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Heating and Cooling with Solar Powered Peltier Elements

- The next generation of sustainable heat pumps?

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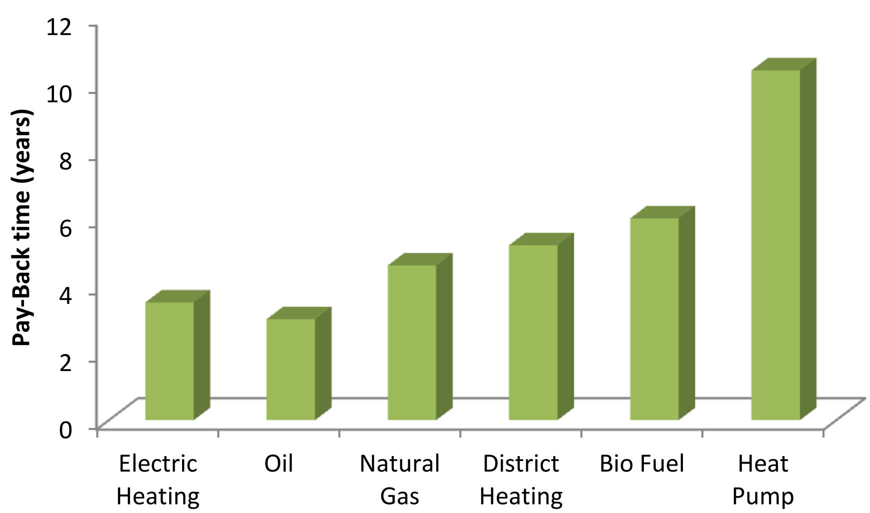
Abstract

The purpose of this project has been to investigate the possibility of heating and cooling air by connecting Peltier Elements to a PV panel. The idea was initiated by Energiteknik i Teckomatorp AB, a company that provides heat pumps and coolers to small scale businesses and private customers. The “climate panel” developed is to be used as a compliment to an existing heating system in order to pre-heat and pre-cool the air coming into the house. By decreasing the heating demand in winter and cooling demand in summer the panel could contribute to lowering the annual energy need and thereby save money. The aim of this project has been to investigate the potential for such a panel, and to perform an economic evaluation in comparison to common Swedish heating systems.

The result presented in this report is based on theoretical and practical simulations. A prototype design has been developed along with the company and tested in their workshop. The results showed that the panel has an annual energy output of 1 300 kWh, which corresponds to 9% of the heating and 5% of the total energy need for a “normal” Swedish house. The economic viability of the panel depend on which heating system it is used along with, and the pay-back time vary between 3-10 years. There are many uncertainties connected to the theoretical model and the practical results and further testing is needed to fully evaluate the system. The conclusion is that there is great potential in developing this product, and that it can be used as a complement to an existing heating system to save both energy and money. Using solar energy to boost the heat production of a building is a sustainable way to reduce the environmental impact and cut the costs, which is why the climate panel should be developed further.



Foreword

This report is the final product of a Master Thesis Project performed at Energiteknik i Teckomatorp AB, in cooperation with the Division of Efficient Energy Systems at Lund University, Faculty of Engineering. The project duration has been 20 weeks, which corresponds to 30 hp. It concludes the Masters Degree in Energy System at the Environmental Engineering Program of five years, 300 hp.

Acknowledgements

I would like to thank my supervisor Patrick Lauenburg at the Division of Efficient Energy Systems for all the help and encouragement I have received during this project. Thanks to Mikael Joó at Energiteknik for initializing this project and given me the chance to use the company's resources. Thumbs up to all the employees at Energiteknik for helping me out in the workshop and taking cover when I put the equipment on fire. I send my best wishes to Per Buch, whom without I would not have found the motivation to keep going as things went wrong and equipment broke down. Without the organization Miljöbron I would never have come across this project or the company to begin with, so lastly I thank Helena Ensgård for believing I was the right person for the job.

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1. Introduction

Sweden is a country with cold climate and a great need for heating. 38% of the total end use is consumed by the building sector and 60% of the energy is used for heating and hot water production (Energimyndigheten, 2013). Since heat is a low quality energy source it is important to create an efficient energy system with low losses. Sweden has a well developed district heating network and most of the inner city buildings are provided by district heating. Amongst free standing houses there is a greater variety of heating systems, but due to a history of low electricity prices electric heating is still the most common. In recent years there has been a trend of switching to more efficient systems, such as heat pumps and bio fuel boilers. It is also becoming more common with small scale energy production using renewable resources. Installing solar panels for electricity or hot water production is becoming more economically viable as the costs are cut, and there is a lot of research on how to better implement such systems into the building structure. The solar heating systems available today are mainly used for hot water production, but there is also a potential for developing solar driven heat pumps. Solar cells tend to give a higher output when the temperature is kept low, and there are systems available today that use either air or water to cool the panel (Tonui J.K Tripanagnostopulos Y, 2006). The efficiency of such systems could further be increased if the heat removed from the panel is made useful, for example by heating a house. This reasoning is the foundation on which the idea for this project is built. The objective is to develop a heating system powered by solar energy, which could be used as a complement to an existing heating system to lower the annual cost of energy.

This project was initiated by Mikael Joó, CEO of Energiteknik AB in Teckomatorp, along with solar energy consultant Per Buch. They came up with the idea of combining solar cells with Peltier elements to create a solar driven air-to-air heat pump, that could be used as a complement to an existing heating system. There are already products available at the Swedish market where solar cells are used to create a flow of hot air. Such panels are used as a passive solution in summer houses to induce air circulation inside the house during winter. By using the electricity from a solar panel to power Peltier elements, the company strives to develop a product that can heat and cool air. Peltier elements are small devices which, when powered by a direct current, gets a hot and a cold side (Manella G.A et al, 2013). If the direction of the current in changed the hot and cold side swaps places. This property makes the elements favorable to use in this solar driven heat pump. By swapping direction of the current the air can be either heated or cooled, which makes it possible to use the product as an all year solution. In summer the system can be used as an air conditioner and in winter as a heat pump. The overall output is not expected to be enough to provide heating for a whole house, and the Peltier elements will only be active as the sun shines. Therefore this product is planned to be used as a complement to an existing heating system only, alternatively as a separate solution for summer houses. The purpose of this project is to determine whether it is possible to design such a product and evaluate its potential.

1.1 Description of the company

Energiteknik i Teckomatorp is a small company, which have worked with heating and cooling systems for almost 40 years. The company has five departments: Cooling Services, Cooling

Installation, Production of Refrigeration Parts, Heat Pumps and Flat Plate Heat Exchangers. Energiteknik has developed an exhaust air heat pump which is produced at the facility in Teckomatorp. The properties and function of the heat pump, ETK5000/ETK6500 is displayed in the attached product sheet (attachment 3). The system recycles the energy of the indoor air, by producing hot water, before it leaves the house through the ventilation system. The heat pump creates an under-pressure within the house that causes outdoor air to be sucked in. There is no pre-heating or pre-cooling of the outdoor air before it enters the house. In winter energy needs to be spent on keeping the indoor temperature constant as cold air is taken in, and in summer the house risks to reach an uncomfortably high temperature if the outside temperature is above the temperature inside the house. If the "climate panel" with the solar powered Peltier elements was to be developed it could be used to pre-heat and pre-cool the air entering the house and decrease the annual energy need. The drive force for the company is therefore to offer this product as a complement to the ETK5000 to make it more effective.

1.2 Objective

The objective of this project is to develop a prototype of an air-to-air heat pump, where Peltier elements are built into a PV panel for pre-heating and pre-cooling of air, and evaluate it from an economic perspective.

1.3 Question formulation

- **Can Peltier elements be used in combination with PV cells to achieve an acceptable level of pre-heating/pre-cooling of incoming ventilation air?**
  - If so, can it be done to a reasonable cost?

  To answer this overall question the following sub-questions have been put up:
- What are Peltier elements and how do they work?
- Have Peltier elements been used previously for the purpose of heating or cooling air?
- Are there other studies where Peltier elements have been connected to PV cells, and what was the outcome?
- Can the system be described by a theoretical model?
- What type of Peltier elements are available at the Swedish market and how can these be used to maximize the output?
- How should the prototype be designed to fulfill the requirements?
- What temperature can be reached in heating and cooling mode at the prototype if connected to a PV panel?
- How far off are the practical results from the theoretical benchmark?
- What is the yearly energy output of the prototype?
- Is it economically viable to use the product designed as a complement to existing heat pump systems?
- How should the product be developed to improve the economic gain?

1.4 Method

The question formulation is intended to be answered by:

- Performing a literature study to provide necessary information regarding:
  - Peltier elements and their function
  - PV cells and their function
  - Previously performed experiments regarding heating and cooling of air using Peltier elements and/or PV cells
- Creating a theoretical model describing the system at hand, which can be used to perform simulations of the system in Microsoft Excel
- Coming up with a design for a prototype which can be built at the company workshop
- Performing relevant practical tests on the prototype to investigate its function
- Comparing the theoretical and practical results to draw conclusions regarding the potential of the prototype
- Estimating the annual energy output from the prototype and compare it the energy need of a "normal" Swedish house
- Evaluating the product's economical viability by comparing it to the most common heating systems

1.5 Report structure

This report is divided into nine parts:

1. **Introduction** – introduces the reader to the problem at hand and the purpose of the project
2. **Background** – provides information on the function of Peltier elements and PV cells and how they can be used to heat and cool air
3. **Previously Performed Experiments** – bring up experiments where Peltier elements and PV cells have been used for similar applications and summarize the result of these
4. **Prototype Design and Theoretical Model** – presents the input parameters, the theoretical model used for computer simulations and the design of the prototype
5. **Simulations** – presents the result of the theoretical simulations and provide a benchmark for the experimental testing
6. **Experimental Testing** – presents the result of the practical tests performed on the prototype
7. **Analysis**
   –contains an estimation of the annual energy output from the prototype
   – evaluates the economic viability of the product compared to commonly used heating systems in Sweden
8. **Discussion and evaluation**
   - evaluates the result presented in the analysis and outlines the potential of the product
   - provides information regarding weak parts of the model and experiments along with suggestions of improvements
   - presents suggestions on how to move on with the project and develop the product
9. **Conclusion** – provides a final conclusion regarding the function and economic viability of the product and determines if the project is worth continuing or not

1.6 System boundaries

The system studied in this project consist of different levels, displayed in figure 1. The overall system is the house and the annual energy need (blue). The sub level is the heating system, which is complimented by the climate panel (purple). The panel itself consist of two parts – the solar cells (orange) and the Peltier elements (green). The output of the PV cells is depending on a number of factors, such as solar irradiance and inclination of the panel, whereas the function of the Peltier elements depend on incoming current and material. These two sub-systems will be studied separately, both theoretically and practically, and the result added together to give a picture of the yearly energy output of the entire panel. The final evaluation of the system will be performed from an economic perspective comparing the climate panel to the heating system of the house (red).

