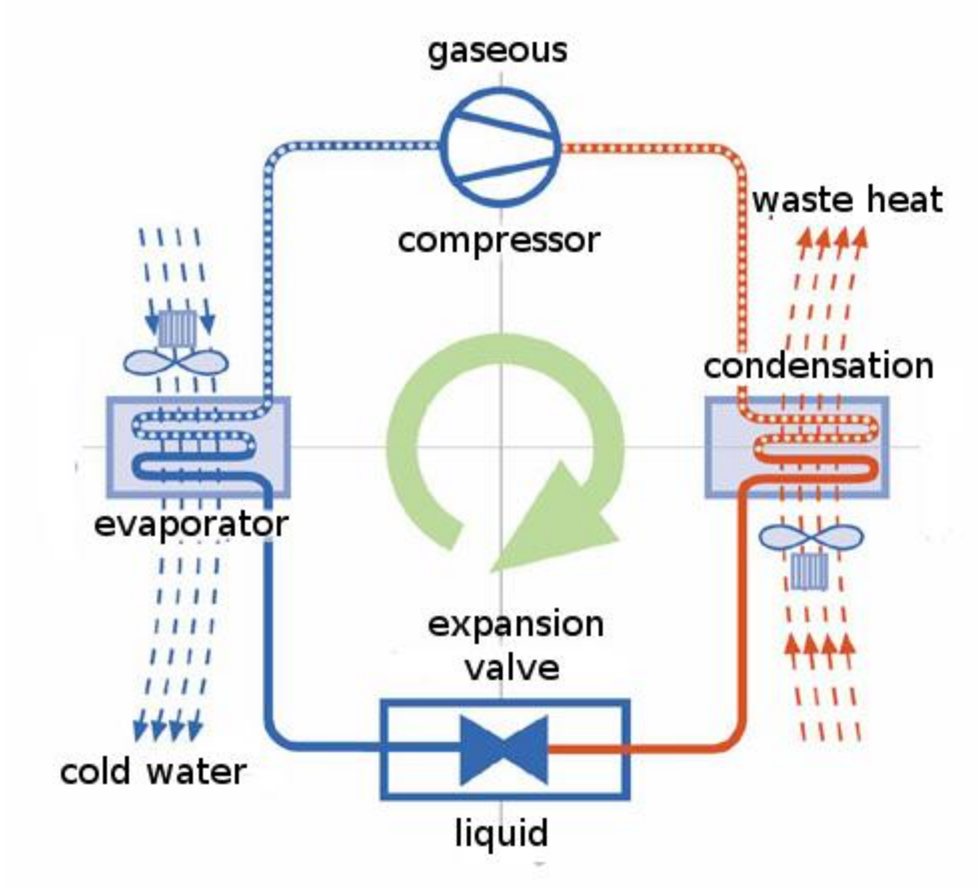


Fig. 2.1: Cool unit schematics (Kaeltebuecher.ch , 2012)

To calculate the released waste energy to the environment the following formula (Hieble, 2000) is used:

$$E= \Delta T * V* \rho *4.184 \text{ kJ/(kg*K)}$$

E… Energy of the cool water

ΔT.. Temperature difference between supply line and return line of the cooling water circuit

V… Medium flow in m^3/h, in that specific case water

ρ… specific weight of the medium in kg, in average $1kg/dm^3$ by water

4.184 kJ/(kg*K)… effective heat capacity of water

With this formula we get with the following figures from the cool unit producing company "Rehsler-Kuehlsysteme" the following energy, which is emitted to the environment. The temperature difference of 5K between the supply-line and the return-line of the cooling unit is a constructive detail of the cooling system.

ΔT = 5K

V = 70 m^3/h = 70,000l/h

ρ = 1,000 kg/m^3

E = 5 K * 70 m^3/h * 1,000 kg/m^3 *4.184 kJ/(kg*K) = 1,464,400 kJ ("Rehsler-Kuehlsysteme", 2012)

To calculate the power in kW a division through 3,600 is needed, so that the power which is given to the environment at this date and time was 406.77 kW.

2.2 Existing relevant knowledge - review of the literature

The usage of thermoelectric generators to transform the waste heat energy direct to electrical energy is a possibility to increase the efficiency of a building cooling unit.

2.2.1 The TEG:

Thermoelectric generators or short TEGs are an old invention based on the Seebeck effect, it transforms heat to electrical energy, at the moment with very low efficiency. With new materials waste energy can be better used with a TEG. The TEG produces up to 20% electrical energy.

Every thermoelectric generator has a hot and a cold surface, the hot surface is the one that is in direct contact with the waste energy transporting medium, in that case the cooling water from the cooling unit to the roof. The cold surface is the surface of the TEG which is in contact with the environment. The heat is transported through the TEG so that the cold surface must be cooled down to the environment temperature using a fan. The energy which such a TEG produces is direct proportional to the temperature difference between the hot and the cold side of the TEG. (Dr.Neumann Peltier, 2012) (International Thermoelectric Society, 2012) (Braitwhaite, 1998)

A thermoelectric generator is a heat engine and like all heat engines it obeys the laws of thermodynamic. The simplest TEG consists of a thermocouple, with legs or thermo elements fabricated from n- and p- type semiconductors. The efficiency of such a generator is given by the following formula:

$$\eta = \frac{\text{energy delivered to the load}}{\text{heat energy absorbed at hot junction}} \quad \text{(Ioffe, 1957)}$$

One other important formula by using thermoelectric materials to build TEGs is the following one :

$$zT = \frac{\alpha^2 T}{\rho k}$$

zT... figure of merit
T... absolute temperature
ρ... electrical resistivity
k... thermal conductivity
α... Seebeck coefficient

The figure of merit determines the maximum efficiency of a thermoelectric material for both power generation and cooling. (Snyder 2008). The practical efficiency is lower than the theoretical.

The following diagrams describe the different figures of merit of state of the art commercial materials (a and b) and those used or being developed by NASA for thermoelectric power generation. Most of the materials are complex alloys.

By altering the dopant concentration (c) of a specific alloy (in that example PbTe) the figure of merit zT can be altered dependent of the temperature. Snyder (2008) shows this behaviour in the next diagram (Fig.2.2).

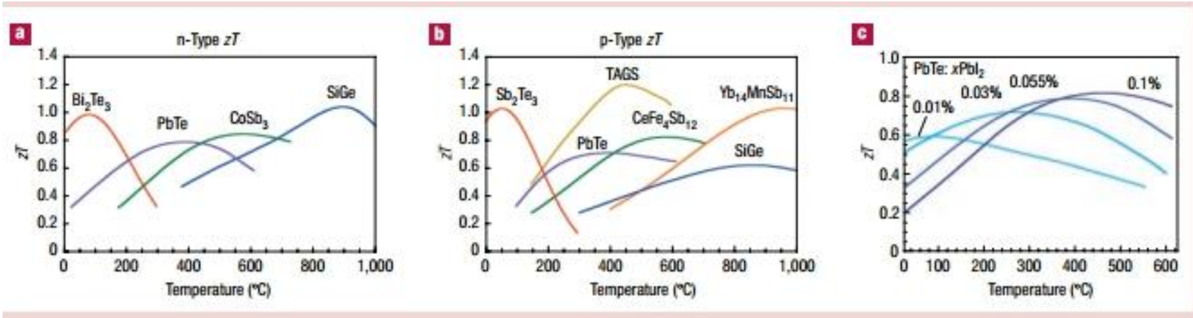


Figure 2.2: different material types with different figures of merit at different temperatures. (Snyder, 2008)

Like all heat engines the maximum power generation efficiency of a thermoelectric generator is thermodynamically limited by the Carnot efficiency ($\Delta T/T_h$). For a TEG the maximum efficiency is determined by:

$$\eta = \frac{\Delta T}{T_h} * \frac{SQRT(1+ZT) - 1}{SQRT(1+ZT) + T_c/T_h}$$

η..... efficiency

ZT... device figure of merit

$\Delta T/T_h$.... Carnot efficiency

SQRT... stands for the square root symbol

T_h... Temperature at hot side

T_c.... Temperature at cold side (Snyder, 2008)

Figure 3 displays the principle construction of such a thermo element. Many single thermo elements build a thermo electrical generator.

The efficiency of a thermo electrical generator can be expressed as a function of the ranged temperature over which it operates.

The construction details of TEG is presented in Figure 2.3 (Snyder, 2008)

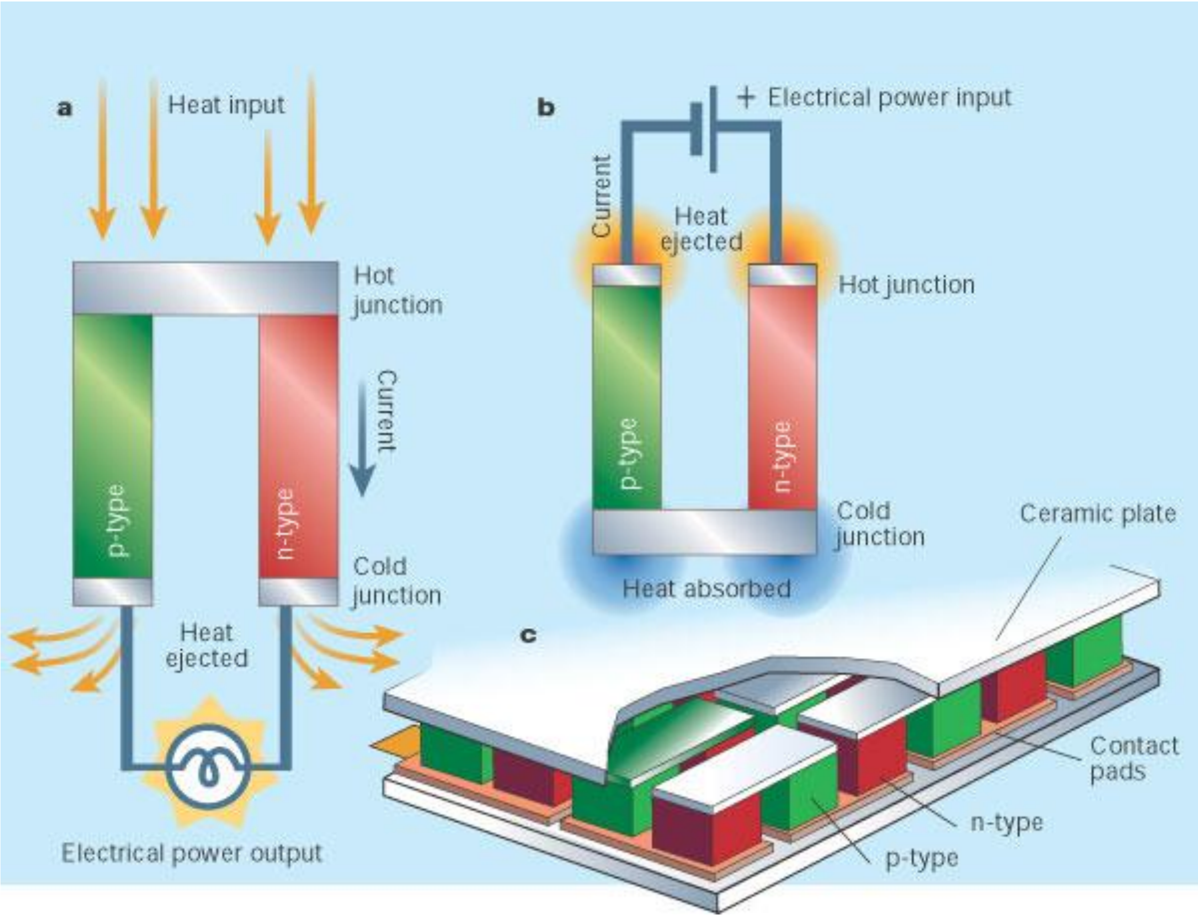


Fig. 2.3: Layout of a thermoelectric generator (Snyder, 2008)

Most of todays used thermoelectric generators will be used to produce heat or chill in the form as thermoelectric element, mostly in small systems like cooling bags, computer processor cooling or laser diode cooling. Thermoelectric elements are the reverse application of a thermoelectric generator. (Schubert, 1984)

Thermoelectric generators work with the "Seebeck" effect and produce an electrical voltage out of a temperature difference. Thermoelectric elements, also use the "Seebeck effect", produce heat and chill if a voltage will be attached on the element. (Schubert,1984)

The usage of thermo electric generators/elements is very wide, from using waste heat to produce energy, to chilling and heating applications and for the use as energy supplier with nuclear material in deep space probes. But space probes also use another effect the so called thermo-photovoltaic effect, which is similar to the photovoltaic effect, but should not be examined deeper in that work. (US Department of energy,2012) (Bellona Foundation, 2012) (Rockwell international,2012) (Stone E., 2003)

The “Seebeck effect” is the occurrence of a voltage and a current between the two different ends of an electrical conductor. The voltage difference is nearly proportional to the temperature difference and it is dependent on the used conductor material. In deep space probes thermoelectric generators will be used to produce electrical energy for the probe, with a so called "Peltier" thermoelectric generator", the heat is produced by a plutonium pellet, with up to 800°C. The cold site of the generator is a big black convector which cools this side down. Like above described the efficiency is not exceeding 7%. (Stone E, 2003)

One “Peltier” element produces several hundred Millivolts up to several Amperes, dependent on the active area of the “Peltier” element. To produce higher voltages it will be necessary to add several of such “Peltier” elements to a battery like element.

At the moment “Peltier” elements or short thermoelectric generators (TEG) are used in deep space probes, in probes which are used in outlying areas, for camping purposes (but most for cooling usage), so that we can say that with now known and used materials, mostly an alloy of bismuth and Tellur - Bi_2 Te_3 is used. As result of this TEG´s will be used to produce small amounts of energy, chill or heat. (Masterbergen, 2012) (Netzsch company, 2011).

This existing TEG´s needs high hot side temperature up to 300°C and low cold side temperatures up to 30°C, and as a result relative high temperature differences of about 270K to reach the maximum theoretical efficiency of about 4% (Tecteg company, 2013).

“Peltier” elements have the advantage that they have no mechanical parts the big disadvantage at the moment is the relative low efficiency.

With new materials the efficiency can be theoretically increased up to 20%. These materials are mostly skutterudites and/or materials which need production methods of the nanotechnology. skutterudites are materials which are in the form of (Co,Ni,Fe) $(Pb,Sb,As)_3$ and are cubic with space group k3. (Zhang, 2009, Zeng, 2006, Salzgeber, 2010). Other materials are part of research, also materials which are based on nanotechnologies (Yang 2006) (Zevalkinh, 2011) (Cuenat, 2010) (Koumotom, 2010) (Kunihito, 2010) (Simonson, 2008) (Tervo, 2011) (Zhanh, 2004)

With skutterudites the greatest possibility is given to produce thermoelectric generators with high efficiency. This is reported because skutterudites have low thermal conductivity caused by a rattling effect of La, Ce, Yb, Ca, Sr and Ba (Guo et.al, 2007)

The new materials are still in development and research and sometimes in industrial test environment, in case of the intensive research on TEG´s new techniques and materials for TEG´s will be available in the near future.

The roof cooler produces relatively low temperatures, and because of that relatively low temperature differences occur, so that a thermoelectric material is needed which can produce by low temperature differences high amounts of power. The long known bismuth tellurium alloy is not a candidate for that, but it is commercial available, so that conclusions can be drawn.

“Dr.Neumann Peltier”, a german TEG company describes in a datasheet of a BiTe TEG three formulas to calculate the no-load voltage, the short circuit voltage and the maximum power of this TEG. The whole datasheet is provided in appendix 1.

Open circuit voltage: U_0 (V) = 0.783 * ΔT (K)
Short circuit current: I_0 (A) = 0.0242 * ΔT (K)
Maximum power : Pmax (W) = 0.004842 * ΔT^2 (K^2)

Pmax (W) = 0.004842*20^2 = 0.19368W * 100*100/(20*20) = 48.42 W

With the above calculation by a supposed temperature difference of 20K and using a one square meter TEG (e.g. 25 pieces of the TEG in appendix 1) containing a 4% tellurium bismuth as material, gives on this square meter with that temperature difference of about 48W on electrical power. On the first sight it sounds not much but it is about a third of the energy of an average modern photovoltaic solar panel, which produces about 120 W to 150W at this square meter under optimal conditions (Conrad, 2012a) (Conrad, 2012b). With new materials like nano based skutterudites, 20% efficiency should be theoretically reached, so that it seems to be possible that one square meter cooler area can produce with this new materials 240W (by a temperature difference 20K). That shows it should be worth to do more research work on this issue.