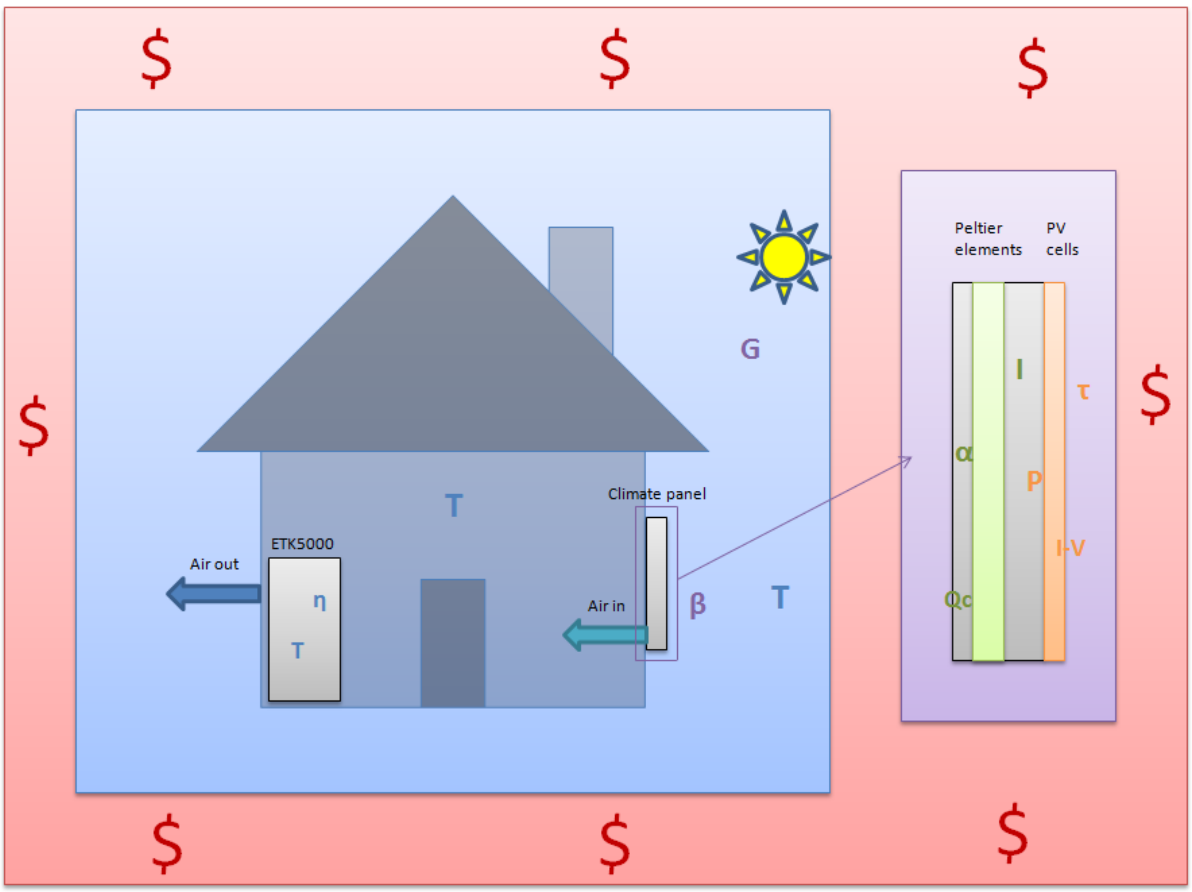

Figure 1. Levels of the system. The overall system is the house and the indoor climate which is connected to the heating system. The sub-system is the climate panel which consist of two parts – the Peltier elements and the PV cells. All parts are dependent on a number of variables and the overall system is evaluated from an economic perspective.

This project has been structured into four parts, displayed by different colors in figure 1. Due to lack of time all parts have not been studied as thoroughly, and the main focus has been to investigate the value of using Peltier elements to complement the PV panel. The four areas of the project are:

1. **Exiting heating system (blue)** - The yearly energy consumption of the building is depending on the desired indoor temperature, the efficiency of the heating system and the outdoor temperature. The goal when developing the panel is to increase the temperature of the incoming air in winter and decrease it in summer. The function of the heating system is therefore of no particular interest in this project. Information regarding the annual energy need of a "normal" Swedish house and required air flow rates are gathered from the Swedish Energy Board and the Building Administration Office.
2. **PV panel (orange)** – The company provides two types of PV panels, one thin film panel and one monocrystalline panel, and the properties of these panels are given by the product information sheets. An investigation of how much the temperature of the air stream can be increased by cooling the PV cells will be performed. Apart from this no further studies have been done on the PV panels and optimum conditions have been assumed.
3. **Peltier elements (green)** – Sine Peltier elements have not been used for this particular application before the main focus of this project has been to investigate their function and usefulness for air heating and cooling. A major part of the background concerns the function and application of Peltier elements and most of the theoretical and practical simulations have been performed on these devices.
4. **Economic evaluation (red)** – The result of the investigations on the PV panel and the Peltier elements will be added together to estimate the annual energy output from the climate panel. This is then compared to the need of the existing heating system and the economical gain for combination with different systems is estimated. The cost of producing the panel is weighed against the fuel cost for different systems and the pay-back time for different combinations is calculated. The overall conclusion of the value of the investment is based on the pay-back time.

1.7 Explanation of words, units and expression used in this report

There are many scientific words and expressions used in this report that may be unfamiliar to the reader. Different sources also use different expression and the vocabulary used here may not agree with that of other reports. To make the reading and understanding easier some of the most frequently used expressions and shortenings are explained in this chapter.

- SI units have been used for all calculations
- Temperatures are presented in Centigrade
- **TE** is short for **thermoelectric**
- Each **Peltier element** is referred to as a **thermoelectric module**, TE module or simply module
- **PV** stands for **photovoltaic**, PV cells are the same things as solar cells
- PV panel referrers to the panel with monocrystalline silicon cells used in this project, which is sometimes also referred to as solar panel
- Ambient temperature is that of the surrounding
  - when referring to the indoor temperature this is set to 20°C
  - when referred to in general terms it is the temperature of the environment in which the experimental tests were performed

- The product developed is referred to as the prototype, which means the prototype developed in built in the workshop, as well as the climate panel, meaning the entire panel including both the PV cells and the Peltier wall
- When estimating financial savings SEK is used which stand for Svensk Krona. US$ 1 is roughly 7 SEK

2. Theory and background

2.1 Basic concept of energy and power

All work with energy is founded in the *First Law of Thermodynamics,* also known as the Law of Conservation of Energy. It states that "The total energy of an isolated system is constant; energy can be transformed from one form to another but can neither be created nor destroyed." The word energy comes from the Greek word *ergon* which means *work* or *force* (Reistad N. Stenström K. , 2010). In other words energy can be seen as a storage of work.

Work divided by time, or work performed per time unit is called power, P. Power has the unit 1 J/s or 1 W and is defined as:

$$P \equiv \frac{dW}{dt} \quad \text{Equation 1}$$

Electric energy is commonly expressed as Wh or kWh. These units are mostly used to expresses the energy needed to use a device with a certain electric power for an hour. It is, however, important not to confuse the units. kWh is an expression for energy, not power. Energy expressed in Joules can be transformed to kWh through the following equation:

$$1kWh = 1 * 10^3\,J * 60 * 60\frac{s}{h} = 10^3 J * 3600\frac{s}{h} = 3.6\ MJ \rightarrow \mathbf{1MJ} = \frac{\mathbf{1}}{\mathbf{3.6}}\mathbf{kWh} \quad \text{Equation 2}$$

Heat machines and heat pumps

Heat machines uses heat to perform mechanical work. The heat is taken from a reservoir with a hot temperature, T_H, and transferred to a reservoir with a cold temperature, T_C. As the heat, Q_H, is transferred from the hot to the cold reservoir mechanical work, W, is taken out and the remaining heat, Q_C, ends up in the cold reservoir (Reistad N. Stenström K. , 2010).

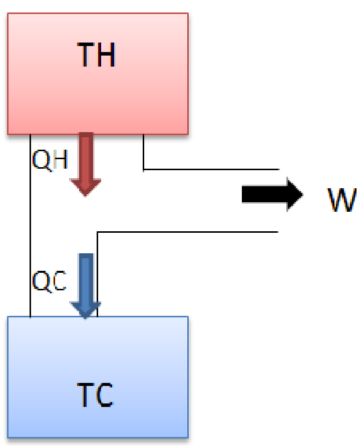

Figure 2. Function of a heat machine.

$$W = Q_H - Q_C \text{ Equation 3}$$

The thermal efficiency of the system is defined as the ratio between the work, W, and the energy content in the hot reservoir, Q_H, which can be expressed as:

$$e = \frac{W}{Q_H} = \frac{Q_C + Q_H}{Q_H} = 1 - \frac{Q_C}{Q_H} \text{ Equation 4}$$

The ideal thermodynamic efficiency is that of a Carnot machine, which has a reversible process. This is defined as the **Carnot efficiency**:

$$\eta = 1 - \frac{T_C}{T_H} \text{ Equation 5}$$

The Carnot efficiency is the maximum possible efficiency of a heat machine with a temperature difference of T_H-T_c K.

If the process of the heat machine is reversed, so that mechanical work is added, the heat flow will be going the opposite direction (from cold to hot). This machine is called a heat pump and is described in figure 3.

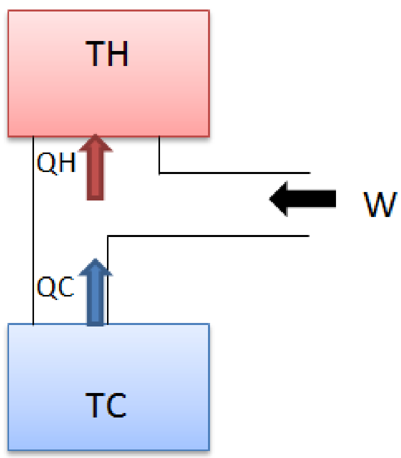

Figure 3. Function of a heat pump.

Heat pumps are commonly used for heating buildings and the efficiency is called **heat factor**. The heat factor is defined as:

$$e = \frac{Q_H}{W} = \frac{T_H}{T_H - T_C} \text{ Equation 6}$$

If the machine is instead used to produce cold from heat it is called cooling machine and the **cool factor** is defined as:

$$e = \frac{Q_C}{W} = \frac{T_c}{T_H - T_C} \text{ Equation 7}$$

Both the heat and cool factor has to be larger than 1 or there is no point of using the machine.

2.2 Solid State Physics

Semiconductors

In electronics, solids are classified into three basic groups; conductors, insulators and semiconductors. The classification is based on the material's ability to conduct (move) electrons, hence transfer an electric current (Kumar S. et al , 2011). Conductors are materials, mostly metals, with loosely bound electrons, which move around during the influence of an electric potential. Insulators have strongly bound electrons and the influence of an electric current has no effect on the material. Therefore they do not transfer electricity. Semiconductors are materials that are neither good conductors of electricity nor good isolators, for example Germanium and Silicon (Gustafsson A, 2011). The symptomatic property of semiconductors is that when mixed with an impurity the resistivity decreases, or in other words the ability to transfer an electricity increases.

An electric current is electrons flowing through the material and the properties of semiconductors can be explained by studying their atom structure. The atoms of the material are bound together with covalent bonds forming a crystalline structure (Gustafsson A, 2011). The bonds consist of a pair of electrons shared between two atoms to a stable electronic configuration. Therefore there are no free electrons within the material, which makes it a bad conductor. If an impurity is added to the material the electron structure is changed, a process called **doping**. The *Bond model* explains the electron movement within the crystal lattice of a semiconductor (Wenham S. R et al, 2012). Silicon, for example, is placed in group four of the Periodic table, meaning it has 4 electrons in its outer shell. In order to fill the outer shell and become stable it forms covalent bonds with its neighboring electrons. At low temperatures the bonds are intact and silicon behaves as an insulator. At high temperatures some of the bonds are broken and electrons from broken bonds can move around. Electrons from neighboring bonds can also move into and fill the holes created. As this happens the material works as a conductor of an electric current.

The electrons in a covalent bond have energies corresponding to those in the valence band (Wenham S. R et al, 2012). A certain amount of energy is needed to release an electron from its covalent bond to the conducting bond where it can conduct a current, called the *bandgap*. The minimum energy required to release the electron corresponds to the breaking bond. This energy can be provided by light or by adding heat.

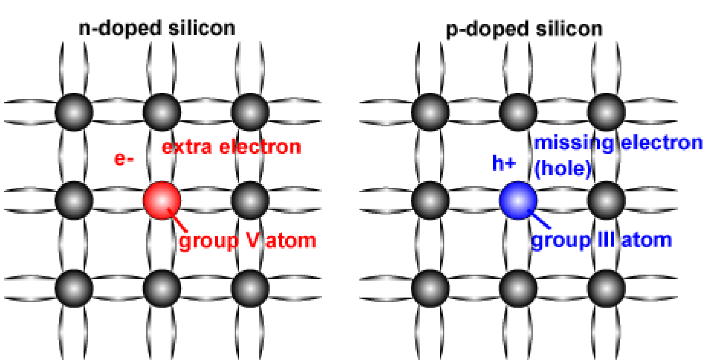

Figure 4. Lattice structure of silicon. If a material is added with an additional electron the silicon becomes n-doped (left), and if a material is added which lacks an electron it becomes p-doped (right). (PV education, 2014)

Doping

The balance of electrons and holes in a semiconductor can be shifted by doping the material with an impurity (Wenham S. R et al, 2012). Atoms with more of less valence electrons are then added to the lattice structure adding extra electrons or holes. Atoms with more valence electrons cause an excess of electrons in the material and the mixture is therefore called a negative-type, or n-type, semiconductor. If atoms are mixed in which have less valence electrons an excess of holes is created and this mixture is called positive-type, or p-type.

Silicon is commonly doped with Arsenic that has five valence electrons, leaving one outside the covalent bonding (Gustafsson A, 2011). The additional electron can move around within the material creating an electric current. The silicon-arsenic mixture is an n-type semiconductor. If instead an element is added that has three valence electrons, such as Boron, there will be a lack of electrons in the mixture creating a hole that can move around. This sort of mixture is creates a p-type semiconductor. A pair consisting of one n-type and one p-type semiconductor can carry an electric current and is used as building blocks for most electronic devices.

Thermoelectric devices

A Peltier element is a thermoelectric cooler, or TEC, which is simply a small heat pump. In 1821 J.T Seebeck discovered that two dissimilar metals connected at two different junctions create a micro voltage between them if held at two different temperatures (Tillmann Steinbrecher, 2010). If two wires are connected, for example iron and copper, and the other ends applied to the terminals of a galvanometer a voltage can be recorded if the junction between the wires is heated. The wires are called a thermocouple (Goldsmid H.J, 2010). J. Peltier realised, in 1834, that the inverse effect is possible as well. If a voltage is applied to a thermocouple a temperature difference will be initiated between the junctions. This is known as the Peltier effect (Tillmann Steinbrecher, 2010). A heating or cooling effect of the junction is created depending on the direction of the current. In 1855 the dependency between the temperature change and the current application was proven by W. Thomson (or Lord Kelvin) who, by applying thermodynamics, established the relationship between the coefficients that described the Peltier and Seebeck effects, which is now known as the Thomson effect (Goldsmid H.J, 2010). This effect described reversible heating or cooling when there is a temperature gradient along with an electric current. What happens is the electrons carrying out the current possess different energy depending on the material. When the current reaches the junction it is transferred from one material to another and the energy is altered, causing the junction to heat up or cool down. Likewise, if the junction is heated the electrons can pass from the material with lower energy to that with higher, giving rise to an electromagnetic force.

Seebeck voltage

In 1821 Seebeck detected that a needle of a magnet placed close to dissimilar metals connected electrically in series and thermally in parallel is deflected and exposed to a thermal gradient (Bell Lon E. ,2008). This discovery is the basis for thermoelectric power generation. If different temperatures are applied to a semi-conductive pair an electrical current will be produced. The voltage potential created by the temperature difference drives the flow of electrons. This is called the Seebeck voltage. Good electrical conductors are needed in order to make the process effective. The thermal conductivity however needs to be poor, or the there will be a backflow of heat which reduces the temperature difference between the junctions. As the moving electrons produce heat (Joule heating) and increased electrical current will reduce the Seebeck effect. Therefore it is necessary to optimize the properties of the semi-conductors. The best performance is found to be achieved by using heavily doped semi-conductors such as Bismuth-Telluride or Silicon-Germanium. A base material that can be both n- and p-doped is preferable to use so that the same material can be used on both sides.

Peltier effect

A Peltier element works inversely to the Seebeck device and consist of a pair semi-conductors which, when imposed by a direct current, generate a heat flow and a temperature difference between the two plates (Manella G.A et al, 2013). This effect, the Peltier effect can be expressed as:

$$\dot{Q} = \alpha T I \quad \text{Equation 8}$$

Q is the heat power, α the Seebeck coefficient, T the temperature and I the current. Peltier cells are used for temperature control in a lot of different fields, such as medical cooling kits, car heating devices, refrigerators and computers. Thermoelectric modules typically consist of an array of Bismuth and Telluride pellets configured so that they are electrically connected in series but thermally parallel connected (Cosnier M. et al, 2008). When a direct current is applied one side absorbs heat (cold side) and the other side supplies heat (hot side). As an electric current is added to the Peltier element the unbound electrons in the n-type material are moving in one direction and the “holes” in the p-type material move in the opposite direction. If a voltage is applied from p- to n-material electrons will move away from the junction in the n-type material and the “holes” will move away from the junction in the p-type material. The energy is “taken” from the junction area, which is cooled. On the opposite side the electrons and “holes” flow towards the junction heating it. A typical thermoelectric device consists of a number of cascaded thermoconductor pairs arranged so that all the junctions one side are heated and the junctions on the other side are cooled (Bell Lon E. ,2008). This way a temperature difference is created between both sides of the module as displayed in figure 5.

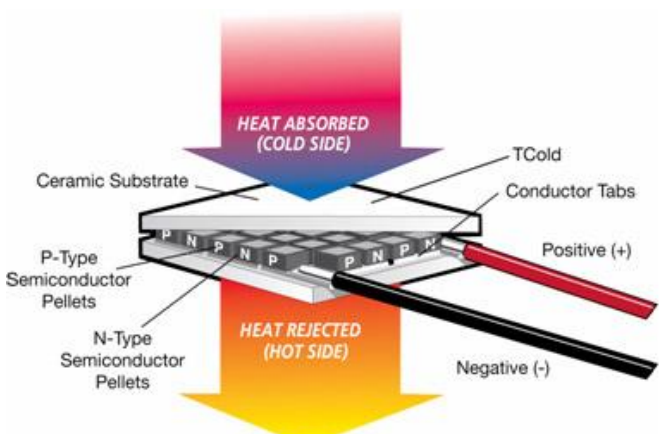

Figure 5. Structure and function of a Peltier element. (Tellurex, 2011)

Relation between the Seebeck and Peltier effect

If two isotropic semiconductors, A and B, are joined together and a temperature difference, ΔT, is applied at the junction whereas the two ends are kept at the same temperature a voltage potential, V, will appear (Goldsmid H.J, 2010). The differential Seebeck coefficient, α_{AB}, is defined as:

$$\alpha_{AB} = \frac{V}{\Delta T} \text{ Equation 9}$$

The Seebeck coefficient is said to be positive if the electromotive force drives the current through the conductor A from the hot to the cold junction.

If the circuit is connected the Peltier coefficient, π_{AB}, is defined as positive if the current enters A is heated and the junction at which the current leaves A is cooled. The Peltier coefficient is equal to the ratio of heating/cooling rate, q, and the electric current, I, at each junction:

$$\pi_{AB} = \frac{q}{I} \text{ Equation 10}$$

The Peltier coefficient can be expressed in terms of the Seebeck coefficient as follows:

$$\pi_{AB} = \alpha_{AB} * T \text{ Equation 11}$$

The Kelvin relation connects the Seebeck coefficient with the Thomson coefficient of the two conductors. The Thomson coefficient ,τ, is defined as " the rate heating per unit length that results from the passage of unit current along the conductor in which there is unit temperature gradient". Mathematically this is expressed as:

$$\tau_A - \tau_B = T * \frac{d\alpha_{AB}}{dT} \text{ Equation 12}$$

Thermoelectric heat pumps and coolers

Thermoelectric devices are usually made up by a number of thermocouples connected electrically in series and thermally in parallel. This enables the usage of a power source that delivers a manageable current and an acceptable voltage drop (Goldsmid H.J, 2010). The theory of thermoelectric refrigeration is based on Altenkirch's model using a single thermocouple of two elements with a non-resistive junction between them (Goldsmid H.J Douglas R.W, 1954). The other ends of the elements are assumed to be connected to a battery and kept at a constant temperature and have a uniform cross section. The maximum possible temperature difference to be reached by a single thermocouple was tested by Altenkirch in 1911, along with the coefficient of performance for temperature differences less than that.

The properties of importance are for the thermoelectric elements are:

- Thermoelectric power
- Thermal conductivity
- Electrical conductivity
- Length
- Cross-section area

There is assumed to be no thermal resistance between the thermocouple and the heat source/sink. The heat flow takes place within the thermocouple, hence the thermal radiation losses to the environment are negligible. The quantity of interest and importance for a refrigerator is the coefficient of performance, or COP, which is defined as the ratio between the heat extracted and the electrical energy added (Goldsmid H.J, 2010). The ideal COP value is the Carnot efficiency, which can be reached only if there were no losses due to heat conduction or expenditure electrical energy. The ideal efficiency is given by:

$$\eta_C = \frac{T_C}{T_H - T_C} \text{ Equation 13}$$

T is the absolute temperature of the source, H, and the sink, C.

When a current flows through a thermocouple there is Peltier cooling at the source. The cooling is opposed by the heat conduction rate and the Joule heating. Considering these effects COP can be expressed as:

$$COP = \frac{(\alpha_p - \alpha_n) * I * T_C - (T_H - T_c) * (K_p + K_n) - I^2 (R_p + R_n)/2}{(\alpha_p - \alpha_n) * I * (T_H - T_c) + I^2 (R_p + R_n)} \text{ Equation 14}$$

α_p and α_n are the Seebeck coefficient for the two conductors, K_p and K_n are the thermal conductances and R_p and R_n are the thermal resistances.

As the equation describes the COP depends on the current , I. The Peltier cooling increases linearly but the Joule heating depends on I^2 meaning there is a maximum cooling power that can be achieved before the Joule heating becomes too great. The maximum cooling is reached is twice as large as the Joule heating reaching the cold junction. The current, I_q, that yields the **maximum cooling power** is given by:

$$I_q = \frac{(\alpha_p - \alpha_n) * T_C}{(R_p + R_n)} \text{ Equation 15}$$

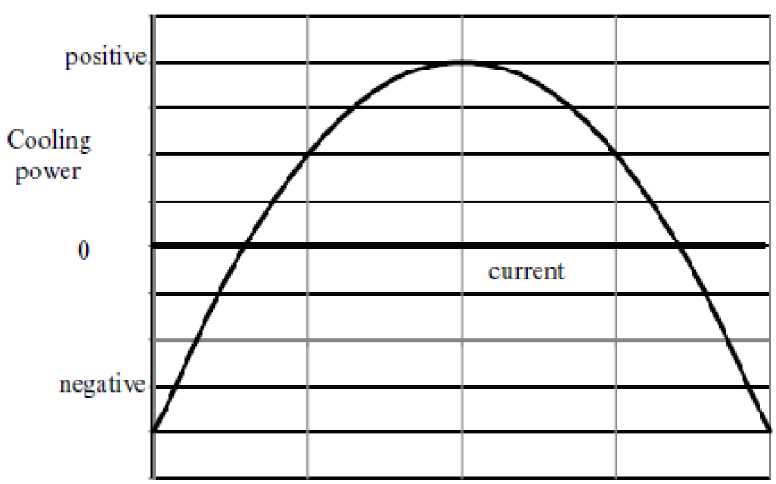

Figure 6. Cooling power of an electric cooler plotted against the current. The cooling power is negative until the Peltier effect becomes large enough to overcome the Joule heating (Goldsmid H.J, 2010).

The COP value for this current can be expressed as:

$$COP_{max-cool} = \frac{Z*\frac{T_C^2}{2}-(T_H-T_c)}{Z*T_H*T_c} \text{ Equation 16}$$

$$Z = \frac{(\alpha_p-\alpha_n)^2}{(K_p+K_n)*(R_p+R_n)} \quad \text{Equation 17}$$

Z is called the figure of merit and has the dimension of 1/T and it is more common to specify the ZT value at a given temperature.