TEGs need a high temperature difference between cold and warm side, to produce a high energy output.

The limit of that temperature difference is determined by the material, the data sheet which is provided in appendix 1 shows the maximum temperature with about 200°C.

2.3 Research questions

The research questions are the following:

a) Which new material can be used best for a low temperature TEG to increase the output power of the combination of a TEG and a roof cooler, based on available diagrams and figures?

b) How much energy can be produced with such a combination containing in theory:
- With a commercial, existing TEG material (4% efficiency)
- With a new developed TEG material (up to 20% efficiency)?

c) How does the energy production and behaviour of the TEG´s in practice, compare to the theoretical predictions, for the temperatures, which occurs in a typical building cooling system cooler unit.

d) How can a roof cooler and a TEG be combined in practice?

e) Why did no one use a TEG in a roof cooler of a cooling unit before?

f) How long is the payback period of such a combination?

g) What are the advantages and the disadvantages of using a TEG in a roof cooler of a cooling unit?

3 Methodology

3.1 Methods and techniques selected

Research methods and techniques

The main research method was a case study based on original data from the cooling machines from the years 2008 and 2010 (2009 is corrupted). The case study which was provided and is explained in the appendix 2 was based on an air conditioning system in one of the buildings of the University of Vienna (laboratory building “Pharmacy and Geology” with an overall area of about 75,000m²).

The roof cooler construction sheet is provided in appendix 3. It shows of the date, the time of day, the supply temperature of the cool water circuit, the return water temperature and the environment temperature at a specific day and time. With these data, especially with the supply temperature and the environment temperature the temperature difference and in case of that the produced power, voltage and the current of a TEG were calculated. In 2012 a so called “trend” was generated with additional data like used electrical power, and cool water temperature. The last two parameters were not used in that work.

A possible construction diagram (provided in Fig. A2.5 in the case study) and an experimental prototype of the cooler/TEG combination was done. This includes two experiments and observations to look at the behaviour of that combination and the single TEG.

The experiments were done with different temperature differences and measurements of the input temperature (=cool water temperature), the environment temperature, the produced voltage and the produced closed circuit current (measured on a resistor). The temperature differences were in a similar range like occurring in the real cooler and in the cooling unit also in the range of about 5K to 35K temperature difference. The experimental prototype is based on a bismuth tellurium TEG with an efficiency of about 4%.

Lacking new experimental material, the work about TEG´s is only a simulation based on existing data and literature with the real world data. This simulation showed what is possible with the new materials TEG, based on the available diagrams and data from the literature. This included the calculation of the payback period, to show if a combination of a TEG and roof cooler is economic.

In the survey some experts (13 persons) were asked about their opinion and knowledge of alternative energy sources, and the technical and economic potential of a TEG roof cooler combination.

3.2 Justification

In this work three research methods were used, the main part is a case study on an existing roof cooler, in a building of the University of Vienna.

Yin (2003) describes a case study *“A case study is an empirical method which investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and the context are not clearly evident, and that relies on multiple sources of evident. The case study can be differentiated in exemplar case studies, in cross-sectional and longitudinal case studies”.*

The research in that work was a case study of the analysis of data over nearly three years; this is described as a longitudinal case study (Yin, 2003).

The case study was chosen, because the data for the analysed years do exist with high validation, and with these data theoretical predictions of the behaviour of a TEG roof cooler combination can be done.

Another research method to examine this issue will be a review research, but in case of the new innovation of this issue no or only spare information is existing. With that information the choice for the main research method was the longitudinal case study.

The usage of a review study is not useful for that research problem, because only few information about the TEG issue exists. A review study reassesses existing work in a subject or it re-evaluates existing work in the light of new information (Open University, 2010).
The case study is a theoretical and simulated model (based on real world data) but to test the theoretical results in the real world, an experiment with a commercial available TEG was done.

An experiment is a practical test of a theory, normally done in a laboratory of a factory but sometimes in a “field” experiment (Open University, 2010).
These experiments which were done will be explained in the research procedures. These experiments have as output a behaviour table and a behaviour curve of the TEG at different temperatures. The experiments will demonstrate the losses through heat transfer between the hot water, the TEG and the environment and suggests possibilities to minimize the losses.

A survey with some experts was done, which shows their opinion to the research issue, but the survey can only to support the case study and the usage of a TEG roof cooler combination.

The survey was also carried out to collect additional information from experts to that issue. Only a small amount of experts were chosen, because the survey is not the main part of that work it should only support or check additional possibilities and acceptance in the real world of the TEG roof cooler combination.
A survey is a systematic collection of information about a representative set of subjects, using a variety of techniques including questionnaires and interviews (Open university, 2010). The survey in this work had some questions to the issue alternative energy sources and to TEG and their usage.

3.3 Research procedures

The case study itself was an exemplar case study of a single roof cooler it had a duration about three years, so that this case study is also a longitudinal. As conclusion the case study was a combination between an exemplary and longitudinal case study.

The research for the case studies was based on theoretical provided formulas and real world data provided by the building control software and the attached sensors. The software had recorded:

- Date
- Time
- Cool water supply temperature
- Environment temperature
- Return cool water temperature

The procedure for that part of the research was data manipulation on a computer with a excel sheet, so that combining existing and provided formulas from a TEG producer power, voltage and current of a TEG under different circumstances and temperature differences could be calculated.

These calculations were based on real world data. The data for the case study were provided in great Excel sheets with over 11 000 cells, an example of that is provided in appendix 4. For that case study one special parameter must be included, the roof cooler transports only energy to the environment if the cool water supply line reaches a temperature above 30°. Appendix 5 shows the E-mail to the head of the facility management unit of the building, Mr.Wallner.

Based on the input data the following figures were calculated out of the original data:

* The temperature difference between supply-line and environment temperature, this is the working temperature difference of the TEG
* The temperature difference between supply-line and return-line
* The transported energy to the roof-cooler in J
* The transported power in kW
* The theoretical power of the used TEG (appendix 1)
* The theoretical power of 1m² of that TEG (25 pieces of the TEG in appendix 1)
* The theoretical power of 45m², this is the sum of the area of the 3 roof coolers
* The theoretical efficiency of the TEG in contrast to the waste heat energy of the roof cooler.
* The theoretical efficiency of a TEG built of another low temperature material like PbTe provided in diagram 2. The diagram is one of the spare sources, which exists of thermoelectric materials with higher efficiency.

The following equations, which will be deeper explained in the chapter "existing relevant knowledge" were used:

Equation 1)

* Equation for the energy content of the cooling water:

$E (J)= V* \rho *4.190kJ/kg/K* \Delta T_{s-r}$ — ΔT_{s-r}... temperature difference between supply line and return line of the roof cooler and the cooling machine

The equation describes the energy which is given to environment by the roof cooler.

Equation 2)

* Energy which is produced by the TEG, which is deeper explained in appendix 1:

$Pmax (W) = 0.004842 * \Delta T_{t-e}^2 (K^2)$ — ΔT_{t-e}… temperature difference between surface temperature of the TEG and the environment

Equation 3)

* Efficiency equation from the knowledge section:

$$\eta = \frac{\Delta T_{t-e}}{T_h} * \frac{SQRT(1+ZT) -1}{SQRT(1+ZT) + T_c/T_h}$$

ΔT_{t-e}…temperature difference between surface temperature of the TEG and the environment

The valid data for the years 2008, 2010 and 2012 result in a relatively big spreadsheet with 11,065 vertical cells, so that the data were clustered. The clustering was done weekly, so that an average value of all above data was the result. The year 2012 consisted of 32 weeks, because the measurement stops on end of August (21.8.2012). The data for the year 2010 consisted of 47 weeks the data were only valid till November 2010. The data for the year 2008 were nearly complete, but as some data were invalid, that year consisted of 50 weeks. The result was a table with 129 vertical data which described the weeks in the years 2008, 2010 and 2012, appendix 4 shows an example of the calculations. Furthermore the weekly results were displayed in line diagrams to show the output relations of the TEG depending on the weeks.

The calculations and the explanation of the spreadsheet were the following:

- The date of the measurement in day, month, year
- The time of the measurement in hour, minute, second
- The environment temperature in °C
- The supply-line temperature in °C
- The return-line temperature in °C
- A flag, which has two values 0, or 1, this flag determines if cool-water is pumped from the cooling machine to the roof. The roof cooler only gets cool-water if the supply temperature is higher than 30°C, this is the reason for the flag.
- The temperature difference between the supply-line and the return-line
- The temperature difference between the supply-line and the environment
- The online time, which determines the time in which the cooling machine is running. The second row has also the label online time, this is the conversion from hours, minutes and seconds in a decimal number e.g. 2:15:00 results in 2.25h
- The power which is produced by one BiTe TEG cell, the used formula is Equation 2 on page 15.
- The power which is produced by 1m² BiTe TEG cells, the used formula is Equation 2 on page 15. The result is multiplied to get 1m² of the BiTe cells.
- The power which is produced by 15m² BiTe TEG cells, the used formula is Equation 2 on page 15. The result is multiplied to get 15m² of the BiTe cells. 15m² are the rounded square meters of the useable BiTe area of the roof cooler.
- The row Wh describes the energy which is produced in the online time by an BiTe element on the whole active area of the roof cooler.

- The row energy to the roof contains the energy which will be transported to the roof cooler. The energy is determined by the supply-line – return-line temperature. To calculate the transported energy in Joule Equation 1 on Page 15 is used.
- The row efficiency shows the efficiency in % between produced TEG energy and the energy which is transported to the roof.
- The rows “average watt” and “week”, are calculation rows for the diagrams.
- The row theoretical efficiency shows the theoretical efficiency of a PbTe alloy, with a figure of merit with 0,58. To calculate the Carnot efficiency equation 3 on page 15 is used.

The following diagrams were worked out,

- For each year a diagram with the relations between environment temperature and the square meter power for a 4% BiTe TEG, the diagram shows the temperature trend and the power trend in one diagram.

- A diagram which shows for all three years the so called “Box-plots”, which show the median power, the average power, the upper quarter power, the lower quarter power, the maximum and minimum values of the power.

- A diagram which shows for all three years the so called “Box-plots”, which shows the median environment temperature, the average environment temperature, the upper quarter environment temperature, the lower quarter environment temperature, the maximum and minimum values of the temperature. The temperature is only shown for the comparison of the environment temperature over these three years.

A further sum page includes the following information per year:

- The duty cycle of the TEG roof cooler combination in hours, this means over which time the combination produces power

- The overall produced power in Watt in that year of the whole case study (if the whole roof cooler with 15m² has TEG installed)

- The average power per hour ($15m^2$) in W/hour per 15 m^2 produced by an existing commercial TEG

- The maximum power which occurs in W/hour per $15m^2$ produced by an existing commercial TEG

- The average efficiency from an existing commercial TEG over a specific year.

- The theoretical average efficiency with new materials based on the diagrams and literature by the assumption that the TEG material can use the same low temperature as the commercial existing TEG. The calculation is based on the efficiency formula from equation 3 on page 15. The formula and the material were used, because the information was available and the material has the right range for a low temperature TEG. The temperatures which occur are in the range between 20°C and 50°C

One further output is a schematic of a possible combination of a roof cooler and a TEG which is provided in the case study description in appendix 2 and in figure 14.

The case study itself answers the research questions b,d and gives suggestions to answer research question a. These suggestions can only help to look at several low temperature materials, which have a relatively high figure of merit (zT). The material and the zT were used, because the material had the right temperature range for that low temperature application. The data for that step were chosen from figure 2.2 on page 11, diagram c. The alloy PbTe x PbI was chosen. The two other diagrams with other alloys had greater figures of merit, but they need higher working temperatures. The figure of merit zT produces higher efficiencies if the figure zT is increasing.

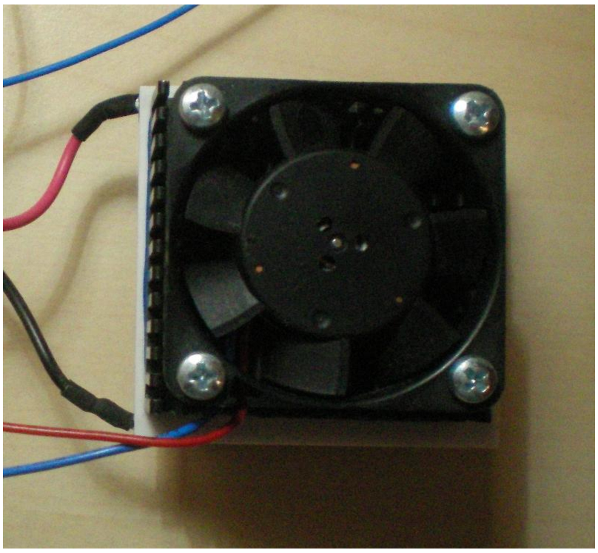
To look at the behaviour of the existing BiTe TEGs two experiments with a commercial TEG were done. The experiments with the TEG answered the research question c. The experiments show the heat losses from the water tank through the pipes to the TEG, it also shows the behaviour of the TEG and it makes suggestions to the construction details of the combination of a roof cooler and TEG. The experiment proofed the suggestion that a TEG has a linear behaviour.

The first experiment is a relatively simple construction. It simulates the roof cooler, with a TEG attached. A second experiment with a similar aim was undertaken, this experiment measured the behaviour of the TEG only and ignored the other parts of the system (pipes, pump etc.).
The TEG which is used in the two experiments itself has the dimension 50mm x 50mm x 4.5mm, it is a thermoelectric element which is based on BiTe. The maximum temperature difference is about 65K. The TEG data sheet is provided in appendix 6. This TEG was used, because it has the right temperature range and it was available for an acceptable price.

The first experiment tested the behaviour and the heat transfer from the heat source to the TEG on the hot side of the TEG and the heat transfer on the cooling side to the environment. The heat source is hot water (80°C) from a water boiler, which boils water for tea or coffee. The water is circulated by a small gear pump through brass pipes. The brass pipes are installed in a CPU cooler, which is glued on the hot side of the TEG. At the cold side of the TEG also a CPU cooler is glued, on that CPU cooler a small 12V fan is screwed. To determine the temperature difference between the hot and the cold side two digital thermometers and one infrared thermometer are used. The electrical output is measured with two digital multi-meters, one measures the voltage the other multi-meter on a load resistor of about 15 Ohm measures the current. Every ~5K temperature difference a measure was taken, the results were written down in a table, and the output power was calculated. The table contains the following parameters:

* Water temperature - hot side temperature
* Environment temperature = cold side temperature
* Output voltage
* Output current
* Output power
* Input power of the water
* Efficiency of the TEG, percentage of input-power to output-power
* Theoretical prediction of a similar TEG which is provided in appendix 1

The experiment provided 7 measurements.