The optimum current, I_{opt}, which gives the **maximum COP** value is given by:

$$I_{opt} = \frac{(\alpha_p-\alpha_n)*(T_H-T_c)}{(R_p+R_n)*\sqrt{1+ZT_m}-1} \text{ Equation 18}$$

T_m is the mean temperature and at this current the maximum COP can be determined by:

$$COP_{max} = \frac{T_C*\sqrt{1+ZT_m}-T_H/T_C}{(T_H-T_c)*\sqrt{1+ZT_m}+1} \text{ Equation 19}$$

Operating at the optimum COP is not the same as achieving the maximum cooling power, especially if the temperature difference is small. Therefore, from an economical point of view it may be viable operating at maximum COP when considering the usage of electrical energy but not the usage of thermoelectric material. Z can be optimized for any given pair of thermoelectric couples.

When the cooling power, and thus the COP value, turns to zero the **maximum temperature depression**, ΔT_{max}, is reached. This value can be determined by:

$$\Delta T_{max} = \frac{Z*T_C^2}{2} \text{ Equation 20}$$

That the performance of a thermocouple can be improved by increasing the Seebeck coefficients was proven by Altenkirch in 1911.The coefficients are improved by increasing the electrical conductivity of the materials while reducing the thermal conductivity. It was, however hard to achieve this at the time being. In the 1950's the semiconductors were introduced which made it possible to further develop how the coefficients should be optimized. A study published by Goldsmid and Douglas 1954 concludes that "It is apparent that the materials in the thermocouple should be prepared with thermoelectric powers between 200-300 m*V/°C" (Goldsmid H.J Douglas R.W, 1954). The semiconductors should be chosen with the highest ratio of carrier mobility to thermal conductivity, and the effective mass of the carriers should be as high as possible. The higher the atomic weight of the semiconductors the larger the ratio of carrier mobility becomes. Therefore the conclusion drawn by Goldsmid and Douglas is that semiconductors used for thermoelectric refrigeration should be those with the highest mean atomic weight, where this is consistent with a large effective mass of the carriers. Experiments carried out with Bi_2Te_3 as the p-type conductor and Bismuth as n-type conductor resulted in a temperature difference of almost 30°C, showing that thermoelectric refrigeration using semi-conductors is a possibility.

Thermoelectric refrigeration

When a current flows through a thermoelectric material it generates resistive heating. 50% of the heat goes to the cold end and 50% to the hot end of the thermoelectric device (Riffat S.B Ma X, 2004). The Joule heating is given by:

$$Q = \frac{2NI^2R}{g} \text{ Equation 21}$$

N is the number of thermocouples within the module and g is the cross section area divided by the thermoelectric element, called geometry factor.

A thermoelectric refrigerator, or TER, consist of thermoelectric components and uses the Peltier effect to remove heat. A DC current is applied to the two dissimilar components creating a temperature difference which is dependent on the Peltier cooling, Joule heating and heat convection. When analyzing a TER two factors need to be taken into account; heat rejection, Q_H, and heat absorption, Q_C. The rejection occurs at the hot junction and the absorption occurs on the cold side (Jugsujinda S. et al, 2011). The expressions for heat absorption, Q_C, and heat rejection, Q_H, are shown below:

$$Q_C = \alpha I T_C - \frac{I^2R}{2} - K(T_H - T_C) \text{ Equation 22}$$

$$Q_H = \alpha I T_H + \frac{I^2R}{2} - K(T_H - T_C) \text{ Equation 23}$$

Where α is the Seebeck coefficient, I the current, T_C the cold temperature, T_H the hot temperature, R the electrical resistance of the TEC material and K the thermal conductivity.

2.3 Solar cells

The photovoltaic effect was first discovered by Edmond Becquerel in 1839 who observed that certain materials produce an electric current when exposed to light (Wenham S. R et al, 2012). This effect is put to use in solar cells, or PV cells, which are manufactured from semiconductors. At low temperatures the semiconductors work as insulators, but when energy or heat is available they function as conductors instead. Most solar cells today are silicon based but there are other materials available as well. Semiconductors used for solar cells can be crystalline, multicrystalline, polycrystalline, microcrystalline or amorphous. The difference between these sorts are the size of the grains in the crystalline structure. Crystalline silicon has the optimum structure which exhibits predictable and uniform behaviour. However, it is the most expensive type of silicon and the sort most commonly used in commercial PV cells is multicrystalline silicon.

When light falls on a semiconductor photons with energy less than the bandgap energy passes through the material. The bandgap energy is the energy required to dislodge an electron from its covalent bond (U.S. Department of Energy, 2013 [1]). The photons with energy greater than the gap interact with the electrons in the covalent bonds creating electron-hole pairs creating an electric current. An electric current is induced by putting an n-type and a p-type semiconductor together forming a p-n junction. When the materials are joined the excess holes in the p-type material flows to the n-type material and electrons flow from the n-type to the p-type material. The flows are created by diffusion, which is a result of the carrier concentration gradient across the junction.

PV design and function

PV cells can be made from many semiconductor materials. The most common type today is made out of crystalline silicon, mostly polycrystalline silicon, which has a thickness of about 100-300 μm thick. There are also polycrystalline thin-film cells with thicknesses of 1-10 μm (U.S. Department of Energy, 2013 [2]). These can be manufactured in large area processes and be deposited on flexible substrate materials. Thin-film PV cells can also be constructed by other materials than silicon which absorb light in shorter distances. These materials can be for example Copper-Indium Gallium-Selene (CIGS), Cadmium-Telluride, or Copper-Indium. The thin-film cells can be placed on more flexible materials making them easier to integrate in building design.

An ordinary silicon based, homojunction solar cell if formed by joining a p-type conductor, usually Boron doped, with an n-type conductor, generally doped with Phosphorus (Wenham S. R et al, 2012). To maximize the power output the absorption must be maximized, which is done by maximizing the "collection" of carriers, or electron-hole pairs. Collected carries are those generating a finite current when there is no voltage applied, V=0. The closer the electron-hole generation is to the p-n junction the greater the chance of collection, and the collection is maximized if the electron-hole pairs are generated within a diffusion length of the junction. The relationship with the current and the voltage, the I-V characteristics, of the cell determined by:

$$I = I_L - I_0 * (e^{\frac{qV}{nkT}} - 1) \quad \text{Equation 24}$$

Where I_L is the light generated current and n is the ideality factor. The I-V curve for a specific PV module is generally given in the product information sheet. The curve shows the relationship between current and voltage for a specific power output or irradiance, which varies over the year.

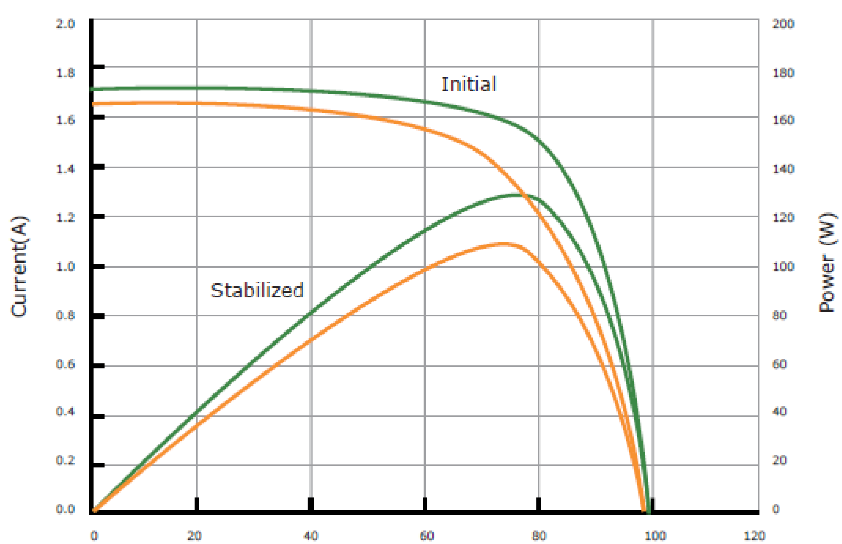

Figure 7. I-V curve for a 100 W thin film solar panel. (Ample Sun, 2014)

The limiting factors of the output current of a solar cell for a given irradiance are: short circuit current, $I_{sc,}$ (maximum current at zero voltage) and open circuit voltage, V_{oc} (maximum voltage at zero current). If V=0 $I_{sc}=I_L$ where I_{sc} is directly proportional to the available sunlight. The value of V_{oc} increases logarithmically with increased sunlight.

$$V_{oc} = -\frac{nkT}{q}\ln\left(\frac{I_L}{I_0}+1\right) \text{ Equation 25}$$

The maximum power point for a solar cell is the product of V_{mp} x I_{mp}. The maximum power output is given by:

$$V_{mp} = V_{oc-\frac{nkT}{q}\ln\left(\frac{V_{mp}}{\frac{nkT}{q}}+1\right)} \text{ Equation 26}$$

The fill factor, FF, is a measure of the junction quality and series resistance of a cell, which is defined as:

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \text{ Equation 27}$$

Which gives a maximum power of:

$$P_{mp} = V_{oc}I_{sc}FF \text{ Equation 28}$$

A high quality cell has a fill factor near unity, which is ideally a function of the open circuit voltage:

$$FF_0 = \frac{v_{oc}-\ln(v_{oc}+0.72)}{v_{oc}+1} \text{ Equation 29}$$

v_{oc} is defined as the normalized V_{oc}:

$$v_{oc} = \frac{V_{oc}}{nkT/q} \text{ Equation 30}$$

FF_0 can only be applied to ideal cases when there are no resistance losses .

Module structure

Solar cells are rarely used individually but are connected to form modules, which are building blocks for solar arrays. To be protected against moisture and other environmental aspects the cells are enclosed within modules. The module usually consist of an aluminium frame covered in a Teldar film (Elforsk, 2014). The cells are “glued” to the Tedlar with an elastic and transparent polymer, most often EVA (etylenvinylacelat)and covered in glass.

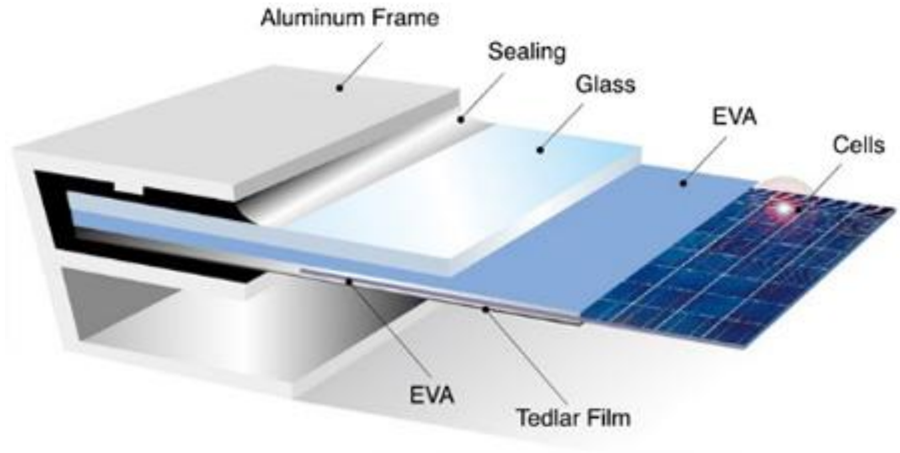

Figure 8. Structure of a PV module. (RITEK, 2014)

The electrical output of a PV cell depends on the semiconductor material and the design of the device. The maximum voltage of a single silicon cell is about 600 mV and cells are connected in order to produce the provide the appropriate electrical power (U.S. Department of Energy, 2013 [2]). The cells can be connected either in series or in parallel. A croup of series connected cells is called a string. The current output of a string is equal to the output of a single cell, but the voltage output is equal to the addition of the voltages of each cell. It is important to have well matched cells when connecting in series, or the whole string will produce as the lowest producing individual cell. If the cells instead are connected in parallel the current of the cell group is equal t the addition of the current from each cell. The voltage, however, remains equivalent to that of a single cell. Again it is important for the cells to be matched or the maximum voltage of the connection will be as low as that of the worst producing cell.