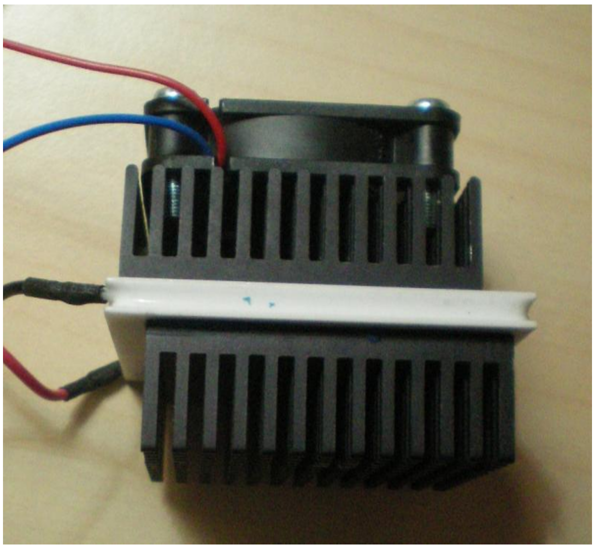


Fig 3.1: "Cool side" of the experimental TEG (Brandl, 2012)

Fig3.2: Lateral view of the experimental TEG (Brandl, 2012)

The second experiment consisted only of a water bath, with hot water (~ 80°C), the TEG was put into the water bath with the cooler. This experiment provided only 4 measurements. The measurements were taken in a similar way as in the first experiment. The parameters which were recorded were the same like in the first experiment, these were:

* Water temperature - hot side temperature
* Environment temperature = cold side temperature
* Output voltage
* Output current
* Output power
* Input power of the water
* Efficiency of the TEG, percentage of input-power to output-power
* Theoretical prediction of a similar TEG which is provided in appendix 1

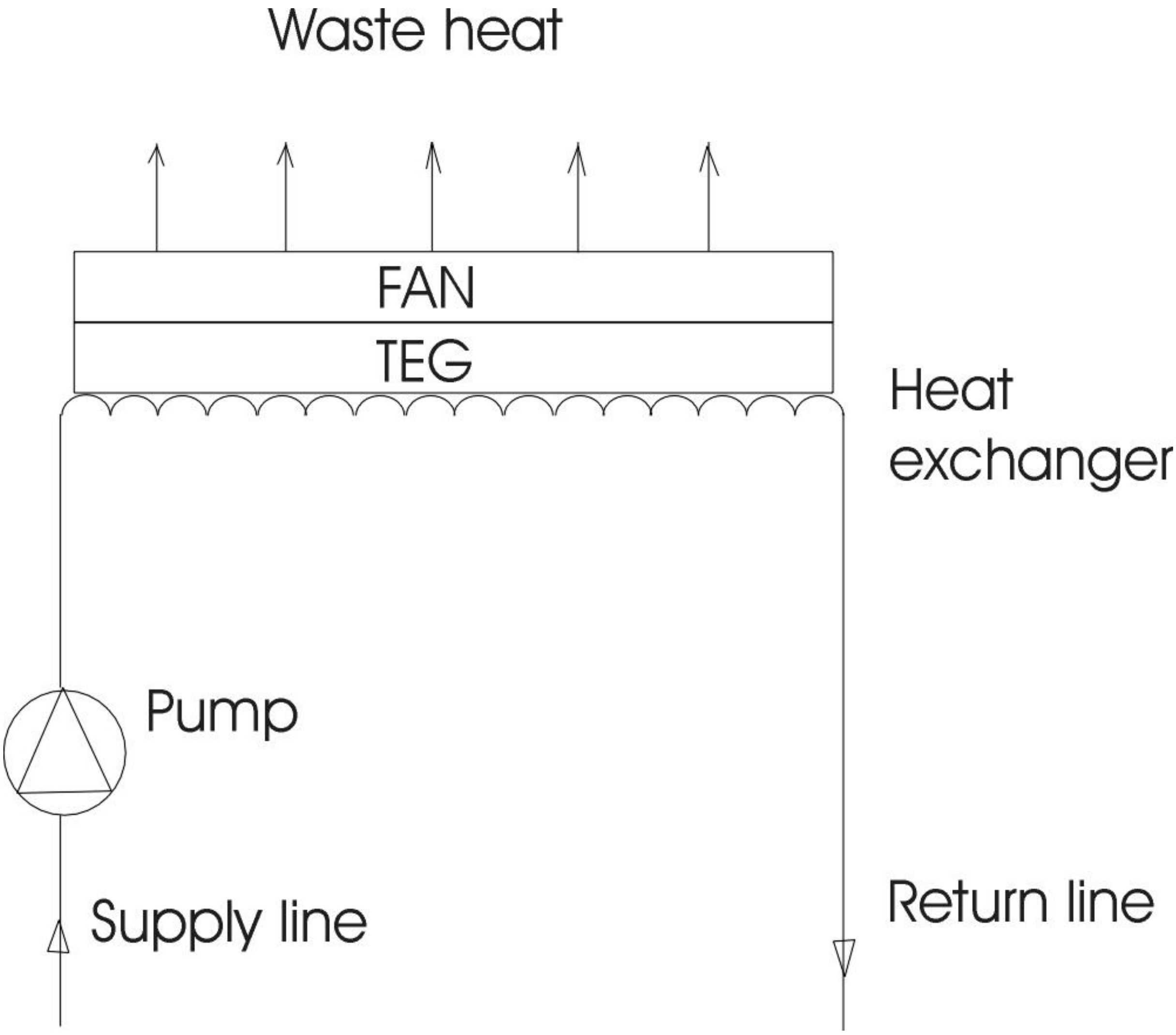


Fig. 3.3 : Schematics of the first experiment (Brandl, 2012)

The survey of a small amount of experts was based on a survey paper which is provided in appendix 7. The survey asked experts, facility manager and was consulting engineers about their opinion of a combination of a TEG and roof cooler. The survey had 14 questions, and was sent to 13 persons. All persons were informed and asked to take place at the survey, to that issue. The result of the survey was to check the acceptance of such a green technology and the acceptance of that technology and got recommendation to install it in an existing system. The survey was only a small part of the primary research and was taken to help to answer the research question g.

The answers for research questions e-g were partly dependent on the results of the case study, the experiment and the survey.

3.4 Ethical considerations

No ethical difficulties at every stage of the research were encountered. The data itself were provided by the central control and communication system of the analysed cooling machine. The permission to use the roof cooler data was given by the head of the department who was accountable for the cooling machines. The photographs from the roof cooler were taken by me, the roof cooler can be reached by stairs to and on the roof, and is surrounded by a handrail and partly by a concrete wall. It was no possibility given to take effect by the roof cooler fans or to fall down from the building.

The experiment was taken with hot water (up to 100°C), but it was taken with care, so that it was not easyly possible to get in contact with the hot water. The experiment was taken on my “kitchen table”, so that no other persons had contact to the experiment, except me. The voltage which was produced by the TEG is in the “milivolt” range, so that no possibility was given for electrifying.

The participants of all the interviews were informed in advance, the information which was given by them will be held strictly confidence and anonymous. All participants have given their agreement to use their given opinion in this work.

No one was harmed during the experiment or in any other action for that work.

4. Analysis and interpretation

4.1 Data Collection and analysis of the case study:

Like in the research procedure described the data from the years 2008, 2010, 2012 were collected, reduced and analysed. For the data collection and reducing Microsoft Excel 2007 was used. Because of the big amount of the data and the problems to display and analyse these data in an appropriate way “Sigmaplot 11.0” was used. In “Sigmaplot 11.0” only simple descriptive statistic was used. The result of this descriptive statistics plot is a diagram of the output power of a BiTe 4% TEG with 1m² area as a “box-plot” (Fig. 4.1) of all three analysed years. It shows that the theoretical output of such a 1m² TEG is similar in each year, except the year 2012, because it includes only data until August 2012.

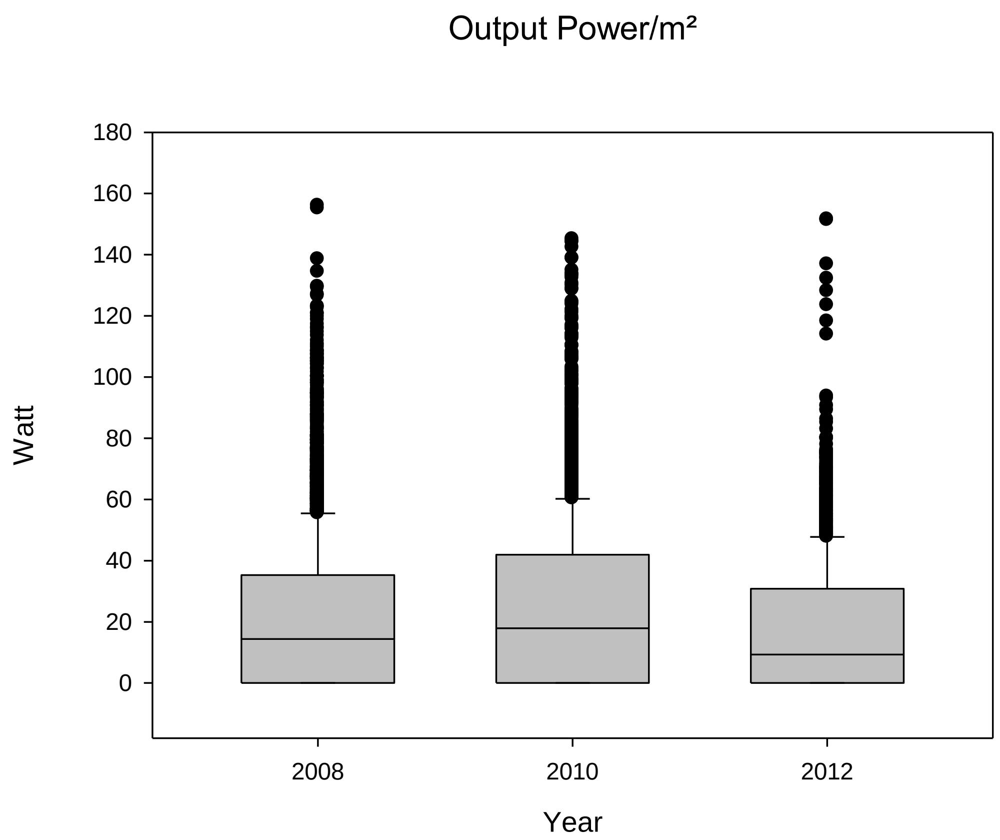


Fig. 4.1: Box-plot of the Output Power/m² in W

For the environment temperature (Fig. 4.2) which is necessary for the case study, because the assumption is that the roof cooler and the TEG has as cold side the environment temperature, also a “box-plot” diagram was done. It shows that the temperatures were nearly the same in the years 2008 and 2010. The year 2012 was somewhat hotter in median, because the data recording ends in August 2012 already.

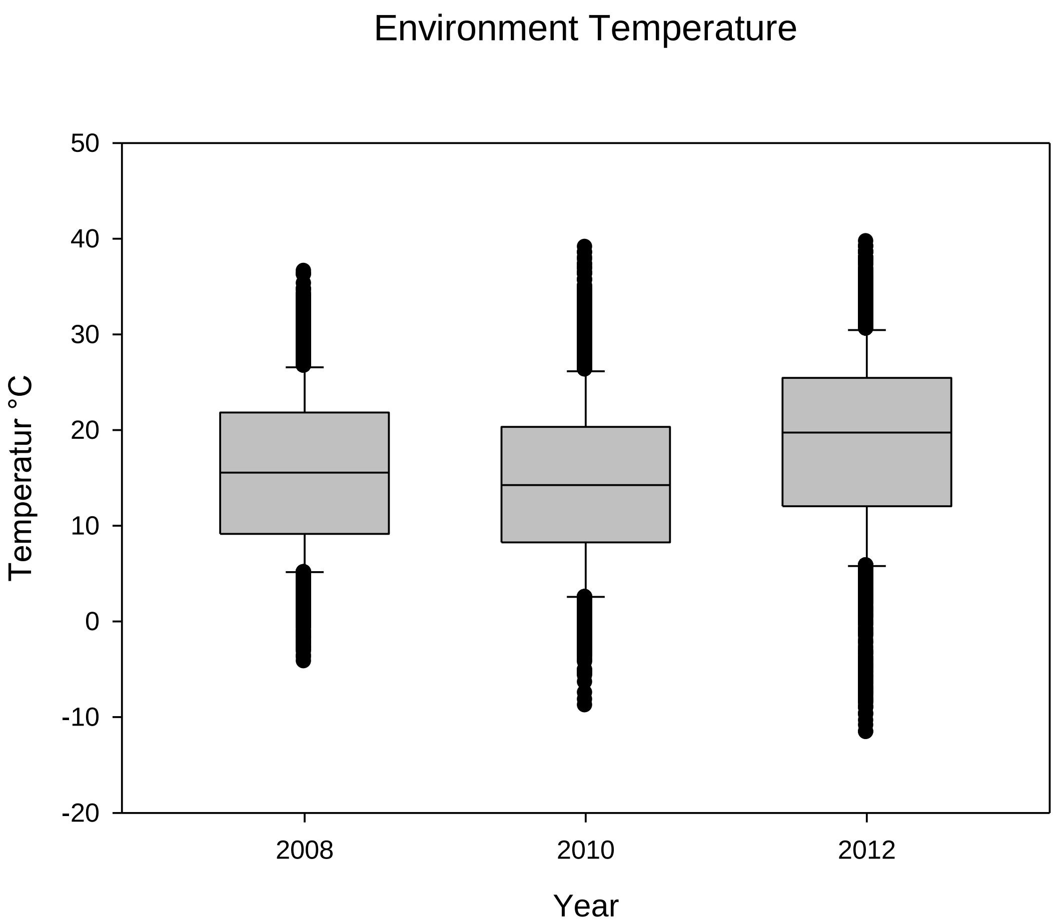


Fig. 4.2: Box-plot of the environment temperature

If we compare the median temperatures and the median output wattage a first trend of the relation between environment temperature (cold side of the TEG) and the output wattage can be seen. By lower environment temperatures higher output power was possible, so that the most power can be produced at low temperatures. Considering that in winter time no or only a small amount of chill is needed, the greatest power can be produced in springtime and in autumn.

Table 4.1 shows the duty cycle of the cooling machine in each of the three years, the produced power in watt in that year, the average produced power per hour in that year, the average produced power per square meter TEG and the maximum occurring power.

Year 2012:			
Duty cycle time:	3 043.37h	Sum Watt: 681 334.10	Maximum W: 2 271.82
Average W/hour produce on 15m²:		223.87W	1m²: 14.92W
Year 2010:			
Duty cycle time:	3 855.86h	Sum Watt: 1 480 903.03	Maximum W: 2 338.71
Average W/hour produce on 15m²:		384.07W	1m²: 25.61W
Year 2008:			
Duty cycle time:	4 062.76h	Sum Watt: 1 447 183.75	Maximum W: 2 174.53
Average W/hour produce on 15m²:		356.21W	1m²: 23.74W

Table 4.1: Duty cycle times, average power

The average efficiencies and the maximum efficiencies in the years (year 2012 is not the whole year, so that the power output is lower) are displayed in Table 4.2, the efficiencies are calculated on the whole roof cooler area of about 15m², in this context this is the relation between transported energy to the roof cooler to the generated energy by the TEG. The duty cycle time is the time during which the roof cooler emits energy to the environment. This occurs by the assumption that the TEG has an equivalent cooling ability like the original roof cooler. A possible alternative roof cooler construction is described in the case study in appendix 2 and in figure A1.5 and figure 4.8. As displayed in Table 4.1 the average power production/m² is about half the theoretical prediction of about 48W/m² by a supposed temperature difference between the cold side of the TEG and the hot side of about 20K. This implicates that the average temperature difference is lower than assumed.

If all cells in the spreadsheet with no energy transport to the environment were omitted, an average temperature difference of 15.32 K was calculated, this supports the hypothesis of lower temperature differences, but this has a big effect on the power production, because the used formula is a quadratic function, dependent on the temperature difference.

Year 2012 with zero efficiency		without zero efficiency	difference
Average efficiency :	0.13%	0.20%	1:1.54
Maximum efficiency :	2.92%	2.92%	
Standard deviation :	0.19%	0.19%	
Minimum efficiency :	0.00%	0.01%	
Year 2010 with zero efficiency			
Average efficiency :	0.20%	0.30%	1:1.50
Maximum efficiency :	2.98%	2.98%	
Standard deviation :	0.39%	0.29%	
Minimum efficiency :	0.00%	0.01%	
Year 2008 with zero efficiency			
Average efficiency :	0.19%	0.26%	1:1.38
Maximum efficiency :	2.92%	2.92%	
Standard deviation :	0.39%	0.25%	
Minimum efficiency :	0.00%	0.01%	

Table 4.2: Calculated efficiency of the TEG

The relatively low average efficiencies occurred because only temperature values above 30°C emits heat to the environment through the roof cooler, this is a constructive detail of the air conditioning system. All temperatures smaller or equal to 30°C produce no power ("row with zero efficiency" in table 4.2). Besides it seems that the TEG cannot use the full energy from the roof cooler. It is supposed that the TEG reached not the optimal working temperature range. The data were based on a 15m² TEG-array which is directly attached to the roof cooler.

In this context zero efficiency means that a measurement occurred in the collected data (and in consequence heat is produced), but no energy is emitted to the environment, the energy is still used in the cooling system to hold a specific temperature of the cooling machine.

If the above described "zeros" are filtered out, the average efficiency was raised like displayed in table 4.2 in the row "without zero efficiency".

The row "difference." shows that the difference between the zero row and the one without zero row is about 1:1.5.

This implicates that with a greater TEG area the similar power like a 15m² TEG at the optimal working point, can be generated.
In consequence this means that the TEG area must be about 250m² to 300m² and the roof cooler needs a complete reconstruction. This area is about 16 to 20 times of the area of the existing roof cooler. This is neither a practical solution nor a commercial possible solution.

The following three diagrams (Fig. 4.3, Fig. 4.4, Fig. 4.5) show the output production of the TEG, depending on the environment temperature. The diagrams show relatively clear (with exception of the year 2012) that if the environment temperature is low, the power production of the TEG is high and vice versa.

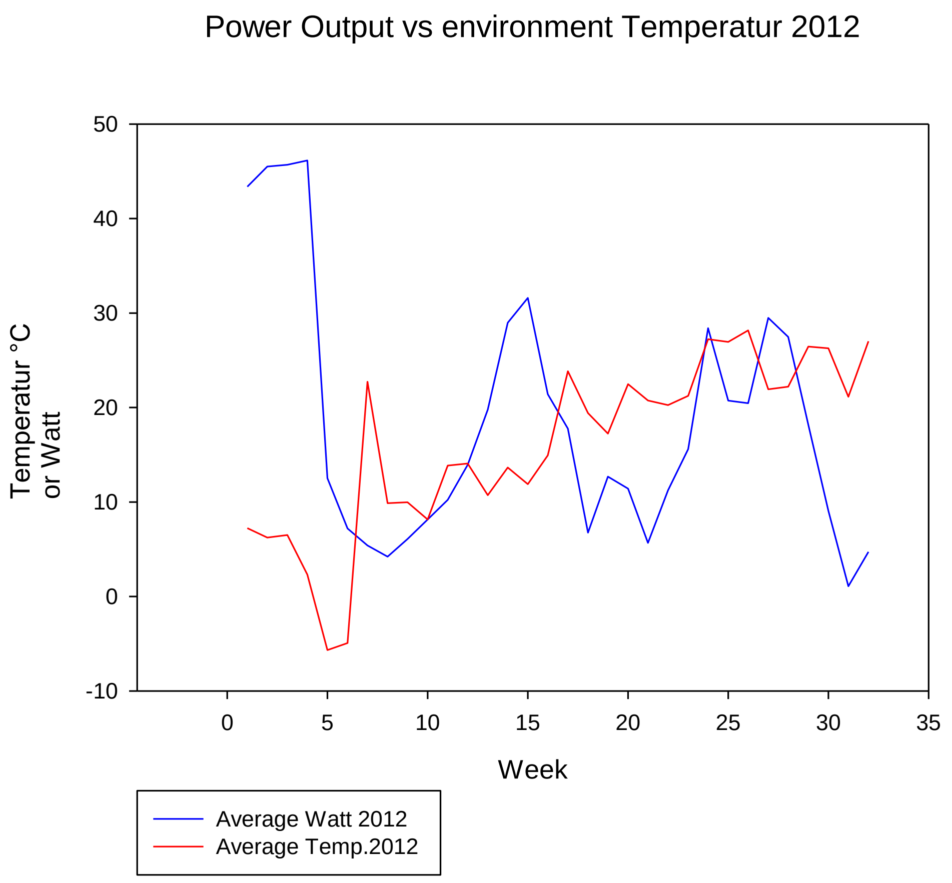


Fig. 4.3: Power output in W vs. environment temperature 2012

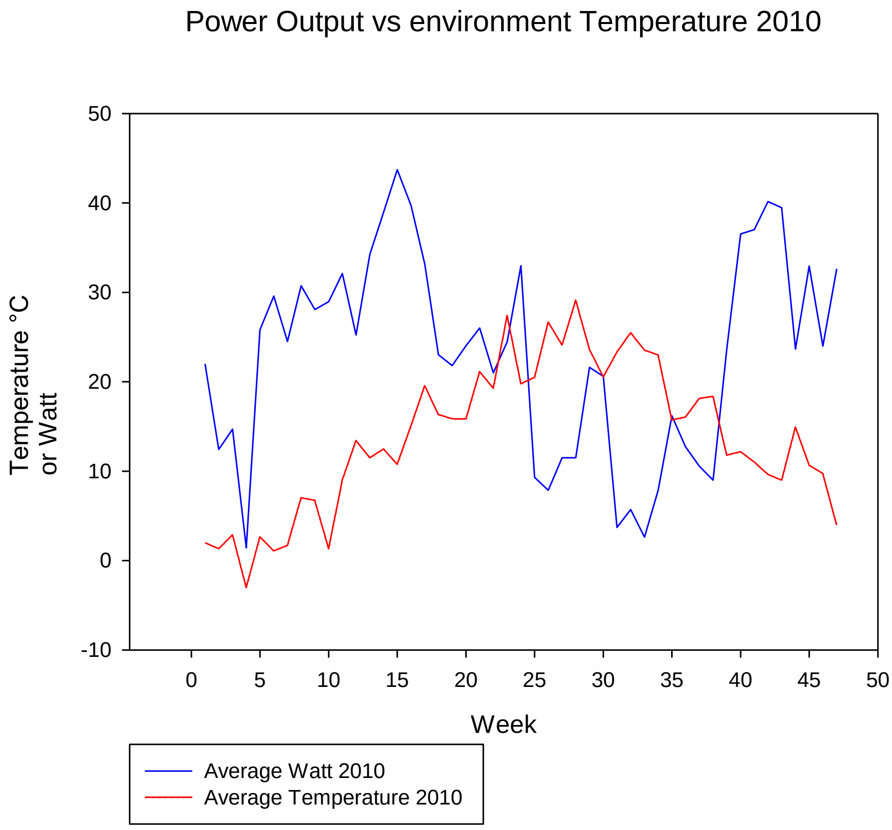


Fig. 4.4: Power output in W vs. environment temperature 2010

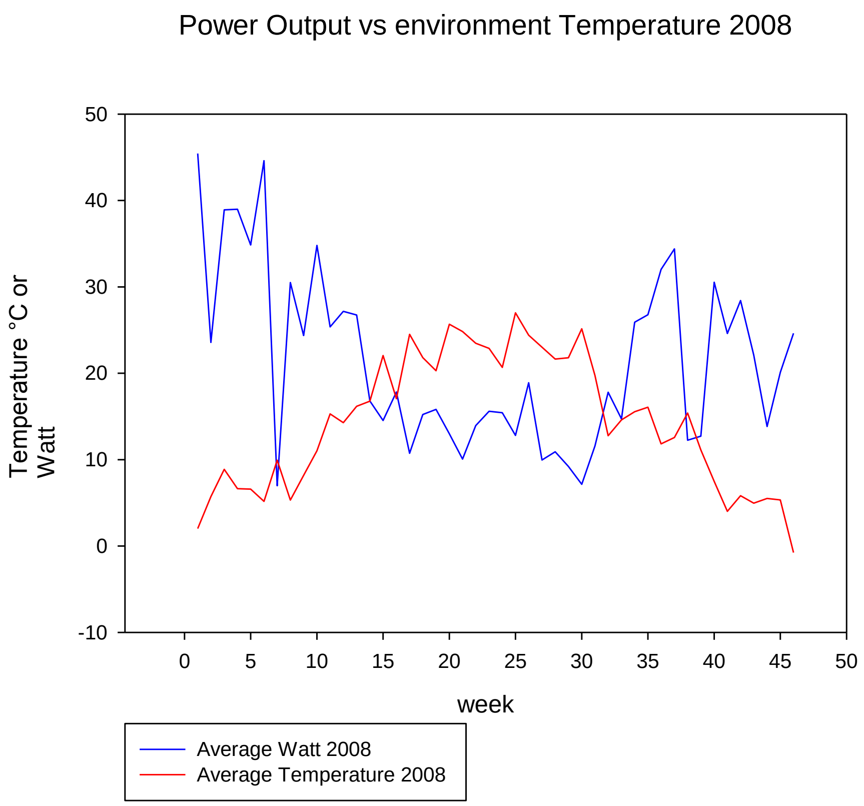


Fig. 4.5: Power output in W vs. environment temperature 2008

The last task in the case study was to calculate the efficiency with another low temperature material for a TEG. The chosen material was a low temperature TEG alloy consisting of Pb and Te.

The temperature range of the roof cooler was between 25°C and <50°C, with this parameters the material was chosen, so that the figure of merit zT of 0.58 was the result. The specific material was selected, because the material behaviour curve was available in literature and the material fulfils the requirements for a low temperature thermoelectric generator. The doping amount of PbI_2 was about 0.01%.

The Carnot efficiency of that alloy was calculated, the data were put into a spreadsheet and the results are shown in table 4.3:

Average Carnot efficiency:	21.82%
Maximum Carnot efficiency:	58.65%
Minimum Carnot efficiency:	1.54%
Standard deviation:	11.48%

Table 4.3: Carnot efficiency

The formula to calculate the Carnot efficiency is the following:

$$\eta = \frac{\Delta T}{T_h} * \frac{SQRT(1+ZT) - 1}{SQRT(1+ZT) + T_c/T_h}$$

The Carnot efficiency is the highest possible efficiency which can occur.
The practical efficiency is about 60% of the Carnot efficiency (Daniel, 1997), so that a TEG with an average Carnot efficiency of 21.82% and with a peak Carnot efficiency of about 58.65% can produce a practical efficiency in average about 14.2% .

The best Carnot efficiencies occur at days with very low environment temperatures. The lowest calculated Carnot efficiencies occur at days with very high environment temperatures. The efficiency varies slightly, because the cold side temperature (environment temperature) and the working temperature (hot side) are not at every time in the optimal working point.

This efficiency is not the really occurring efficiency, but the practical efficiency will follow the Carnot efficiency.

With these figures the spreadsheet was calculated for the three years the following practical efficiencies and practical useable powers (table 4.4):

2012	Average pract.efficiency	:	11.27%
	Maximum pract.efficiency	:	33.29%
	Standard deviation pract.efficiency	:	6.16%
	Average power production 1m²	:	1756W
	Average power production 15m²	:	26343W
	Maximum Power production 15m²	:	176969W
	Standard deviation power prod.	:	17314W
2010	Average pract.efficiency	:	14.16%
	Maximum pract.efficiency	:	35.20%
	Standard deviation pract.efficiency	:	7.00%
	Average power production 1m²	:	1968W
	Average power production 15m²	:	29520W
	Maximum Power production 15m²	:	104088W
	Standard deviation power prod.	:	14956W
2008	Average pract.efficiency	:	13.08%
	Maximum pract.efficiency	:	34.82%
	Standard deviation pract.efficiency	:	6.97%
	Average power production 1m²	:	1871W
	Average power production 15m²	:	28072W
	Maximum Power production 15m²	:	97036W
	Standard deviation power prod.	:	18202W

Table 4.4: Practical efficiency and power production of a supposed TEG with alternative materials

Over the three years a maximum practical efficiency of 35.2%, a maximum average practical efficiency of 14.16%, and a theoretical maximum average practical power production of

29,520W/15m² TEG area was occurring. The maximum average power production per square meter was 1,968W.
These are theoretical figures but this is an issue for further practical research to check the results in reality.

This was a good result it was in the same range an an average solar cell, which has an average efficiency of about 14%, but a solar cell uses only 14% of the solar constant of about 1,367W/m² (Wagemann et al, 1994). The PbTe doped TEG can theoretically use the full energy of the heat source, so that by an optimal chosen material with an optimal working point nearly the relatively high amount of power can be produced on a relatively small area.

4.2 Data collection and analysis of the experiment:

The experiment was done to look at the behaviour of a TEG and to find out the problems with the heat transfer from a hot water tank to the TEG. The experiment was done on two experimental designs.

One design was to simulate the air conditioning system, with a cooling machine (simulated by a hot water tank), a pump, a pipe system and the TEG inclusive the roof cooler (a processor cooler).

At the other design the TEG was put with the hot side in a water bath to measure the power. As a result of the two possibilities the generated power of the TEG was measured and the overall efficiency was calculated. Table 4.5 shows the results of the experiment, figure 4.6 and figure 4.7 show the results of the different measurements.

The water reservoir was needed, because no other possibility to calculate the energy, which is stored primary in the system, was given. So the calculation with the known water volume and the temperature was possible.

Experiment with pump 400ml water								
T °C	U (mV)	I (mA)	Delta T	Hot Side	Cool Side	P (mW)	P water (W)	efficiency %
88	500	33.00	26	56	30	16.50	40,97	0,40
80	415	27.60	25	51	26	11.40	37,24	0,30
75	360	23.50	18	49	31	8.40	34,92	0,24
70	325	21.50	18	47	29	6.90	32,59	0,21
65	295	19.50	14	44	30	5.70	30,26	0,19
60	260	17.00	12	40	28	4.40	27,93	0,15
55	210	14.00	12	38	26	2.90	25,61	0,11
50	197	12,90	10	36	26	2.50	23,28	0,10
45	179	11,80	8	33	25	2.10	20,95	0,10
Experiment with waterbath 180ml								
58	629	77.50	23	58	35	48.75	12.15	0.40
55	600	70.00	21	55	34	42.00	11.53	0.37
50	555	59.50	20	50	30	33.02	10.48	0.32
47	500	59.50	17	47	30	29.75	9.85	0,30

Table 4.5: Experiment results

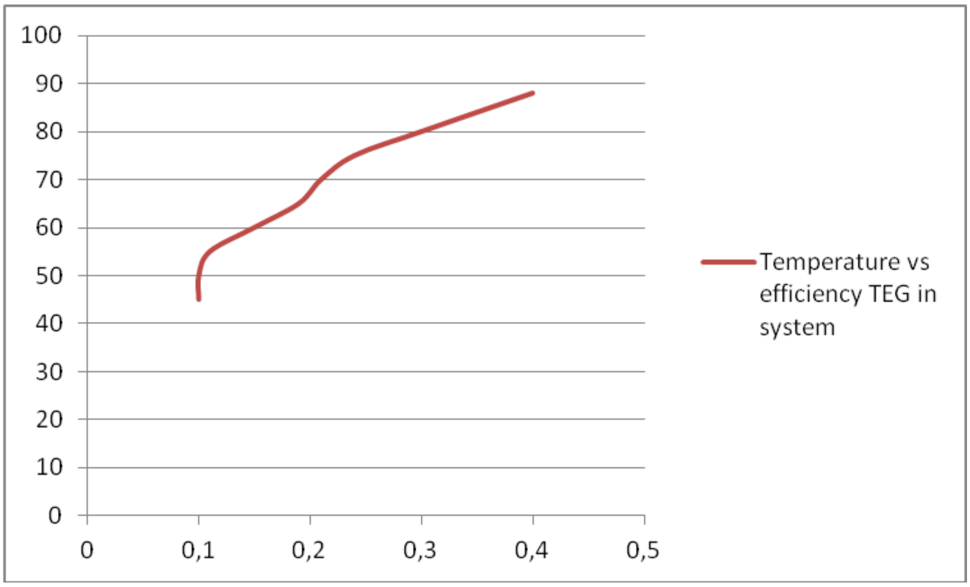


Fig. 4.6: Results of the experiment, simulated roof cooler, on the y-axis is the temperature (°C), on the x-axis is the efficiency (%)

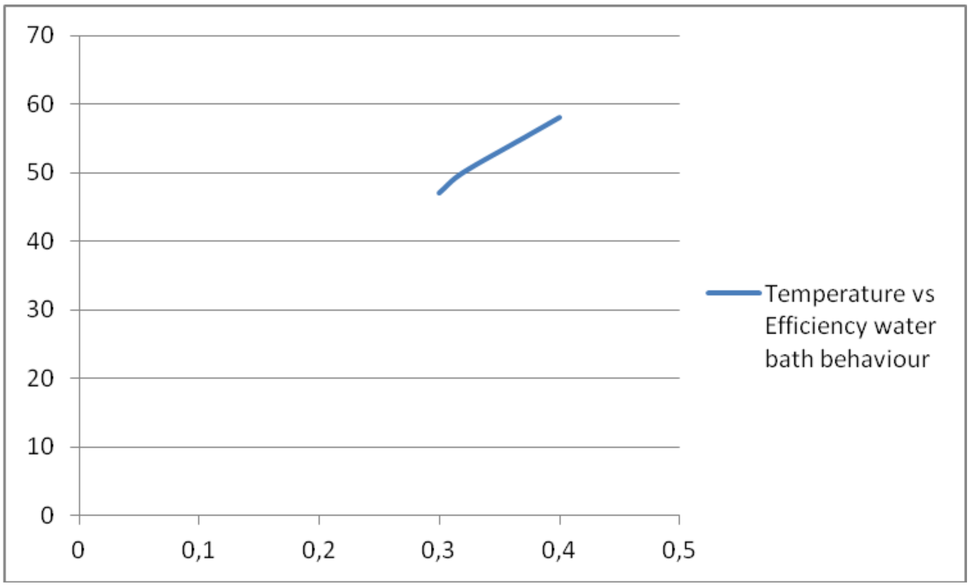


Fig 4.7: Results of the experiment, water bath, on the y-axis is the temperature (°C), on the x-axis is the efficiency (%)

Both diagrams show a relatively linear behaviour of the two experiment measurements.
The experiment showed clearly, that the efficiency of the commercial available TEG is linear dependent on the hot side temperature and the temperature difference. The efficiency will decrease if the temperature of the medium and furthermore the temperature difference (in relation to the environment) is decreasing. The power which such a TEG produces is not only dependent on the temperature difference, it also dependence on a specific working temperature range. This is shown in figure 4.6 and slightly in 4.7, which shows that between 55°C and 45°C the efficiency decreasing is stopping and the efficiency is relatively stable at the low efficiency of about 0.1%. It shows also that a TEG and the used material has a working point and that this working point was not reached by the experiment, because it lies at higher temperatures as tested.