Improving PV efficiency with air cooling

Under laboratory conditions the maximum efficiency of ordinary PV cells achieved today is bout 24-25% (Wenham S. R et al, 2012). For commercial use, however, the efficiency of mono-crystalline solar cells is typically 13-19%. Commercial cells with an efficiency of above 20% should be expected in the coming years and improvement progresses. With an increased efficiency less PV cells are needed to for a given output, which both reduces cost and the area needed. There are several losses within the system that can be reduced to optimize it and improve the efficiency. Such are: optical losses, recombination losses, resistivity and shading losses.

When the operating temperature of the PV module increases the electrical efficiency goes down. Cooling the cells is a way of keeping the efficiency as high as possible. The cells can be cooled by a circulating fluid, air or water, on the back side or the front. The temperature of the fluid increases, recovering the lost heat is a way of using the energy more efficiently. Solar thermal collectors, or PV/Ts, are combined systems that recover heat as well as producing electricity (Tonui J.K Tripanagnostopulos Y, 2006). The systems are named according to the heat removal fluid used, PVT-Water or PVT-Air. Air cooled PV modules have been studied mainly for building integration where the panels are built into tilted roofs of facades. In these solutions the air gap between the module and the building fabric is used for circulating air, and the heated air stream can be used for thermal needs within the building. The air gap behaves like a natural draught and the air flow is driven by buoyancy (hot air rises). The naturally caused air movement is quite low, studies have shown air velocities of around 0.5 m/s. There are several designs for PV/T systems with different types of air channels. Fins are commonly used, but there are also designs with packed air flow passages and porous plates for unglazed collectors.

In a PVT-Air collector incident solar radiation is captured by the PV module and a fraction of it is transferred to the air flow. According to Florschuetz law the electrical efficiency of the module decrease linearly with the operating temperature.

$$\eta_{pv} = \eta_{ref}(1 - \beta(T_{pv} - T_{ref})) \quad \text{Equation 31}$$

η_{ref} is the reference efficiency at the reference temperature T_{ref} of 25°C, and β is the cell efficiency temperature coefficient. The electrical efficiency of the I-V circuit is determined through:

$$\eta_{pv} = \frac{P_{max}}{A_a * G} = \frac{I_{max} * V_{max}}{A_a * G} \quad \text{Equation 32}$$

P_{max} is the maximum power, A_a is the module area and G is the solar insolation.

The thermal efficiency is:

$$\eta_{th} = F_R * \tau * \alpha_a - F_R * \frac{U_L(T_{in} - T_a)}{G} \quad \text{Equation 33}$$

F_R is the heat removal factor, τ the transmissivity of the glass, α the absorptivity of the PV cells, U_L the overall heat loss coefficient, T_{in} the inlet temperature and T_a the ambient temperature. If introducing η_0 as the efficiency at $T_{in}=T_a$ the thermal efficiency can be written as:

$$\eta_{th} = \eta_0 - \frac{U \Delta T}{G} \quad , \quad U = F_R * U_L \quad , \quad \Delta T = T_{in} - T_a \quad \text{Equation 34}$$

The thermal efficiency can also be determined by using:

$$\eta_{th} = \frac{\dot{m} * C_p(T_{out} - T_{in})}{A_a * G} \quad \text{Equation 35}$$

Where m is the mass flow rate, Cp the specific heat capacity of air and T_{out} the air outlet temperature.

2.4 Energy usage in buildings and indoor comfort

In 2006 the Law of Energy Declaration (2006:985) was introduced in Sweden, with the purpose to promote an efficient energy usage and create a good indoor quality. The law states that an Energy Declaration needs to be established for new buildings and that the owner of an existing building need to make sure that one exists. The declaration needs to be put up by a certified “energy expert” and handed to the Swedish Building Administration (Boverket). The annual energy usage in new buildings can be determined using the following equation:

$$EP_{ref} = (E_{heating} * X_{age} * X_{manucipality} + E_{vv}) * X_{heat\ source} + E_{property} + E_{cooling} \quad \text{Equation 36}$$

The air flow is 0.35 l/s*m^2 and the reference is a house situated in Eskilstuna, free standing with two stories built 1975 and heated by district heating. $E_{heating}$ + E_{vv} for the reference building is 120 kWh/m^2 (BFS 2013:14). The X values are adjustment factors depending on type of building, location and heat source.

Regulations regarding indoor comfort, temperature and ventilation, are stated in the Swedish Environmental Code (SFS 1998:808). The recommendation air quality says that the air exchange rate should not fall below 0.5 room volumes per hour and that the outflow of air should be above 0.35 l/s*m^2 or 4 l/s*person (BFS 2013:14). The indoor temperature should not be lower than 18°C in living and working areas and above 20°C in service homes and schools. A summary of the regulations on indoor comfort can be found in the appendix, chapter 11.2.

3. Previously performed experiments

Thermoelectric small-space air conditioner

In an investigation carried out by Gillott et al in 2010 the operating conditions for a thermoelectric cooler, designed for small-scale space conditioning in buildings, was tested. The tests were performed in laboratory conditions and thermoelectric modules UT8-12-40-RTV made of Bismuth Telluride thermoelements were used (Gillott M. et al, 2010). The TE modules were sandwiched between two aluminium heat sinks. The unit consisted of 8 pieces of TE devices with the electrical connection in parallel of four strings of two modules in serial (2Sx4P). Eight fans, with a power of 3 W each, were placed on the hot side to remove the produced heat by forced convection. On the cold side the air was forced through the heat exchanger via a duct by using a blower. The work within an environmental chamber indicated that the TEC unit used could generate up to 220 W cooling with an operating COP of 0.46 when the input current to each single TEC was 4.8 A. When testing the unit in a small room it provided a temperature difference of 7°C between inlet and outlet. This experiment provides a good indication of the cooling power and temperature difference that can be achieved when using TE modules for air conditioning.

Active Building Envelope prototype

Another way of using TE modules for air conditioning is through Active Building Envelopes, or ABE's. These systems use PV cells transform solar energy into electrical energy which is used to power a TE heat pump system. Both systems are integrated into one enclosure surface and the system can operate on both heating and cooling mode depending on the direction of the current. ABE systems actively use solar energy to maintain a temperature gradient across a material surface, which is accomplished by compensating for the passive heat transfer through walls with heat transfer from the TE system (Xu X. Van Dessel S. , 2007). This has been tested out in several ways at the Renesselaer Polytechinic Institute in New York. Using PV cells connected to a TE heat pump system the heat flow across a surface can be controlled and the solution integrated in the building structure. The developed prototype consisted of eight TE modules mounted on two aluminum tubes placed on both sides of a window (Xu X. Van Dessel S. , 2007). An external heat sink, which either absorbed or dissipated heat was connected to the TE modules. The heat sink released heat into the air through natural convection. The aluminum tubes were filled with water and worked as a thermals bank for the system. PV panels with an area of 1 m^2 and a rated power output of 115 W and a voltage of 25 V DC was used. The model used was SW115 from SunWize and the panels were connected to a battery storing energy which can be used at night to provide a constant flow of electricity. Tests of the prototype showed that a temperature change of 2-6°C was possible to achieve with the system. The overall efficiency was 11% and the efficiency for cooling mode was around 5%, whereas the heating efficiency was 13%. As this numbers show the system was more effective for heating than cooling. Suggested improvements were to use more efficient PV cells and TE modules, reducing the electrical losses and increasing the heat dissipation to the sinks.

Pre-heating and pre-cooling of air for a two-story house

One of the experiments most relevant for the purpose of this report was carried out in the Alp regions of France with a climate somewhat similar to that in Sweden. The TE modules were used for pre-heating and pre-cooling of incoming air to a ventilation system and the modules were also directly coupled to the PV cells (Le Pierrés N. et al, 2008). The PV cells used for the experiment were polycrystalline of the model PW1250-24 V from Photowatt, and the TE modules of the model CP2-127-06 L by Melcor. The modules were located at the inter-phase of the incoming and outgoing counter-current ventilation air of a house. A solar irradiation of 800 W/m² was used as standard. The optimum irradiation decreased as the number of TE modules increased because the electrical resistance of the PV modules went up. Therefore the optimum number of TE modules varied over the year. The optimum number for the study was determined to eight modules. A numerical study was performed along with a case study. A simulation of one year showed that cooling only was needed in the summer months June-August. The switch from heating to cooling mode occurred at an ambient temperature of 22°C.

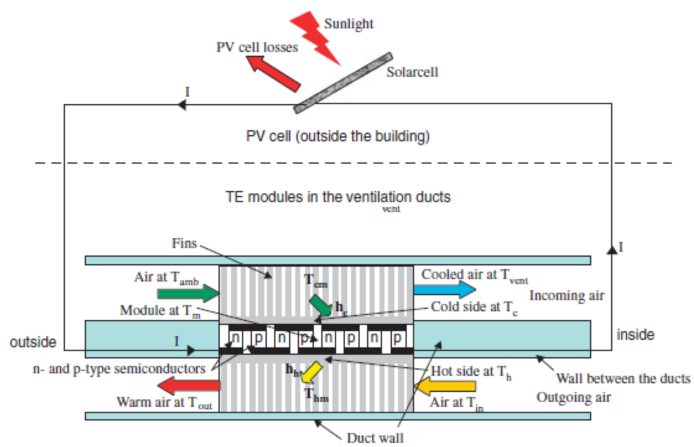

Figure 9. Graphical description of the system studied by Le Pierrés et al. (Le Pierrés N. et al, 2008)

The case study included a 120 m² house with two floors located in southern France. The air renewal rate was set to 0.5 exchanges per hour and the TE modules were assumed to produce an incoming temperature 5°C lower than the inside temperature. If the temperature indoor exceeded 30°C the air exchange rate went up to 1.5. Several scenarios were tested out and the overall result showed that to achieve an acceptable indoor temperature in summer 1 179 kWh per year was needed, with a maximum power to 1.8 kW. This was equivalent to 40 TE modules and a PV cell area of 11 m². This result is a good indicator that using solar powered TE modules for pre-heating and pre-cooling of air could be a good idea. The house used in the French study was roughly the same size as a house using the heat pump provided by Energiteknik, that is the base for this project.

Designing wall for air duct in PV panel

Compared to the experiments above the TE modules in the prototype developed by Energiteknik are to be integrated in the PV panel. In order to figure out the most effective way of creating an air flow through the panel with maximum heat transfer efficiency PV/T systems have been studied. An experiment for increasing the efficiency of PV/T modules with air cooling was carried out by Toniu et al who tested different air channel constructions (Tonui J.K Tripanagnostopulos Y. , 2006). Two types of air channels were tested out, one containing a TSM sheet to create a double-pass configuration and the other using fins at the back wall of the air duct. The reference is a typical single-pass air channel behind the PV module.

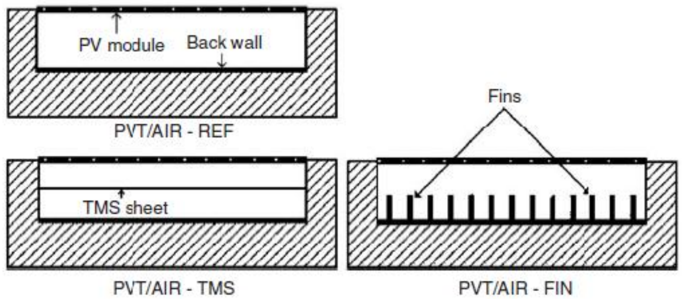

Figure 10. Cross section view of PTV-Air collector models, flow is perpendicular to the page.
(Tonui J.K Tripanagnostopulos Y. , 2006)

Two commercial pc-Si modules were used with an area of 0.4 m^2 and a rated power of 46 W. The air channel depth was 15 cm attached at the rear surface of the modules. The casing of the air channel was constructed from a thermal insulator with aluminum edges. The inlet and outlet vents were 5 cm in diameter, placed at top and bottom of the panel. The fins had a height and spacing difference of 4 cm. The system was mounted with a tilt angle of 40°C and the experiments was carried out with both forced air circulation using a pumps and with natural air circulation driven by buoyancy.