So the usage of a BiTe TEG for such a low temperature application was not the optimal choice. Table 4 shows that the heat losses through the heat transfer, is relatively high, especially by the simulation of the roof cooler system. The temperature losses of (and within that of energy) is about 20°C to 30°C. A calculation of the heat loss is not easy to do, perhaps a simulation with finite element analysis could be helpful. This implicates that by a usage of that system the heat insulation is one necessary point.

4.3 Data Collection and analysis of the survey:

From the 13 sent survey forms only 6 returned. One survey participant died with cancer, so that the return rate is about 50%. The survey was arranged in 4 sections. Because of the small amount of returns, a statistic analysis made no sense, so that the next lines will describe the answers in the survey.

The first section asked the survey participants of their knowledge and their usage, including planning and installation of alternative energy forms. Nearly all participants knew all the 7 alternative energy forms. The participants were all of the planning or the facility management branch, but they installed or used only the most common energy forms, these are photovoltaic, geothermal energy, sometime waste heat for warm water purposes. All other energy forms were not planned or installed by the participants.

Section 2 asked the knowledge of a cooling machine and the amount of waste heat of it. The knowledge of the relatively high amount of waste heat which a cooling machine roof cooler can produce exists. Most of the participants of the survey would use the waste heat for warm water preheating.

Section 3 included questions to the issue thermoelectric generators. Most of the participants did not know the “Seebeck effect” and did not know the working principle of a TEG. If someone knew a TEG, the knowledge of the usage was limited to refrigerator and computer cooler purposes.

Section 4 included questions to the roof cooler TEG combination

Half of the participants could not imagine to install such a system with an existing TEGs (4%) in an existing roof cooler. If the overall efficiency raised 5 of 6 could imagine to use it in an existing roof cooler. The future potential of such a 4% system was marked in average by 3.5, if the efficiency will raise in the range of an average solar cell (>10%) the potential was marked with 2.5.
As a great advantage was seen, that this is a new form of green energy and that it makes sense by lacking energy resources to examine this energy form in future examinations and experiments. As a great disadvantage was mentioned, that the cost effectiveness must be

given and that no reference objects (in facilities) are existing and that the overall knowledge of that energy source did not exist.

The survey shows that most of the experts see the TEG roof cooler combination as a good possibility to produce green energy, if the efficiency raises and the prices will be moderate.

4.4 Payback period and commercial look on the TEG – roof cooler combination

The price of the TEG which consists of BiTe and which is used in the experiments is by a buy-off of 120 pieces 4.67 US$ (Aliexpress, 2013b). This TEG has the dimensions of 50mm x 50mm, so that for one square meter 400 pieces are necessary. 400 pieces will cost without installation and without shipping 2,240 US$/m² = 1,685 Euro = 1397 Pounds. This square meter has a practical power of about 27 W/m². For comparison a mono crystalline solar cell with 156 mm x 156mm costs by the same source like the TEG per square meter 57 US$ (Aliexpress, 2013a), but by a efficiency which is 3.2 times that of a commercial available TEG (4% for a TEG and 13.44% for a mono crystalline solar cell) and by an average power of about 130 W.

So that a TEG with the now commercial existing technology and by an average temperature difference between the hot and cold side of 15K has only about 1/5 of the energy production of a commercial available solar cell. The costs without installation and manufacturing of such a TEG in contrast to a mono crystalline solar cell will be more extreme, the relation is about 1:40, this means a TEG is 40 times more expensive as a solar cell.

The payback period can be calculated:

$$\text{Payback period} = \frac{\text{capital costs}}{\text{annual benefits} - \text{annual costs}}$$ (wirtschaftslexikon24.com, 2013)

One roof cooler has roughly 15m² so that a roof cooler TEG combination costs without installation costs about 25,250 Euro= 20,978 pounds.

The costs for the installation can only be estimated, the installation time is estimated from the experience from the author of that work,

165 hours/month* 45 Euro/person* 3 man-month= 22,275 Euro= 18,488 pounds.
So that the whole installation could cost 47,525 Euro=39,445 pounds.

At the beginning of that work it was assumed that a 15m² 4% TEG can produce 24,000 kWh /year, this is an amount of 3,120 Euro/year which such a system can produce. With the results of the case study the energy production was in maximum 384Wh/roof cooler. This results in a yearly energy maximum production of about 1,480.90kW/h. This produced energy costs on the market about 197 Euro= 163 pounds (13 Eurocent/kWh).

With these figures a payback period can be calculated, the payback period will be 241 years. This explains why the TEG technology with commercial available BiTe TEG´s is not commercial useable at the moment and this is the reason why no one had the idea to extend a roof cooler with a TEG.

The payback period of the theoretical PbTe x PbI_2 TEG should be with the calculated power production in an acceptable range. For the assumption of 29,520W/h/15m² (the maximum predicted power from table 4) power production in a year 118,080kWh/15m² can be produced by such a system. This is an equivalent of about 15,350 Euro.

By using the above investment of about 47,525 Euro a payback period of 3.10 years were calculated. This looks not realistic, because TEGs in greater amounts with that supposed material are not commercial available, but if the payback period gets lower than 10 years, the technology will be interesting from the economic point of view.

This results further that a TEG with an average practical efficiency of about >4.4% will produce enough power that it will have a payback period of <=10 years.

This implicates also that a new identified TEG material can cost 3.2 times of a commercial available TEG to reach a payback period of <=10 years.

4.5 Interpretation in relation to the research question or hypothesis

This section answers in short paragraphs the research questions:

a) Which new material can best be used for a low temperature TEG to increase the output power of the combination of a TEG and a roof cooler, based on available diagrams and figures?

Today existing TEG materials need a temperature difference which exceeds 20K and which needs a working temperature more than 150°C and a working temperature difference of 120K to reach efficiencies up to 4%.

The case study shows that a low temperature TEG with new materials, like PbTe doped with PbI_2 can reach a Carnot efficiency of about an average 21.82% and a theoretical practical efficiency of about 14.16% by low working temperatures and by low temperature differences. $PbTe_2$ x PbI_2 was chosen because the material seems to have the best figure of merit in dependence of the prospected low temperature range for this application. This material is a good choice as an alternative material for a low temperature TEG. The alloy PbTe x PbI_2 is an experimental material, which has no practical usage at the moment, so that the calculations are theoretical predictions.

b) How much energy can be produced with such a combination in theory:
   - With a commercial existing TEG material (4% efficiency)
   - With a new developed TEG material (up to 20% efficiency)?

With the BiTe TEGs the expected 4% efficiency was not reached, so that the average power production of 1m² is between ~15W and ~26W. These power ratings were calculated with help of real world data. So that a 15m² roof cooler produced, dependent to the occurring temperature differences and maximum temperatures in a year between 681kWh and up to 1480kWh. This produced energy was under the expected 24,000kWh.

An assumed TEG with a higher efficiency and the possible gain of average efficiency of about 14.16% will produce an amount of 118,080kWh, this is high enough that it is in an economic range and that the power production can be commercially used. The calculations were done with the same real world data like the BiTe TEG calculations.

c) How does the energy production and behaviour of the TEG´s in practice, compare to the theoretical predictions, for the temperature, which typical occurs of a building cooling system cooler unit?

The BiTe TEG has a behaviour which cannot be used in such a low temperature usage. The optimal working point of a BiTe was in a higher temperature range, this TEG needs also a higher temperature difference to work in an acceptable range. The optimal temperature range will be about 150 to 200°C and the temperature difference should reach 170K. A roof cooler temperature is in the range from 30°C to 55°C, the temperature difference is in the range of 20K to 25K, so that with that figures the resulting efficiency is very low and has an average of 0.3%. The experiment which was done supports that assumption and calculation.

In contrast to that the predictions for a low temperature and low temperature difference TEG was in an acceptable range, but this should be verified in further research. The calculated efficiencies can reach up to 14.16%.

d) How can a roof cooler and a TEG be combined in practice?

A roof cooler and a TEG can be combined in practice by two possibilities:

- The first construction is to attach the TEG directly to the supply side of the roof cooler between the supply pipes and the cooling fans. This can cause problems, if the TEG – supply pipes heat transfer cannot transfer enough energy to the environment, so that an overheating situation of the cooling machine will be possible.
- The second construction possibility is the better solution, first a plate type heat exchanger with the attached TEG will be installed and as a second stage a regular cooler with the fans will be installed.

In the next schematic a supposed combination is shown:

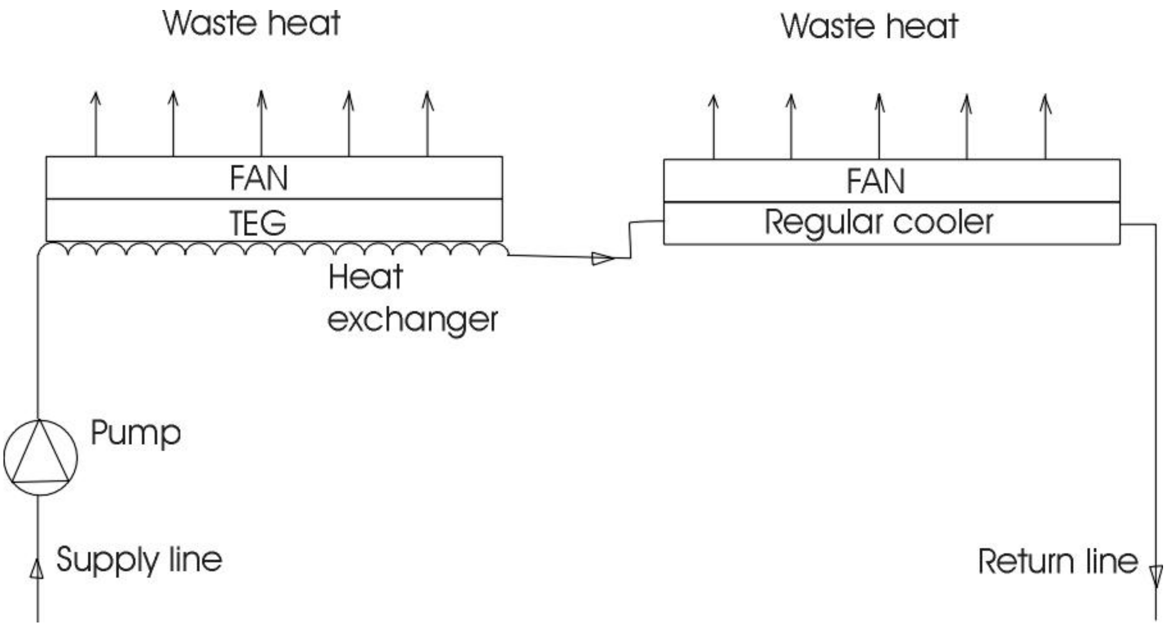


Fig. 4.8: Schematics of a TEG roof cooler combination (Brandl, 2012)

e) Why had no one used a TEG in a roof cooler of a cooling unit before?

It seems that the relative great payback period with common TEG´s is the problem, further that a commercial BiTe has a relative high working temperature, which is over the expected roof cooler temperature and a low overall efficiency. And finally this is a technology comprehensive issue, so that simply no one had the idea. Most of the participants in the survey knew the TEG technology, but they did not think of a combination between a cooling machine and a TEG. The survey and the opinions of the experts support that assumption.

f) How long is the payback period of such a combination?

The payback period was if we use the data from the case study and a BiTe TEG about 241 years.

On usage of a possible PbTe x PbI_2 TEG the payback period can theoretically be, if the theoretical assumptions are right, in a range between 3 to 5 years. This will be an acceptable payback period and makes the technology interesting for commercial usage.

In further consequence we can see that, if the payback period is reduced to <=10 years a new developed and identified TEG can costs 3.2 times of a BiTe TEG to fulfil this demand.

g) What are the advantages and the disadvantages of using a TEG in a roof cooler of a cooling unit?

There were several advantages identified, these are the following:

- A TEG uses waste heat energy, which will normally blow to the environment and it can generate power out of that waste heat.
- A TEG has no moving parts, so that the maintenance is not expensive and intensive.
- A TEG can easily be attached to a plate heat exchanger.
- A prospected PbTe x PbI_2 TEG has a theoretical efficiency up to 14%.
- The TEG can lower the ecological footprint of a cooling machine, especially with the new identified material.

The identified disadvantages are the following

- A commercial available BiTe TEG has a low theoretical efficiency up to 4%.
- A BiTe TEG has a specific working temperature and temperature difference, so that this sort of TEG cannot be used in a roof cooler to use the waste heat.
- A BiTe TEG has payback periods in the range of several hundred years.
- A prospected PbTe x PbI_2 TEG is a totally new technology and is not constructed and used at the moment.
- The costs of a prospected PbTe x PbI_2 TEG are not known.
- The PbTe x PbI_2 TEG material is a low temperature TEG, no one knows the behaviour of that material, these includes the production process, the availability, the toxicity, the effects on the environment and the durability.

4.6 Interpretation in relation to the research aim

The commercial BiTe TEG does not fulfil the theoretical assumptions, this has several reasons. One of these reasons is that a commercial available BiTe TEG has a higher working temperature range as reachable with a roof cooler. The efficiency of such a combination lies theoretically at about 4%. But the test figures showed and the done experiment supported, that the really occurring efficiencies and in consequence the generated power production was 16 to 20 times beyond these predicted efficiencies. With an existing BiTe TEG an increasing of the overall efficiency of a complete cooling unit is not given.

With a prospected low temperature PbTe x PbI_2 TEG the efficiency can be raised up to 14% and the power production will be in a commercial interesting range. This will be recommendation to raise the overall efficiency of a cooling unit.

The asked experts in the short survey have the opinion in majority that the technology was interesting but only if the technology can be used in a commercial usable range and the efficiency is in an acceptable range.

The recommendations are the following:

1) The usage of a BiTe TEG makes no sense because of this low temperature application. The power production is low the payback period is too long for a commercial usage.
2) The further research on a low temperature PbTe x PbI_2 TEG makes sense and is recommended, in a further step a prototype of such a TEG system should be constructed to prove the theoretical predictions.
3) A combination between a TEG and a roof cooler makes sense, especially with new TEG materials but it needs a reconstruction of the existing roof cooler. The existing roof cooler should get a serial connected upstream plate cooler with attached TEG´s, these TEGs are electrically connected together, like described in figure 14.

5. Conclusions

5.1 Conclusion about the research questions

The BiTe TEG cannot fulfil the expectations, the efficiency in consequence as the power production is much lower than expected. The BiTe TEG has a higher working temperature and it needs a higher temperature difference as a roof cooler can supply. As consequence of this the power production in average was 27W/h/m². The payback period of such a system was in the range of about 240 years, so that such a system is commercial not usable.