The results showed that the thermal efficiency increased with an increasing flow rate. The system using fins was proven to be most efficient in this case. The trend was the same for natural air flow. The TMS system proved to increase the thermal efficiency with 12% and the fins with 20%, for both forced air flow and natural air flow. The module temperature with no air circulation was measured to 55-75°C for an ambient temperature of 30°C at an insolation level of 700-800 W/m^2. With air circulation the module temperature varied between 45-65°C depending on the flow rate. Air circulation was proven to lower the module temperature with at least 5°C, which improved the electrical output. As it seems, using fins is the most effective way to achieve a large heat transfer. The results also showed that a large flow rate results in a lower temperature change of the air, and that it is possible to use natural convection only to create an air flow.

4. Prototype design and theoretical model

4.1 Design

The design of the climate panel has been inspired by existing panels for solar air heating. These panels consist of two parts, one black surface which heats up when the sun shines, and one small surface of PV cells. The electricity produced by the PV cells is used to run a circulation fan. Air is taken into the panel and heated up when passing the black surface. Hot dry air is then blown into the house by the fan. The purpose of this panel is to create air circulation within the house and keep the moisture level down, mainly in winter. The simple function is described in figure 11 below. According to manufacturer the panel shown can achieve a temperature increase of up to 30°C.

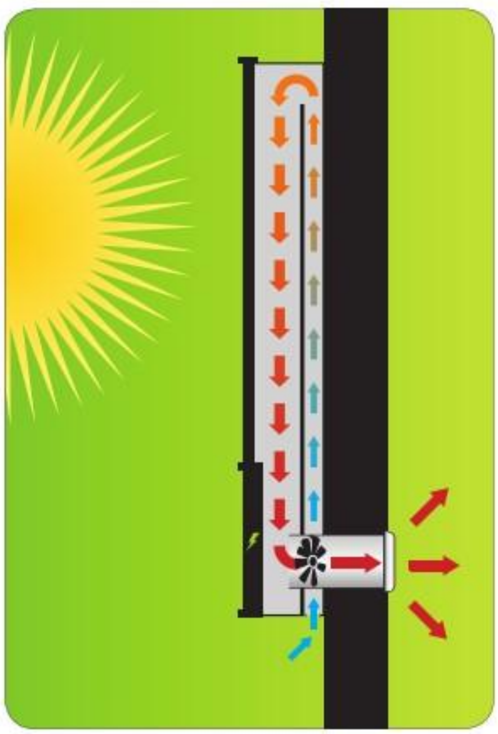

Figure 11. Function of solar thermal air panel (Scanheat, 2014)

The design of the climate panel is shown in figure 12 and 13 below. Instead of the black surface used in other products the entire panel is here covered in PV cells. The cells work best if cooled, and transporting heat away from the cells by the incoming air stream has therefore been one of the objectives when developing the product. After passing the cells the air stream is further heated by Peltier elements in winter time, and the total heating power is that which is produced by the PV cells and the Peltier elements combined (figure 12). In summer time the air taken into the house should be cooled down instead of heated and the air stream cooling down the PV cells is therefore exits the panel outside, after passing the hot side of the Peltier elements. The air flow entering the house passes the Peltier elements on the cool side to lower the temperature (figure 13).

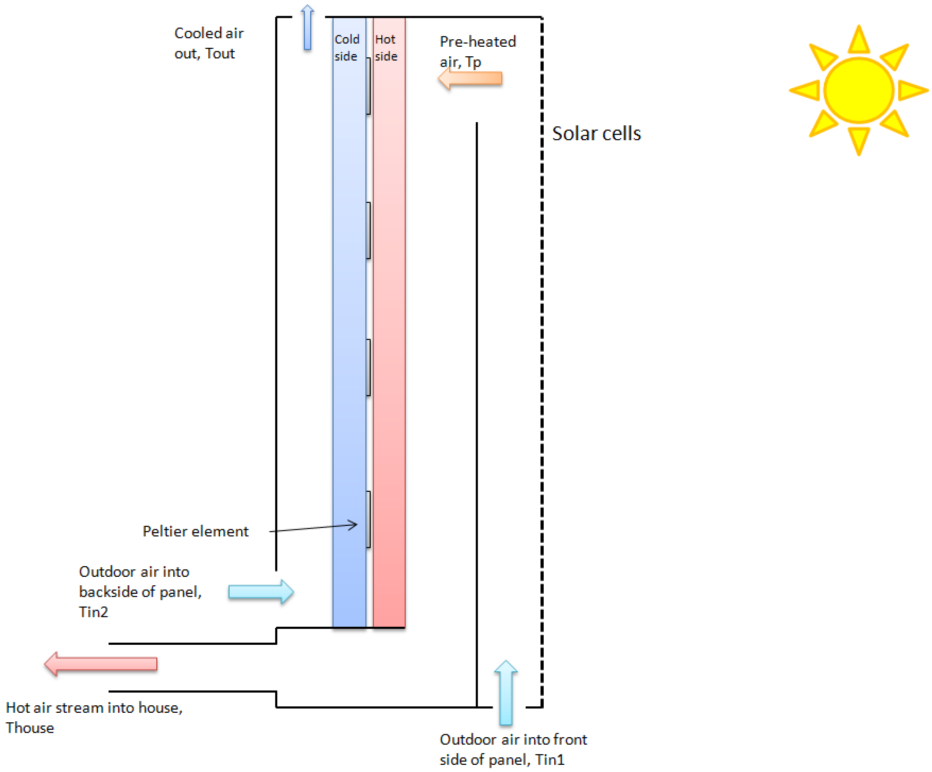

Figure 12. Heating mode. Used when the outdoor temperature is below 20°C.

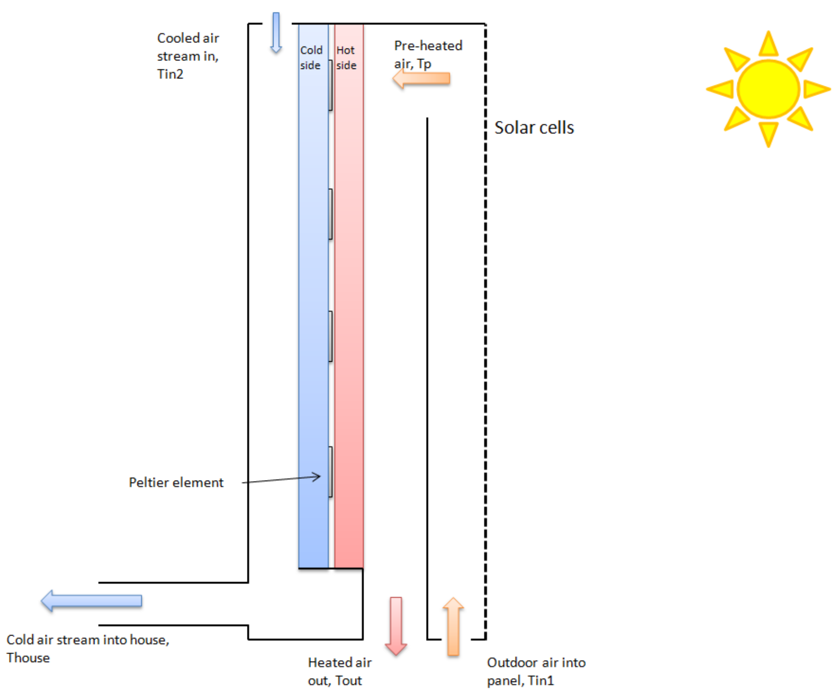

Figure 13. Cooling mode. Used when the outdoor temperature is above 20°C.

4.2 Theoretical model

The following theoretical model has been derived from the equations in chapter 2 It describes the maximum temperature increase of the air stream cooling the solar cells (Tonui J.K Tripanagnostopulos Y. , 2006). The temperature increase varies with solar irradiance and the mass flow of air, as described below.

$$\eta_{th} = \eta_0 - \frac{U\Delta T}{G} \quad , \quad U = F_R * U_L \quad , \quad \Delta T = T_{in} - T_a$$

$$\eta_{th} = \frac{\dot{m} * C_p(T_{out} - T_{in})}{A_a * G}$$

$$\eta_0 - \frac{U\Delta T}{G} = \frac{\dot{m} * C_p(T_{out} - T_{in})}{A_a * G} \rightarrow \boldsymbol{T_{out}} = \frac{\boldsymbol{A_a * G(\eta_0 - \frac{U\Delta T}{G})}}{\boldsymbol{m * C_p}} + \boldsymbol{T_{in}}$$

The temperature change of the air stream caused by the TE modules, along with maximum possible heating and cooling power and maximum COP has been determined using the following model derived from the equations connected to thermoelectric coolers (Gillott M. et al, 2010) and (Riffat S.B Ma X, 2004). The equations derived in this chapter has been used as a foundation for the computer simulations presented in chapter 5.

Cold side heat transfer

Peltier cooling:

$$Q_{cs} = 2 * N * \alpha * I * T_c$$

Joule heating:

$$Q_J = \frac{2 * N * I^2 * R}{g}$$

Conducted heat:

$$Q_{con} = 2 * K * N * (T_H - T_C) = 2 * K * N * g * \Delta T$$

Energy balance cold side:

$$Q_C = 2 * N * \left(Q_{cs} - \frac{Q_J}{2} - Q_{con}\right) = 2 * N * (\alpha * I * T_c - \frac{I^2 * R}{2g} - K * g * \Delta T)$$

Electrical energy consumption:

$$Q_E = 2 * N * (\frac{I^2 * R}{g} + \alpha * I * \Delta T)$$

COP:

$$\boldsymbol{COP} = \frac{\boldsymbol{Q_C}}{\boldsymbol{Q_E}} = \frac{(\boldsymbol{\alpha} * \boldsymbol{I} * \boldsymbol{T_c} - \frac{\boldsymbol{I^2} * \boldsymbol{R}}{\boldsymbol{2g}} - \boldsymbol{K} * \boldsymbol{g} * \Delta\boldsymbol{T})}{(\frac{\boldsymbol{I^2} * \boldsymbol{R}}{\boldsymbol{g}} + \boldsymbol{\alpha} * \boldsymbol{I} * \Delta\boldsymbol{T})}$$

Optimum current (maximum COP):

$$\boldsymbol{I_{opt}} = \frac{\boldsymbol{K} * \Delta\boldsymbol{T} * \boldsymbol{g} * (\boldsymbol{1} + \sqrt{\boldsymbol{Z} * \boldsymbol{T_m} + \boldsymbol{1}})}{\boldsymbol{\alpha} * \boldsymbol{T_m}}$$

T mean:

$$T_m = \frac{(T_H + T_c)}{2}$$

Figure of merit:

$$Z = \frac{\alpha^2}{R * K}$$

Hot side heat transfer:

$$Q_H = 2 * N * (\alpha * I * T_H + \frac{I^2 * R}{2g} - K * g * \Delta T)$$

Seebeck coefficient (V/K):

$$\alpha = \left(\alpha_0 + \alpha_1 * T_m + \alpha_2 * {T_m}^2\right) * 10^{-9}$$

Resistivity (Ω*m):

$$R = \left(R_0 + R_1 * T_m + R_2 * {T_m}^2\right) * 10^{-10}$$

Conductivity (W/m*K) for $225 < T_m < 300$:

$$K = \left(K_0 + K_1 * T_m + K_2 * {T_m}^2\right) * 10^{-8}$$

Input voltage:

$$V = 2 * N * (\alpha * (T_H - T_C) + I * \frac{R}{g}))$$

Cooling effect produced on the cold side:

$$Q_C = 2 * N * \left(\alpha * I * T_C - \frac{R}{g} * \frac{I^2}{2} - K * g * (T_H - T_C) \right) = A_{TE} * h_c * (T_{cm} - T_c)$$