As a potential low temperature material a PbTe alloy doped with PbI_2 was identified. The alloy has a figure of merit of 0.58 (z.T), the theoretical highest Carnot efficiency was by 58.65%, the average Carnot efficiency was by 21.4%. The practical occurring efficiency is about 60% of the Carnot efficiency. This alloy has a theoretical practical efficiency of about 14.2%, the working temperature lies around 30°C to 50°C. With these relatively high figures, the payback period is in a commercial useable range between 3 to 5 years, so that a combination of TEG and roof cooler with this new material makes sense. The theoretical produced power was between 1,756W/m² and 1,968W/m² this is about 73 times the power production of a BiTe TEG under the similar conditions. These are theoretical figures and these theoretical figures should be tested by further research and experiments.

In this research two designs of a reconstruction of a roof cooler were discussed. The best version was a serial connected upstream plate cooler with attached TEG´s ahead the regular roof cooler with fans.

It looks that no one has extended a roof cooler with a TEG, because the payback period and the efficiency of the now commercial available TEG´s is not in the commercial range. Also the commercial available TEG´s have a higher working temperature and need higher temperature differences. These are the main reasons why no one combines the two technologies.

The advantages of a combination of roof cooler are obvious, the TEG has no moving parts the energy, which the TEG uses for the power production is waste heat, which is normally given to the environment. The maintenance of such a system is at a low rate. But to get a high efficiency and a commercial useable application a new material must be designed. The now existing commercial available TEG´s have too high a working temperature to get the best efficiency. This results in a development of a new TEG material, which is at this point of research a theoretical material, but with high efficiency.

The disadvantages of this material are that it is not tested or available in greater amounts to test it in a practical environment, this includes the electrical and mechanical behaviour, the availability, the toxicity, the production process and the durability. By the look at the cost aspect, the cost of such a material is not assessable at the moment, but it is expected that the material should be in the same range as a commercial available BiTe TEG.

5.2 Conclusions about the research aim

The aim of that work is to make recommendations on how a TEG can be used to make use of the waste energy which a roof cooler emits to the environment and to increase the efficiency of the complete cooling unit.

The commercial available TEG´s have only a low efficiency in practice the efficiency is much lower than expected. The power production was very low and was 16 to 20 times below the expected values. This had several reasons one major was the working temperature, which is by the commercial available TEG higher than expected.

A new material was identified, to reach a commercial usable range and which produces by low temperatures and low temperature differences enough power to fulfil this.
The PbTe x PbI_2 alloy is a theoretical material, but it looks good for that application. This material has an average practical efficiency of 14%, and it has a payback period of about 3 to 5 years.

Some experts were asked to support the usage of TEG roof cooler combination. The experts have consistently a positive opinion of the usage of this combination and would use it in own installations if the efficiency and the payback rate is in a commercial useable frame.

5.3 Further work

The further work is to extend the research, especially the test of the identified PbTe x PbI_2 TEG alloy in practice.
The research should include the following points:

- To design and construct the alloy and test it.
- The power production of such a TEG under the conditions of a low temperature environment.
- To test the practicable efficiency of that identified alloy.
- The durability of this TEG under real conditions, this includes temperatures, light, UV radiation etc.
- The toxicity of this TEG material.
- A practicable solution to combine a heat source with this type of TEG.
- To calculate the costs of mass production and the payback period of that TEG.
- The electrical and mechanical behaviour of the TEG.

5.4 Implications of the research

One implication of that research was that the idea of a combination of a TEG and roof cooler has at the moment because of low efficiency of the used TEG material no commercial usage.

But with the identification of a low temperature TEG material this technology is interesting for science and commerce. Also the implications of that technology to the whole green power industry and for the cooling machine producers are interesting. The technology can help to decrease the CO_2 output and it can lower the ecological footprint of a cooling machine.

5.5 Reflection on the experience of the research process

The research itself was an interesting work, but it was a high time consuming process. The most time consuming process was the analysis of the relative large Excel sheets. The sheets have more than 11,000 cells, so that this was a time consuming but necessary work.
My sight on this research process changed over the time, from a little bit frustrating at the beginning in February 2012 by acceptance not until the 6^{th} draft of the research proposal, till

the different TMA´s which had a lot of remarks from my tutor till this dissertation.

The interpretation of the big amount of data was not easy, but with the help of my tutor it was a possible task. The experience of the research process was a demanding process, but it developed my sight on things from the scientific side of view. The research was full of surprises, some expected behaviour was not fulfilled e.g. I overestimated the average temperature, so that the average efficiency was lower than expected.

I had some troubles by the division of the dissertation in 4 parts, so that sometimes I had to search the famous “red thread”, but I hope with the help of my tutor I found this thread again.

The OU library and the access to many journals through this library helped me to write this dissertation. Also the broadband connection to the internet helped to find the necessary information.

This dissertation is important for me not only to develop scientific aims, but also to write it in a language which is not my native one.

Word count = 13682

References:

Agentur für erneuerbare Energien (2012) *Erneuerbare Energie mit hohem Ausbaupotential*, [online], http://www.unendlich-viel-energie.de/de/wirtschaft/potenziale.html , last accessed 1.4.2012

Aliexpress (2013a) *Price für Solarcell for price comparision* [online] http://www.aliexpress.com/item/4x100W-mono-12V-solar-panel-for-total-400W-for-home-use-solar-street-light-A-grade/570077366.html, last accessed on 12.1.2013

Aliexpress (2013b) *Price for TEG for price comparision*, [online] http://www.aliexpress.com/wholesale?SearchText=TEC+12708&catId=0&manual=y, last accessed on 12.1.2013

Bellona Foundation (2012) *Radioisotope thermoelectric generator* [online] http://www.bellona.no/bellona.org/english_import_area/international/russia/navy/northern_fleet/incidents/37598 , last accessed on 1.4.2012

Braitwhaite N., Weaver G. (1998) "Electronic Materials - inside electronic devices", The Open University, Butterworth Heinemann

Conrad Datenblätter (2012a) *Solar module AS120* [online], http://www.produktinfo.conrad.com/datenblaetter/100000-124999/110120-da-01-en-Solarmodul_AS120.pdf , last accessed on 1.4.2012

Conrad Datenblätter (2012b) *Monocrystalline Solar cells* [online], http://www.produktinfo.conrad.com/datenblaetter/175000-199999/193852-da-01-en-MONOKRISTALLINE_SOLARZELLEN.pdf , last accessed on 1.4.2012

Cuenat A., Winkles L. (2010) "Nanostructured Materials", NPL Nanomaterials, National physical Laboratory

Daniel H. (1997) "Physik", Berlin, de Gruyter, ISBN 3-11-0102031-5

Dr.Neumann Peltier (2012) *Datenblatt Thermogenerator TG -200* [online], http://www.dr.neumann-peltier.de/pdf/Datenblatt-TG-200.pdf , last access on 31.3.2012

E-control.at (2012) *Kraft Wärme Kopplung* [online] http://www.e-control.at/de/industrie/strom/kraft-waerme-kopplung, last accessed on 27.8.2012

Faninger, G. (2006) "Alternativenergie in Österreich Marktentwicklung", BMVIT

Forster, P., Venkatachalam, R. et.al. (2007) "Changes in Athmospheric Constitutents and in Radiative Forcing", Section 2, p131 - 234,

Guo, J., Geng, H, Ochi, S. (2007) "Thermoelectric Properties of $(Yb, Ca)_x(Co, Fe)_4Sb_{12}$ Skutterudites", University of Tokyo

International Thermoelectric Society (2012) *Promoting thermoelectric technology to mitigate global climate change* [online] http://www.its.org/ , last accessed on 1.4.2012

Ioffe, A.F. (1957) Semiconductor Thermoelements and Thermoelectric Cooling, Infosearch, London

Kaeltebucher.ch (2012) *Kältekreislauf - schematics* [online] http://www.kaeltebucher.ch/kaelteanlagen_kaeltetechnik_kaeltemaschine , last accessed on 10.8.2012

Koumotom, K. Wang, Y, Zhang R. (2010) "Oxide Thermoelectric Material: A Nanostructuring Approach", Annual Review Material Research

Kunihito K., Yifeng W, Ruizhi Z., Atsuko K., (2010)"Oxide Themoelectric Materials: A Nanostructuring Approach", Annual Rev. Material Research 2010, Vol 40, Annual Reviews

Hieble, E., (2000) "*Fachdidaktik Physik, Wärmekapazität Wasser*", [online], http://physicbox.uni-graz.at/unterrichtsmaterial/demonstrationsexperimente/kalorik/waermekapazitaet_wasser.php, Universität Graz accessed online 9.5.2012

Masterbergen D., Willson B., Joshi S. (2012) *producing light from stoves using a thermoelectric Generator* [online], www.leverred.com last accessed on 6.3.2012

Open University (2010) "Methdodology and Techniques", Open University, Milton Keynes

Recknagel, H., Sprenger, R., Schramek, E et.al. (1997) "Taschenbuch für Heizung, +Klimatechnik", Oldenburgverlag, 68. Auflage

Rehsler-Kuehlsysteme (2012) *Kühlmaschinen – Schema* [online], http://www.rehsler-kuehlsysteme.de/pdf/Flyer-Kuehlturm.pdf, last accessed on 18.8.2012

Rockwell International (2012) *Basic Elements of static RTG* [online], http://fti.neep.wisc.edu/neep602/SPRING00/lecture5.pdf , last accessed on 1.4.2012

Salzgeber,K. (2010) "Skutterudites: Thermoelectric Materials for Automotive Applications?", Springer Verlag

Snyder J., Toberer E. (2008) "Complex thermoelectric materials", Nature Materials Vol 7, Nature Publishing Group

Simonson J. (2008) "Investigation of high temperature thermoelectric material", University of Virginia

Schubert, J. (1984) "Physikalische Effekte", Weinheim Verlag, 2.Auflage

Stone, E. (2003)"*Basic of Space Flight*" [online] http://www2.jpl.nasa.gov/basics/bsf1-1.php last accessed on 1.4.2012

Tecteg company (2013) *Specifications TEG Module* [online], http://www.tecteg.com/pdf_files/SpecTEG1-12610-5.1TEG-POWERGENERATOR-new.pdf , last accessed on 10.1.2013

Tervo J., Manninen A., Illola R., Hänninen H. (2011) "State of the art of thermoelectric materials processing", VTT Working Papers 124, VTT

Toschiba (2012) *Toshiba the aircondition Innovators - Homepage* [online], http://www.toshiba-aircon.co.uk/ , last accessed on 27.8.2012

Netzsch company (2012) *Thermoelectric Materials* [online] http://www.netzsch-thermalanalysis.com/download/Thermoelectric_Materials_0709-w_neu_457.pdf , last accessed on 5.3.2012

Wagemann, H.H, Eschrich H. (1994) "Grundlagen der photovolatischen Energiewandlung", Teubner Sudienbuch, Stuttgart

Wirtschaftslexikon24.com (2013) *Amortisationsrechnung* [online], http://www.wirtschaftslexikon24.com/d/amortisationsrechnung/amortisationsrechnung.htm , last accessed on 15.1.2013

Wölfing, B., (2001) "Tl9BiTe6, a new thermoelectric material with record efficiencies", dissertation, University of Konstanz

Yang, R., Gang C.(2006)"Nanostructured thermoelectric material: from superlattices to Nanocomposites", MIT

Yin, R.K. (2003) Case Study Research Design and Methods (3rd edn), Thousand Oaks, Ca, Sage Publications

York - Homepage (2012) *Information über Kältemaschinen allgemein* [online] http://www.york.com/ , last accessed on 31.3.2012

US Department of Energy (2012) *Radioisotope heater units* [online], http://www.ne.doe.gov/space/neSpace2f.html , last accessed on 1.4.2012

Zevalkinh A., Toberer E., Zeier W., Flage-Larsen E. (2011) "Ca3AlSb3: an inexpensive, non toxic thermoelectric material for waste heat recovery, energy environ Sci

Zeng G., Bowers J. (2006) "ErAs: InGaAs/InGaAlAs superlattices thin film power generator array", Applied Physics Letters 88, American Institute of Physics

Zhanh P., Habermeier H.U. (2004) "new thermoelectrical materials and new applications", Institute of advanced materials for photelectronics and Max Plank Institute for solid state research

Zhang, L. (2009) "Nanostructured bulk thermoelectric materials (Skutterudites)", dissertation, University of Vienna

Appendix 1

Data Sheet TEG TG-200

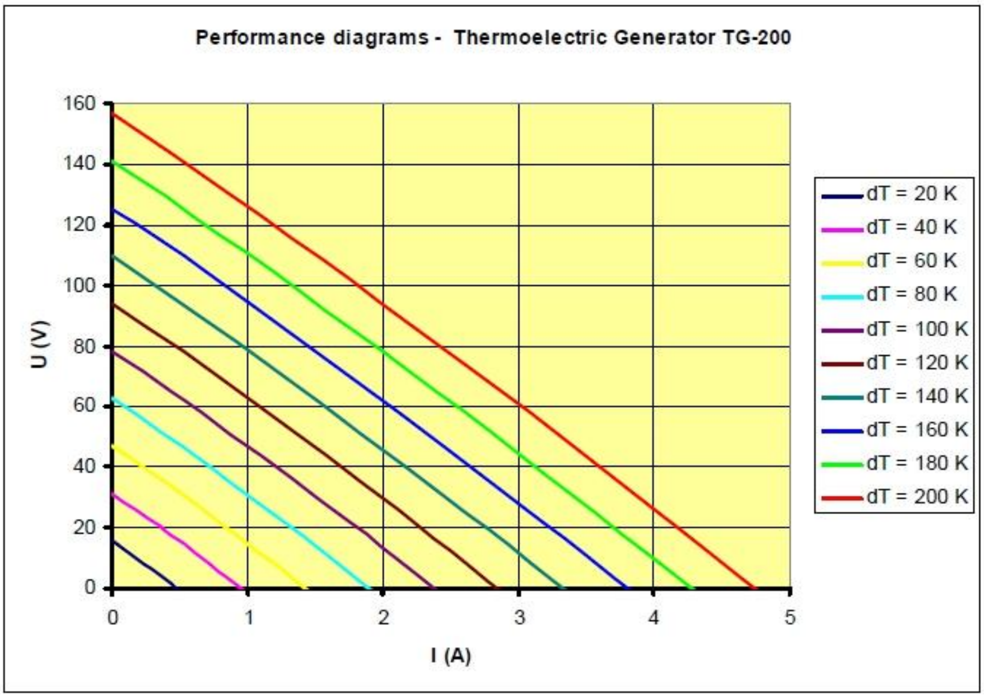
Data Sheet
Thermoelectric Generator TG-200

DR.NEUMANN Peltier

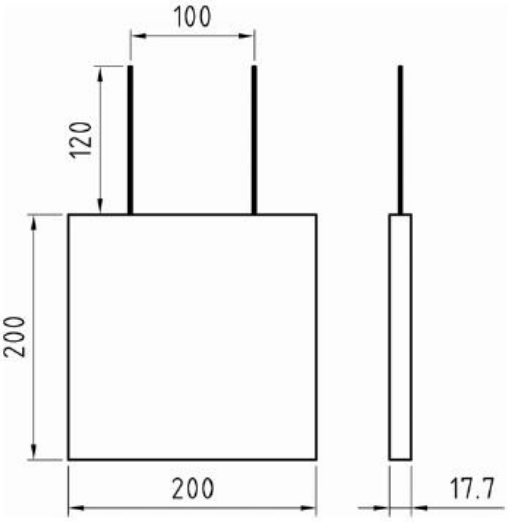
Technical Data:

Weight	ca. 1800 g
Maximum operating temperature	200 °C
Open circuit voltage	U_o (V) = 0,783 $\cdot$ ΔT (K)
Short circuit current	I_o (A) = 0,0242 $\cdot$ ΔT (K)
Maximum power	P_{max} (W) = 0,004842 $\cdot$ ΔT^2 (K^2)

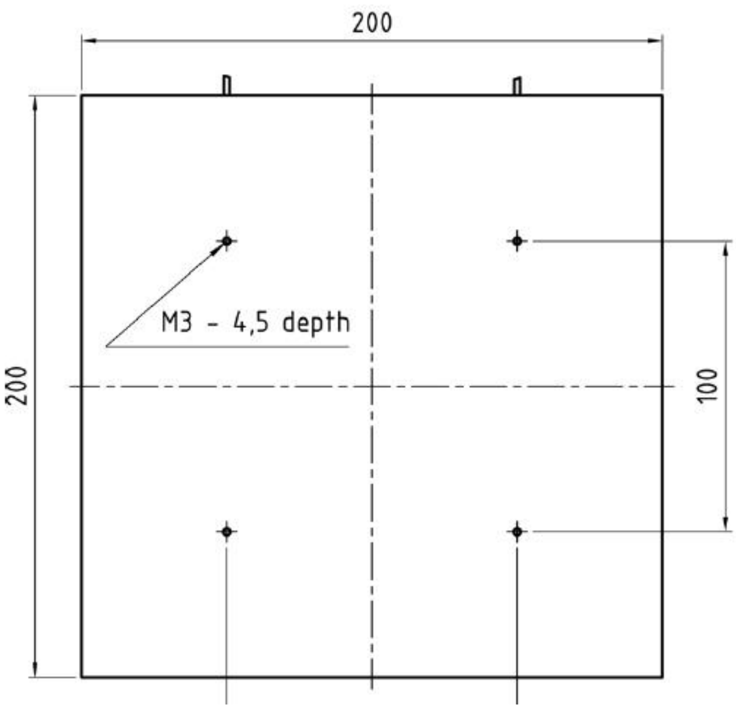
Performance range:



Main dimensions:



Connecting dimensions:



Datasheet of the used TEG in the case study, (Dr. Neumann Peltier, 2012)

Appendix 2

Description of the Case Study:

This case study includes a cooling unit with a roof cooler in one building of the University of Vienna. The building has 3 cooling units installed.

A cooling unit works on thermodynamic principles (Recknagel, 1997) and simply spoken it transports energy from one system (most closed) to the environment. The cooling unit uses the so called Carnot circuit process and transports the energy with a cool water circuit to the environment and it produces waste heat energy.

The research of this work is based on real world data from these cooling machines. The provided data look good and tell us that the best efficiency is in the time between February and June, and between September and November, so that it looks possible that additional electrical energy can be produced during 8 months in a year.

This work will analyse the usage of a thermo electrical generator in the cooler of a cooling unit, this includes an experimental model of an existing cooler, the existing materials, materials on research, the payback period of such an installation all based on real world data from the years 2008, 2010 and partly 2012.

The data which are used in that work are produced by a building cooling unit produced by the company York/Johnson Controls with a connected wattage of about 150 kW and a cooling wattage of about 600kW under full load. On the observed cooling unit energy will only be transported to the roof cooler if the cool water temperature reaches a temperature of about 30°C. By environment temperatures of about -5° in winter, the temperature differences reach 35K, so that the theoretical maximum power which is generated by an attached TEG can produce more power than a solar cell. In summer the temperature difference is lower, but reaches in average 10K - 15K, because the cool water temperature has a maximum temperature of about 45°C. The temperature of about 50°C is the upper limit, because if the temperature is rising, the pressure of the cooling circuit is rising and the coolant in the machine is rising, so that the cooling machine makes an emergency stop by high temperatures in case of rising coolant pressure. To the bottom the cool water circuit is also limited, because if the temperature is too low, the machine can be damaged by freezing. The lower limit lies by about 30°C, this will be reached by a hydraulic bypass. So that we can use by this sort of cooling machine a temperature band from 30°C to 45°C for other purposes, like an attached TEG.

The cool water is transported by a pump with a fixed water flow of about 62.3m³/h, so that a relative big energy amount circles in the system (York, 2012)(Recknagel, 1997). The so transported energy to the roof is in average 148 kWh and reaches in some situations a peak energy of 439 kWh. In the building 3 cooling units of this dimension are installed, so that in average 444 kWh will be transported to the roof and it gives this energy to the environment and has a peak energy of 1.317 kWh which will also be emitted to the environment. To use this energy the idea was born to use it for preheating the warm water circuit, but the temperature difference was too low (<20K), the hydraulic complexity was too high and the needed amount of warm water was too low for a cost effective usage .
In this work this waste heat should be analysed and used for electrical energy production in combination with a thermoelectric generator.

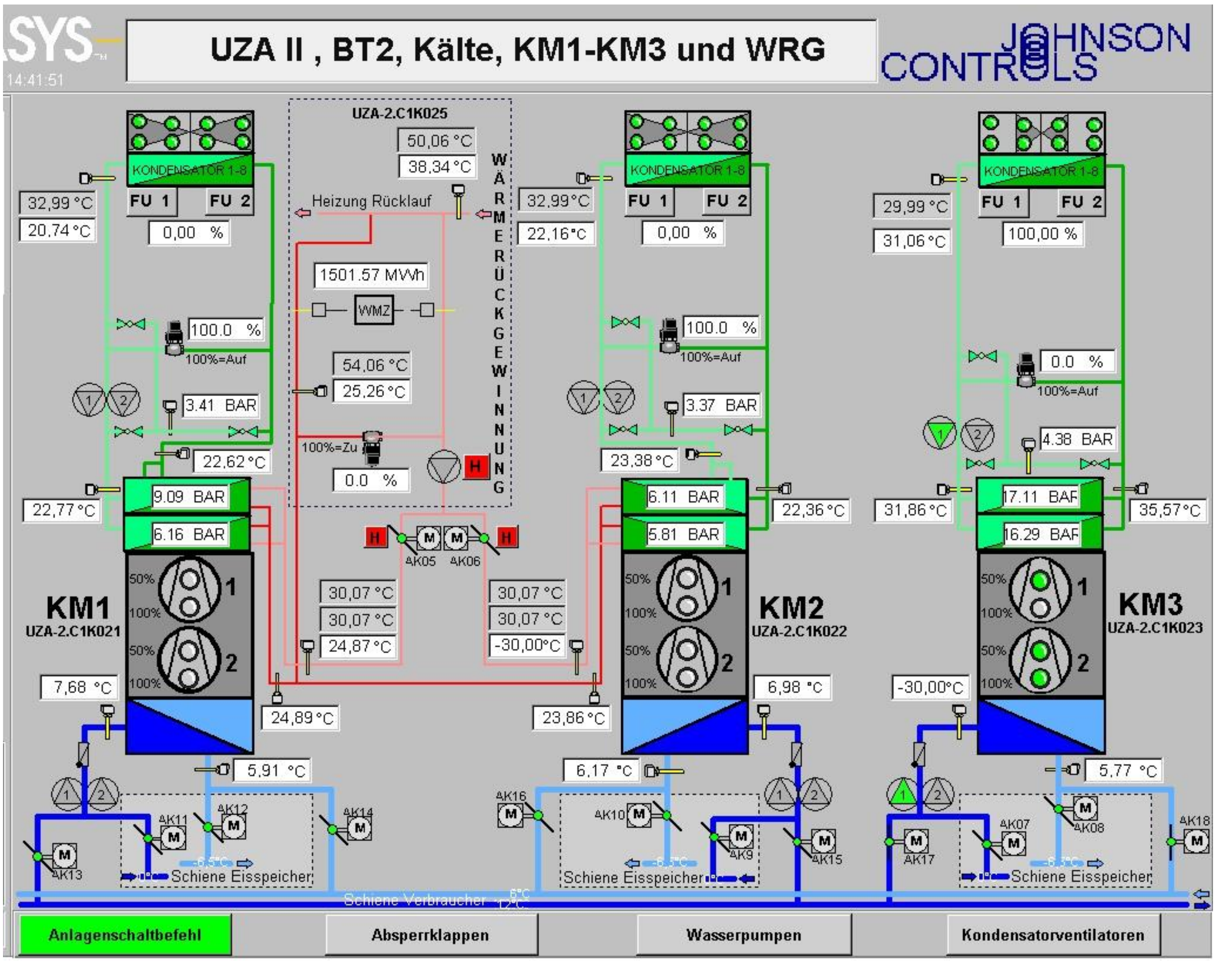


Fig A2.1: Cooling system layout (photo Brandl 2012; original York/JCI, 2000)

In Fig.15 the layout of the complete researched cooling system is shown, the picture is taken by the author from the central control centre. The picture has of 400 data points, this includes the cool water temperature, the cooling water temperature, the pressure from the cooling machine, the roof cooler fan usage in %, the position of the valves, the pump status etc. .

Fig A2.2: Cooling machine (Brandl 2012)

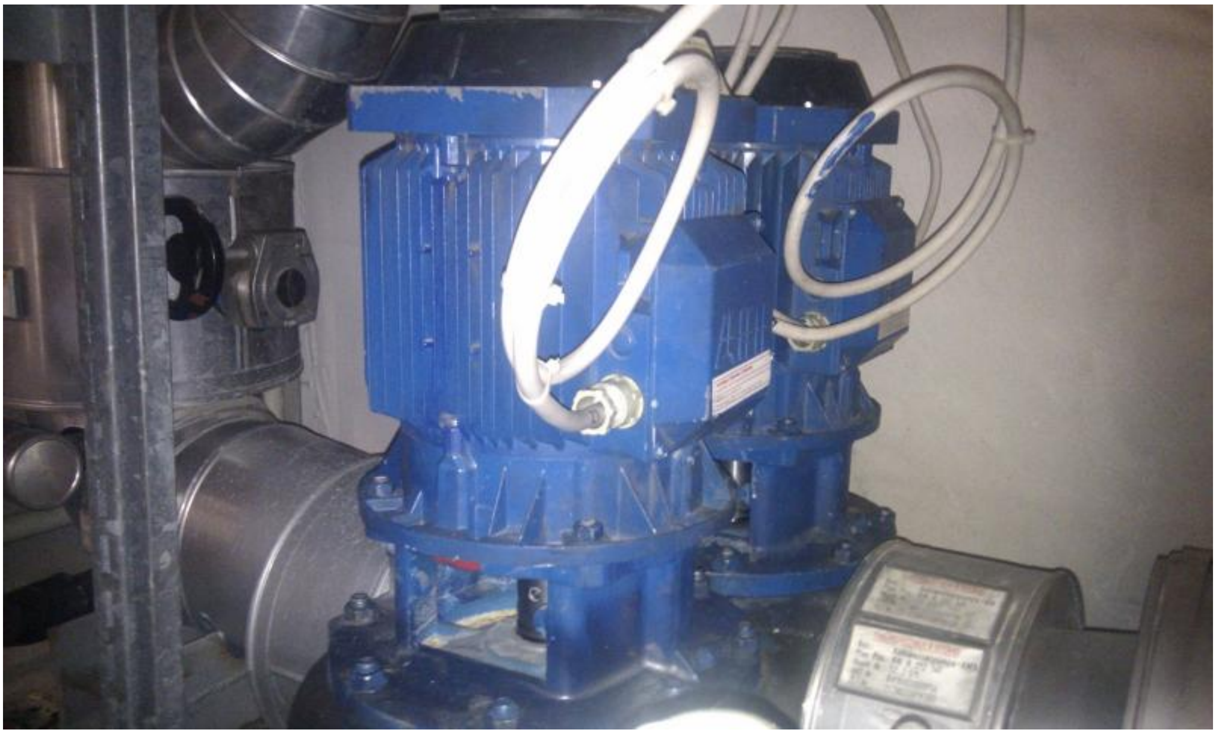


Fig A2.3: Cooling water "twin"pump with 6kW power (Brandl 2012)

Fig A2.4: Roof cooler (Brandl 2012)

The whole cooling system consists of 3 cooling machines, every machine has 4 stages and every machine has one roof cooler with 8 stages. The fans of the roof cooler are also attached to a frequency converter to provide a smooth power curve, dependent of the needed load.

The layout shows that only cooling machine 3 is working with 3 stages out of 4 at this day. The temperature which was transported to the roof is of about 35.57°C, and the roof cooler is working with 100% power. The return line has 31.06°C at this day and time.

The blue lines are the cool water lines with a cool water temperature of about 6°C. The cool water line goes to the consumers of the cool water, like fan coils, air conditioning system etc.
The green lines are the cooling water circuit which goes to the roof cooler, this is the line which is interesting for that work. This line transports the “waste heat” to the roof and this energy can be used for further purposes. The deep green line is the supply line, the light green line is the return line of the cooling water circuit.
The red line is not used, but it is an installed line for the additional heating circuit for the preheating circuit of the warm water.

The system layout with the above data is from the 23.03.2012, 14.41 o´clock, the environment temperature at this date and time was 9°C. The temperature difference which can be used by an attached TEG of about 26°K.

This results by using the formula from appendix 1 in,

Pmax = 0.004842 * ΔT^2 = 0.00482* 26^2 = 3.25 W

For a TEG with the dimension of 200mm x 200mm, $1m^2$ of this TEG will produce 81.25 W.

The whole roof cooler has the dimensions 2400mm x 6060 mm, this results in $14.544m^2$, with this figures a TEG in that dimension produces 1.1kW. Three roof coolers with that dimensions are installed in the building so that at this specific conditions a total of 3.3 kW will be produced. This is about half the power of one of the twin pumps which transports the cool water to the roof.

This TEG from Appendix 1 is a BiTe based element. For the TEG´s which are based on other materials, like Skutterudites at the moment only theoretical figures are known, so that only an estimation of the theoretical power out of the publications can be calculated. Under an estimation of about 20% efficiency, this is up 5 times the power of the BiTe TEG 16.5kW can be produced.

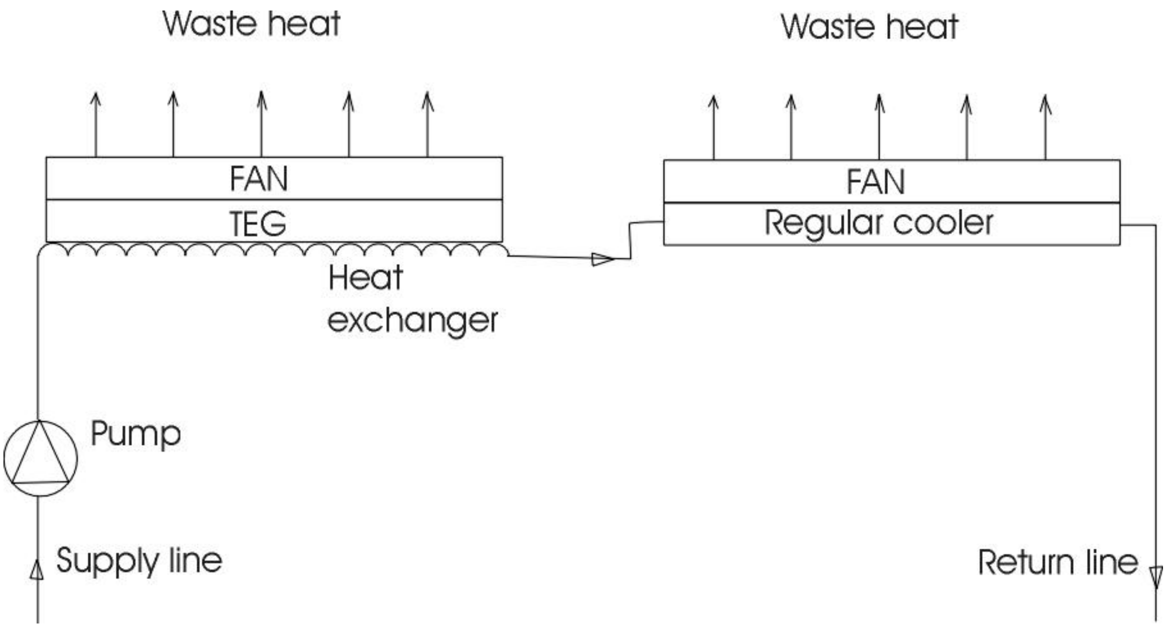
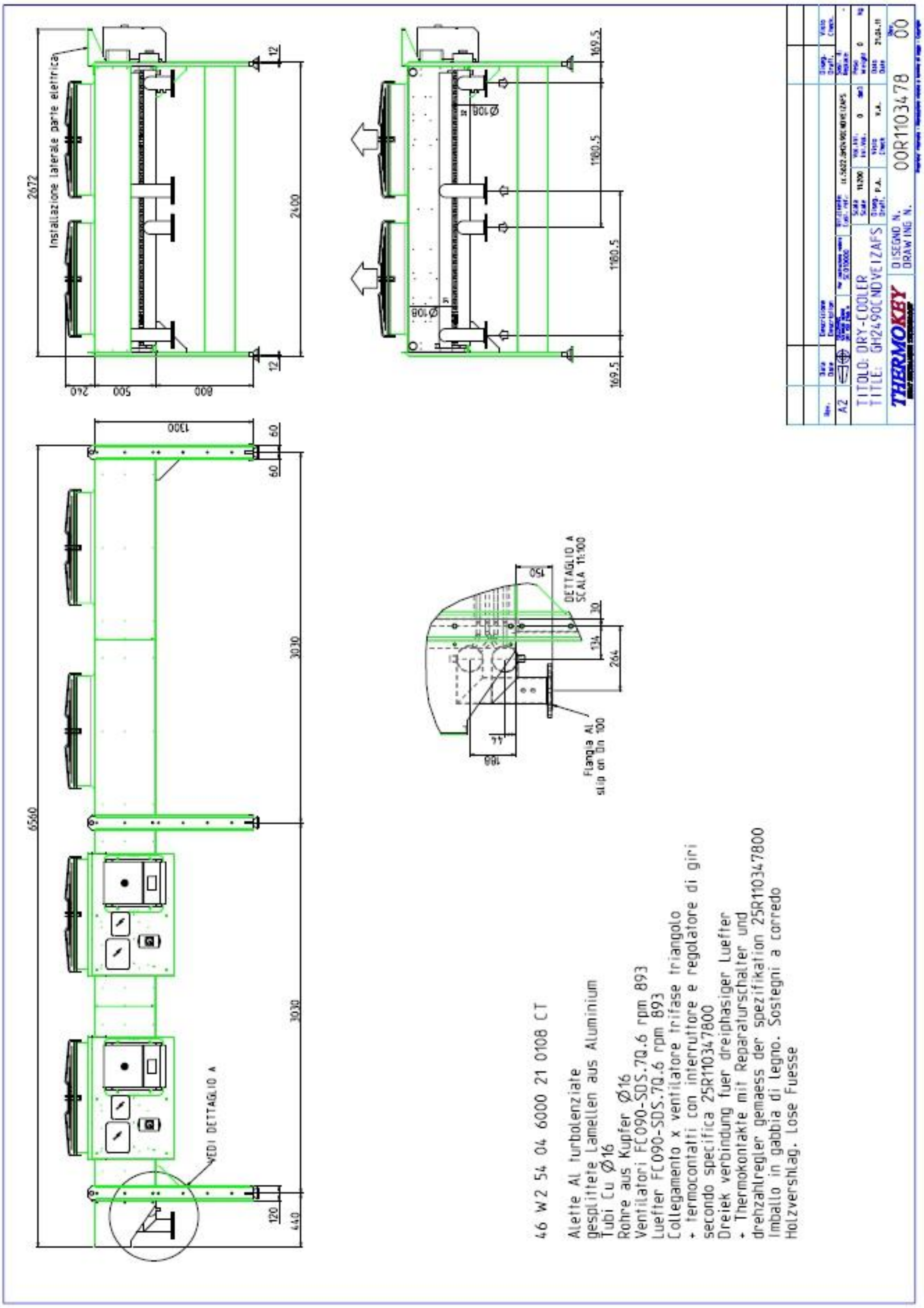