Heating effect produced on the hot side:

$$Q_H = 2 * N * \left(\alpha * I * T_H + \frac{R}{g} * \frac{I^2}{2} - K * g * (T_H - T_C) \right) = A_{TE} * h_h * (T_h - T_{hm})$$

Energy balance in air flow:

Cooling mode:

$$Q_C = \dot{m}_{air} * C_{p,air} * (T_{in} - T_{house})$$

Heating mode:

$$Q_H = \dot{m}_{air} * C_{p,air} * (T_{house} - T_{in})$$

Thouse cooling mode:

$$2 * N * \left(\alpha * I * T_C - \frac{R}{g} * \frac{I^2}{2} - K * g * (T_H - T_C) \right) = \dot{m}_{air} * C_{p,air} * (T_{in} - T_{house}) \rightarrow$$

$$\boldsymbol{T_{house} = T_{in} - 2 * N * \frac{\left(\alpha * I * T_C - \frac{R}{g} * \frac{I^2}{2} - K * g * (T_H - T_C) \right)}{\dot{m}_{air} * C_{p,air}}}$$

Thouse heating mode:

$$2 * N * \left(\alpha * I * T_H + \frac{R}{g} * \frac{I^2}{2} - K * g * (T_H - T_C) \right) = \dot{m}_{air} * C_{p,air} * (T_{house} - T_{in}) \rightarrow$$

$$\boldsymbol{T_{house} = 2 * N * \frac{\left(\alpha * I * T_H - \frac{R}{g} * \frac{I^2}{2} - K * g * (T_H - T_C) \right)}{\dot{m}_{air} * C_{p,air}} + T_{in}}$$

COP of elements:

Cooling mode:

$$COP_{TE} = \frac{Q_C}{I * V}$$

Heating mode:

$$COP_{TE} = \frac{Q_H}{I * V}$$

4.2 Input

Solar panels

The company provides two types of PV panels, one 100 W thin film panel and one 250 W mono-crystalline panel with the following properties at 1000 W/m^2 irradiance and 25°C :

Table 1. Properties of the Himin 250 W mono-crystalline PV panel(See attachment 1).

Himin PV 250 W	
Model	HG-250S/Da
Peak Power (W)	250
Open circuit voltage (V)	37.6
Short-circuit current (A)	8.68
Optimum power voltage (V)	**31**
Optimum power current (A)	**8.06**
Power output tolerance (%)	0-3
Optimum system voltage (VDC)	1000

Table 2. Properties of the Ample Sun 100 W thin film panel (See attachment 2).

Ample Sun 100 W	
Model	ASF100
Peak Power (W)	100
Open circuit voltage (V)	99
Short-circuit current (A)	1.65
Optimum power voltage (V)	**77**
Optimum power current (A)	**1.29**
Power output tolerance (%)	0-3
Optimum system voltage (VDC)	1000

The objective of this chapter is to determine which type of TE modules are suitable to combine with these panels in order to get the largest possible heating and cooling output. The key parameters are the optimum power current and voltage, which will determine the type and number of modules used. The value of these parameters listed in the table are for optimum conditions, meaning an irradiation of 1000 W/m2. In order to get a the actual output for different insolation the I-V curves, provided in the product information sheet (attachment 1-2), has been used.

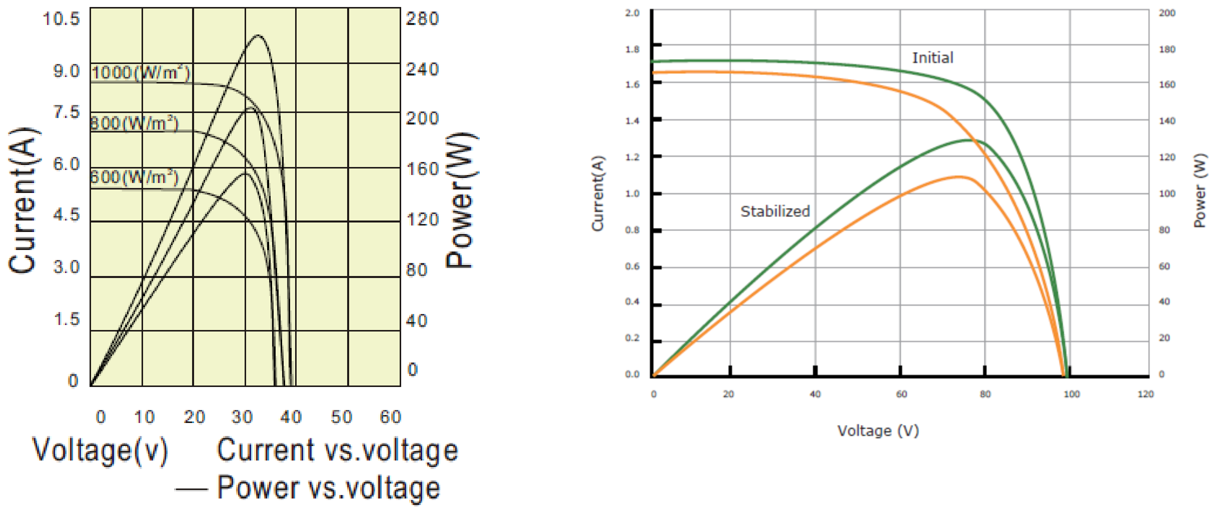

Figure 14. -V curve for the 250 W panel (left) and the 100 W panel right). (Himin, 2014, Ample Sun, 2014).

TE module

A number of modules available on Swedish web-sites have been picked out and their properties recorded. For the sake of simplicity it has been decided that only one type of module will be used in the prototype. Since the product will be used for heating most part of the year the output heating power of the module has been used to rank the models. By applying basic electronics the optimum number and connection, giving the highest power output, has been determined for each one of the models available. The result of all modules investigated is presented in table 12, appendix 11.3, and the properties of the chosen model is presented in table 3 below. As it turned out the 100 W panel provided currents that were too low to be suited for all but a few models, which resulted in low output powers, and the choice was therefore made to base the prototype on the 250 W solar panel only. Since the area of the solar panel is large compared to that of a single module it was agreed to use as many modules as possible. Spreading out the modules is thought to give a more effective heating/cooling of the air flowing across the surface. Based on the result the model **QC-71-1.4-3.7M** was chosen. The properties are presented in table 3. With an estimation of 80% power output (200 W), resulting in a 7.5 A current output and 30 V voltage, eight modules of these module could produce up to 400 W of heat. This output is reached by mounting two rows of four modules in series, and connecting the rows with a parallel connection.

Table 3. Properties of the TE module chosen to be used along with the 250W PV panel from Himin.

Model	Number of elements	Connection	P=Imax*Umax (W)	Qc (W)	Qh (W)	ec	eh
QC-71-1.4-3.7M	8	4Sx2P	242.72	154.4	397.12	0.772	1.9856

4.4 Prototype

The final product will, as figure 11-12 shows, consist of the existing PV panel with two extra "walls" added. The first will be an aluminum sheet creating a channel for the air to flow past an cool down the PV cells. The second wall will consist of two aluminum sheets, acting as fins, put together holding the TE modules within. One of the fins will be heated and the other cooled by the modules, and to prevent heat transfer between the two sides the sheets will be separated by insulation. In order to achieve maximum heat transfer where the fins are in contact with the TE modules the aluminum sheets have been shaped to each contain eight squared dents. The dents will be pressed against each other holding the TE modules and the rest of the surface will be covered in insulation to prevent heat transfer. Each of the aluminum sheets have been cut out to fit the PV panel. The measurements of the sheets and the connection of the TE modules is shown to the left in figure 14. When finding the type of module appropriate to get the largest power output it was found that two rows of four modules connected in series, with a parallel connection between the rows, would give the most output. The input voltage and current is displayed to the right in figure 15.

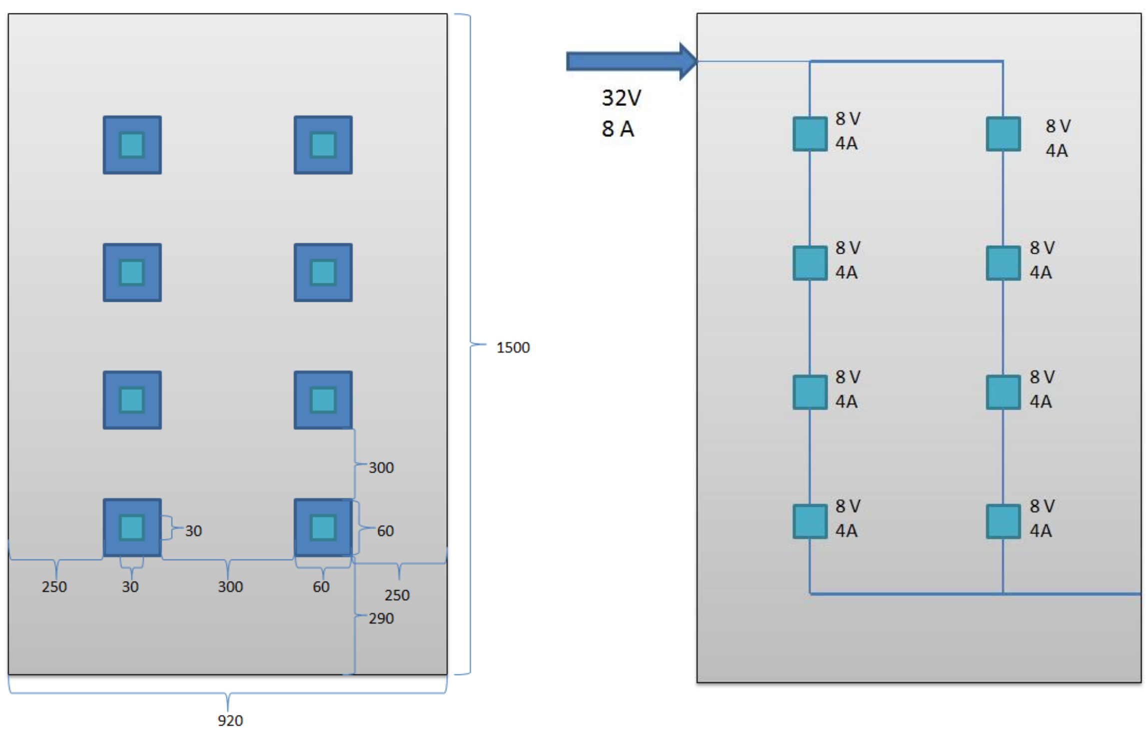

Figure 15. Design and measurements for the aluminum sheets. The dark shade displays the dents in the material and the light the size of the TE modules. The right picture shows the input currant and voltage from the PV panel.

5. Simulations

The following simulations were performed in Microsoft Excel using the theoretical model presented in chapter 4. The input parameters can be found in appendix 11.4.

PV cells

The maximum current and voltage is dependent on the solar irradiance, G, and the values are collected from the product information sheet (attachment 1). The corresponding temperature change of the air stream cooling the PV cells has been simulated and the result is presented in figure 16. As can be seen the temperature of the air stream changes linearly with solar irradiance.

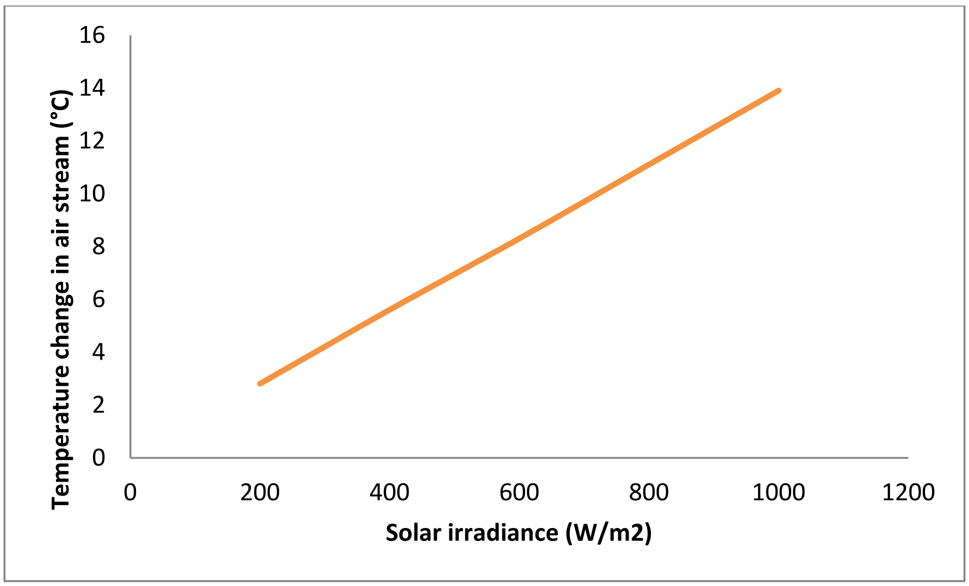

Figure 16. Relationship between temperature change of air stream cooling the PV cells and solar irradiance, Tamb=25°C, mass flow 35 l/s.