Fig. A2.5: possible schematic for a combination of a TEG and a regular roof cooler

Appendix 3

Data sheet of the installed roof cooler, which provides the data for the case study:



Documentation of the roof cooler of the cooling unit in the University building, (Offner GesmbH., 2011)

Appendix 4

Sample of the Excel sheet.

Date	Time	Environment Temperatur °C	Supplyline°C	Returnline °C	flag	Delta T S-R
01.01.12	01:28:10	5,863	30,441	28,043	1	2,398
01.01.12	02:28:10	6,453	30,441	28,043	1	2,398
01.01.12	04:43:10	7,047	30,441	28,043	1	2,398
01.01.12	04:59:56	7,047	30,441	28,043	1	2,398
01.01.12	08:28:10	6,453	30,441	28,043	1	2,398
01.01.12	10:59:54	6,454	30,441	28,043	1	2,398
01.01.12	16:59:51	8,453	30,441	28,043	1	2,398
01.01.12	22:59:50	8,454	30,441	28,043	1	2,398
02.01.12	00:00:00	8,453	32,766	28,566	1	4,2
02.01.12	19:28:20	7,156	30,816	28,043	1	2,773
02.01.12	22:58:20	8,543	32,664	28,566	1	4,098
02.01.12	23:28:20	7,355	33,738	29,09	1	4,648
03.01.12	01:28:30	7,949	33,664	29,09	1	4,574
03.01.12	02:28:30	8,543	30,789	28,043	1	2,746
03.01.12	04:58:30	9,859	30,59	27,992	1	2,598
03.01.12	04:59:58	10,543	30,57	27,992	1	2,578
03.01.12	10:59:56	10,059	33,391	29,141	1	4,25
03.01.12	12:28:30	8,148	33,516	29,141	1	4,375
03.01.12	13:28:30	7,555	31,242	28,617	1	2,625
03.01.12	16:28:30	6,344	32,566	28,617	1	3,949
03.01.12	19:28:30	6,453	33,191	28,59	1	4,601
03.01.12	20:28:30	6,453	30,914	28,066	1	2,848
03.01.12	22:28:30	5,863	30,941	28,016	1	2,925
04.01.12	00:58:30	8,344	30,867	27,992	1	2,875
04.01.12	09:58:40	10,145	33,863	29,641	1	4,222
04.01.12	11:58:40	11,355	33,539	29,066	1	4,473
04.01.12	12:58:40	10,059	30,789	28,516	1	2,273
05.01.12	06:28:50	7,156	33,539	28,941	1	4,598
05.01.12	07:28:50	7,75	30,766	28,418	1	2,348
05.01.12	11:58:50	7,047	33,488	28,992	1	4,496
05.01.12	17:59:00	5,949	31,617	28,965	1	2,652
05.01.12	20:58:50	5,949	33,113	28,441	1	4,672
05.01.12	22:58:50	5,949	33,539	28,965	1	4,574
05.01.12	23:29:00	5,949	30,742	27,918	1	2,824
06.01.12	01:59:00	5,863	30,664	27,918	1	2,746

Delta S-Env	Online Time	Online Time calculable	Power 1 cell W	Power 1m^2	Power 15m^2	Wh
22,18	0		2,38	47,64	714,61	714,61
21,59	01:00:00	1,00	2,26	45,14	677,10	1523,47
20,996	02:15:00	2,25	2,13	42,69	640,35	178,94
20,996	00:16:46	0,28	2,13	42,69	640,35	2222,38
21,59	03:28:14	3,47	2,26	45,14	677,10	1712,30
21,589	02:31:44	2,53	2,26	45,14	677,03	4061,65
19,59	05:59:57	6,00	1,86	37,16	557,46	3344,61
19,589	05:59:59	6,00	1,86	37,16	557,40	557,40
20,113	#########	1,00	1,96	39,17	587,62	11442,35
20,887	19:28:20	19,47	2,11	42,25	633,72	2218,02
20,023	03:30:00	3,50	1,94	38,83	582,38	291,19
21,735	00:30:00	0,50	2,29	45,75	686,22	1372,45
21,141	#########	2,00	2,16	43,28	649,23	649,23
19,5	01:00:00	1,00	1,84	36,82	552,35	1380,88
18,133	02:30:00	2,50	1,59	31,84	477,62	11,68
17,449	00:01:28	0,02	1,47	29,48	442,27	2653,37
19,082	05:59:58	6,00	1,76	35,26	528,92	780,75
20,993	01:28:34	1,48	2,13	42,68	640,17	640,17
21,062	01:00:00	1,00	2,15	42,96	644,38	1933,15
22,273	03:00:00	3,00	2,40	48,04	720,62	2161,85
22,137	03:00:00	3,00	2,37	47,46	711,84	711,84
21,613	01:00:00	1,00	2,26	45,24	678,54	1357,08
22,153	02:00:00	2,00	2,38	47,52	712,87	1782,18
19,648	#########	2,50	1,87	37,38	560,77	5048,46
19,496	09:00:10	9,00	1,84	36,81	552,12	1104,25
17,711	02:00:00	2,00	1,52	30,38	455,65	455,65
18,457	01:00:00	1,00	1,65	32,99	494,84	0,00
21,785	#########	0,00	2,30	45,96	689,38	689,38
20,668	01:00:00	1,00	2,07	41,37	620,50	2792,26
21,945	04:30:00	4,50	2,33	46,64	699,55	4199,23
23,016	06:00:10	6,00	2,56	51,30	769,49	2306,35
22,492	02:59:50	3,00	2,45	48,99	734,86	1469,71
23,016	02:00:00	2,00	2,56	51,30	769,49	386,88
21,969	00:30:10	0,50	2,34	46,74	701,08	1752,70
22,055	#########	2,50	2,36	47,11	706,58	1415,12

Energy to roof	Effiency between cooler energy and TEG output	Average watt	Average Temp	week	theoretical eff. %	zT
173.879,65	0,41			1	38,28	0,58
173.879,65	0,39				36,77	
173.879,65	0,37				35,28	
173.879,65	0,37				35,28	
173.879,65	0,39				36,77	
173.879,65	0,39				36,76	
173.879,65	0,32				31,93	
173.879,65	0,32				31,93	
304.543,17	0,19				30,85	
201.071,00	0,32				34,66	
297.147,12	0,20				30,74	
337.027,77	0,20				33,26	
331.662,01	0,20				32,03	
199.113,22	0,28				31,43	
188.381,70	0,25				28,58	
186.931,50	0,24				27,13	
308.168,68	0,17				27,93	
317.232,47	0,20				31,79	
190.339,48	0,34				34,25	
286.343,09	0,25				35,87	
333.619,79	0,21				34,99	
206.509,27	0,33				36,32	
212.092,56	0,34				37,69	
208.467,05	0,27				31,74	
306.138,39	0,18				28,16	
324.338,47	0,14				25,20	
164.815,86	0,30				28,82	
333.402,26	0,21				33,64	
170.254,13	0,36				33,90	
326.006,21	0,21				34,01	
192.297,26	0,40				38,36	
338.768,02	0,22				36,00	
331.662,01	0,23				36,43	
204.769,02	0,34				37,52	
199.113,22	0,35				37,82	

Appendix 5

EMail to Mr.Wallner, head of the facility unit of the building in which the cooling unit for the case study is installed.

Lieber Karl Wallner,

bist Du so nett und lasst Du mir ab morgen den 2.4.2012 bis 28.10.2012 einen Trend der Kältemaschine(n) einrichten, dieser sollte wie folgt aussehen :

Datum, Vorlauftemperatur, Rücklauftemperatur, Außentemperatur, Kältemaschinenenergieverbrauch/Stufe, Rückkühlerventilatorenstufe.

Darüber hinaus bräuchte ich am Besten eingescannt die Technischen Daten der Kältemaschine, der alten und neuen Rückkühler (Ventilatoranschlussleistung wäre interessant), sowie die Abmaße der alten und der neuen Rückkühler.

lG

Christopher BRANDL

Dear Mr.Karl Wallner,

would you be so kind to install a trend analysis of the cooling unit(s) from tomorrow 2.4.2012 till to the 28.10.2012, this trend should include:

Date, supply temperature, return flow temperature, environment temperature, cooling unit energy consumption/level of the cooling unit, roof cooler level.

Further I need the technical data of the cooling unit, the old and the new roof cooler (fan power is interesting), the dimensions of the new and old roof coolers.

Best regards

Christopher BRANDL

Appendix 6

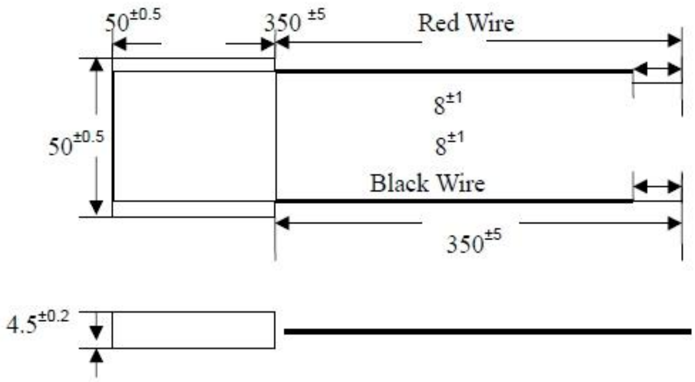
Experimental TEG

Peltier Element Type 12708: Specification / Data Sheet

I.Model

TEC1—12708 / RO8.5-76.0 (B/N193623)

II.Size



III. Character

Item	Description	Unit	Value	Condition
1	Allowed Use Room Temperature	T	<90 ℃	
2	Max Q Watt	Q_{max}	76 W	T_a =30℃
3	Max Temperature	ΔT_{max}	>65 K	T_a =30℃
4	Max Voltage	U_{max}	15.4 V	T_a =30℃
5	Max Temp. Current	I_{max}	8.5 A	T_a =30℃
6	Resistance	R	1.4-1.7 Ω	T_a =25℃
7	dH & dP		≤0.05 mm	
8	Wires	UL	0.5 mm	

Remarks: Resistance will be changed depends on the room temp , every room temp drop or rise 1℃, resistance value will be increased or decreased 0.015 Ω.

V2.0 rew. HM.
OCT 08

Datasheet of the experimental TEG, Conrad (2012)

Appendix 7

Survey Questions

1. First some question to alternative energy sources to check your information level about the issue.

1.1 Which alternative power sources do you know?
o Solar heating
o Photovoltaic
o Solar cooling
o Wind power
o Wave power
o Geothermal
o Use waste heat of a machine e.g. out of a production process
o other energy forms:

1.2 Which alternative power sources do you use(d), planned or installed:

o Solar heating
o Photovoltaic
o Solar cooling
o Wind power
o Wave power
o Geothermal
o Use waste heat of a machine e.g. out of a production process
o Other energy forms:

2. An average roof cooler (cooling machine ~ 600kW cooling power) gives up of about in average 150kWh on waste heat to the environment.

2.1 To you know that relative high amounts of waste heat is radiated to the environment by a cooling device o yes o no

2.2 How can you imagine do use the waste heat to increase the overall performance of a cooling device?

o Heating purposes for the building heat system
o Water heating (warm water, pool heating etc.)
o Generate electrical power with that waste heat
o Produce process heat
o An other energy form, which:

3. Some questions to a thermoelectric element.

3.1 To you know the „Seebeck effect"? o yes o no

3.2 To you know the working principle of a „Thermoelectric generator" o yes o no

3.3 Can you tell us a practical example of a TEG:

4. With a thermoelectric generate it is might be possible to generate from the waste heat of a roof cooler from a cooling machine electrical energy.
At the moment the efficiency of a TEG is ~4%, so that an amount of energy which can be additional produced is of about 80W/m².

4.1 Can you imagine to install the above described system in your facility with the above parameters o yes o no

4.2. If you say no in the above question, at which efficiency and energy can you imagine that it make senses to build it in such a system:

>=6%, 120W/m² o yes o no
>=8%, 160W/m² o yes o no
>=10%, 200W/m² o yes o no
>=20%, 400W/m o yes o no

4.3. On a scale between 1 and 5 (1... good potential, 3… average potential, 5… no potential) do you see a future potential of a system with 4% efficiency, based on now existing BiTe TEG´s?

o o o o o
1 2 3 4 5

4.4. On a scale between 1 and 5 (1... good potential, 3… average potential, 5… no potential) do you see a future potential of a system with >10% efficiency, based on actual researched materials?

o o o o o
1 2 3 4 5

4.5. Please tell us your opinion about the advantages of a combination of a TEG and a roof cooler

4.6. Please tell us your opinion about the disadvantages of a combination of a TEG and a roof cooler

Survey will goes to the following persons:
Dr.Helmut MOSER, generaldirector of the Austrian federal ministry of education and art
Ing.Martin BRUNNER, consulting engineer, ITGA Austria
Ing.Michael WALLNER, MSc , consulting engineer, Hypercube consulting
Ing. Harald LAUER, consulting engineer, IHL Consulting
Karl JANDRASITS, company owner and consulting engineer, KJW FM consulting
Ing. Stephan PFNEISL, consulting engineer, ITGA Austria
Ing. Gerhard WEISSKIRCHNER, facility manager, Immosolution Austria
Thomas WEBER, facility manager, Facility Management University of Vienna
Ing.Karl WALLNER, facility manager, YIT Austria
ass.Prof. Dr. Gert BACHMANN, Institute of ecology, chairman of the building council of the university of Vienna
Petra KOPER, facility manager, Facility Management University of Vienna
Ing.Christian HÜTTER, facility manager, Facility Management University of business and economics, Vienna