Studying the temperature of the air stream while varying the flow rate it becomes apparent that with an increasing flow rate the temperature decreases in a non-linear fashion. Figure 17 shows the temperature change of the air stream at an outdoor temperature of 25°C. If the outdoor temperature changes so does the output current and voltage from the panel. Taking this into consideration the simulation shows the same result as in figure 17 for an outdoor temperature of -5°C as for 25°C.In other words, the energy uptake depends on the mass flow of air only and do not vary with outdoor temperature.

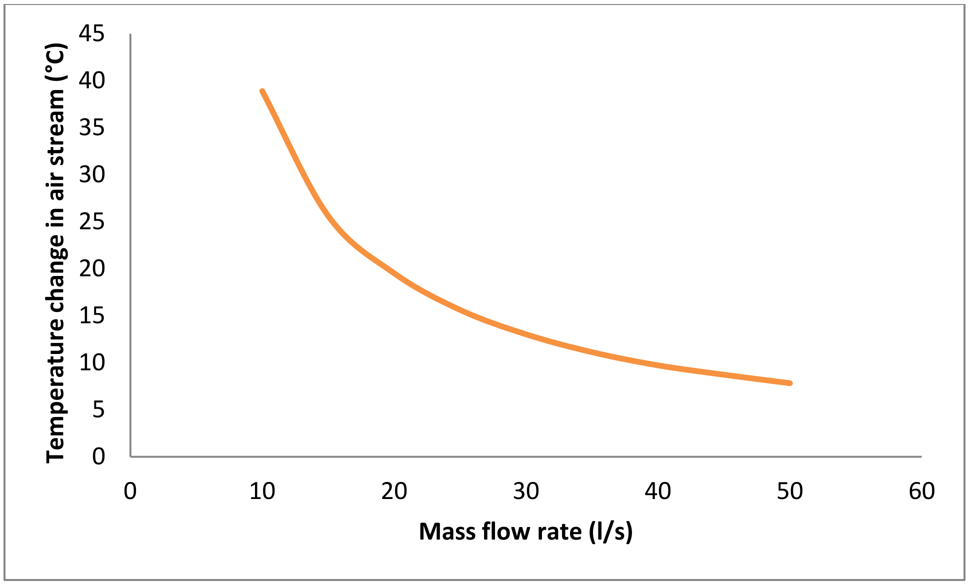

Figure 17. Relationship between mass flow rate of air stream and temperature change of the air passing the PV cells. G is constant at 800 W/m².

TE modules

The temperature change of the air stream achieved by the TE modules has been simulated and the result displayed in this chapter. Two basic modes have been used; summer mode with and outdoor temperature of 25°C and winter mode with an outdoor temperature of -5°C. Naturally the modules were put in heating mode in winter and cooling mode in summer. The simulations have been performed using the equations in chapter 4. When studying the result it is important to keep in mind the difference between the optimum current, which give the highest COP, and the input current. What complicates the simulations is that most parameters vary with temperature. In order to get a result some parameters need to be kept constant while others are varied. In reality, however they all depend on each other.

Power output and COP

Figure 18 shows how the power output of a single TE module vary with the optimum current. As can be seen the heating power increases with an increasing optimum current. If using the module for heating no time needs therefore be spent on finding an optimum. To increase the power output the current needs simply to be raised. The cooling power, however does not follow the same trend. As the figure shows there is a maximum cooling power for a certain optimum current. To optimize the system the peak during certain conditions needs to be found. Maximizing the cooling power is therefore a bit more tricky than maximizing the heating power.

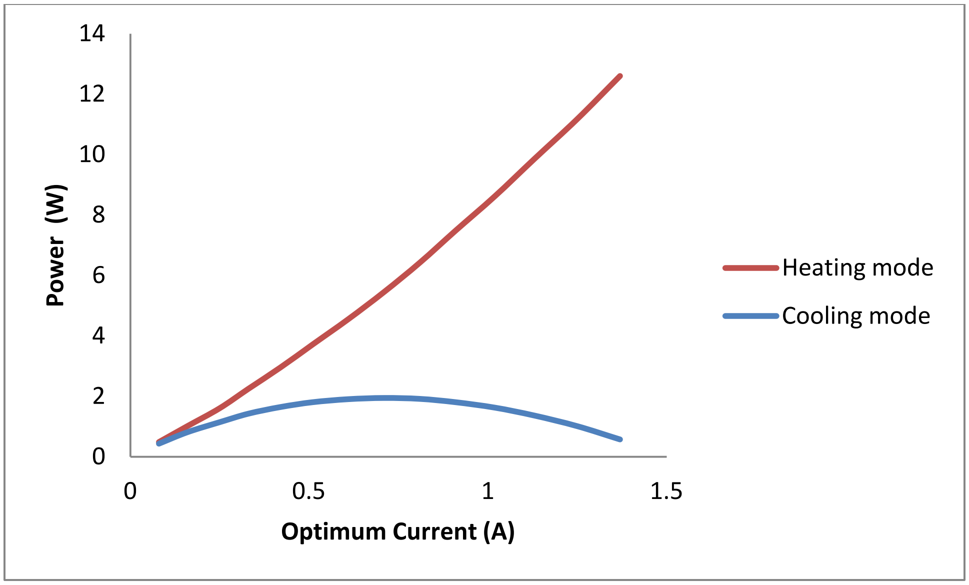

Figure 18. Variation of heating and cooling power with optimum current.

The variation of the COP value for heating and cooling mode is displayed in figure 19. The efficiency is always higher in heating mode than cooling mode for the same current. As the figure shows the COP value can become large if the optimum current is kept low. For currents around 1 A and above the COP of the TE module cannot be expected to exceed 100%.

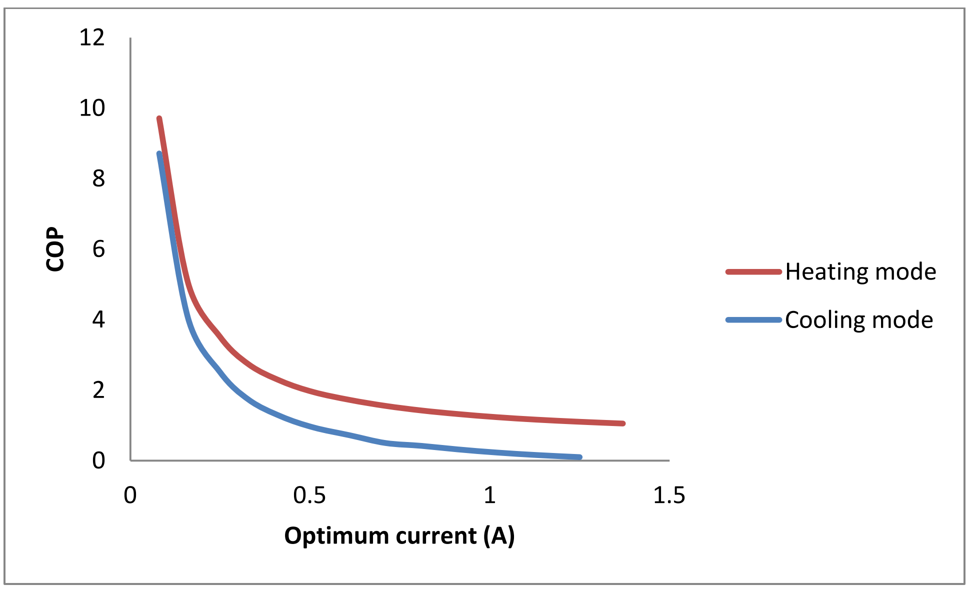

Figure 19. Variation in COP with optimum current for heating and cooling.

Temperature change of air stream

In this project the TE modules will be used to heat or cool air. This will be done by transferring the heat from the module to an aluminum fin, and from the fin to the air stream passing by. The heat is transferred from the TE module to the fin via conduction and from the fin to the through convection. The mathematical model used to describe the heat transfer is given in chapter 4. When performing the simulations the conductive part of the heat transfer was excluded, due to lack of available information. The resulting temperature change of the air stream, displayed in figure 20, is therefore not completely reliable. In reality the temperature change would be larger, and the result presented can be seen as a minimum temperature change.

The simulation result presented in figure 20 shows the temperature change achieved by a single TE module, without a fin, in an air stream with a flow rate of 35 l/s. In correlation to the power output shown in figure 18 the temperature rises with an increasing optimum current in heating mode. In cooling mode there is a maximum temperature decrease achieved for a specific optimum current. As the graph shows the temperature change achieved by a single module very small for this particular air flow. The amount of heat transferred to the air stream depend on the flow rate. If the flow rate is decreased a higher temperature will be achieved in heating mode and a lower in cooling mode. Simulations have shown that the temperature change would double if the flow rate is decreased to 10 l/s.

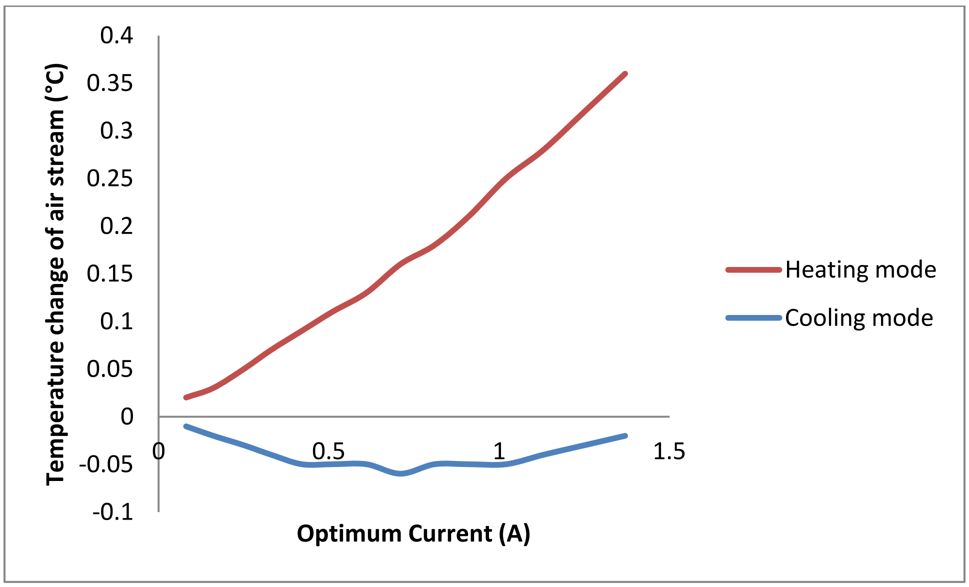

Figure 20. Temperature change of an air stream with a flow rate of 35 l/s caused by one TE module in heating and cooling mode.

Prototype output

The result presented above describes the function of the TE module from a theoretical perspective where optimum conditions can be chosen. This may, however, not give a clear picture of what can be expected when testing the prototype. The simulations above have all been performed using the optimum current, giving the highest COP value. In this project the modules will be connected to PV cells and the input current cannot be controlled. The prototype has been constructed so that when the solar irradiance is 1000 W/m^2 it will provide the TE modules with the maximum current and voltage they can handle. The known properties, when testing, are the input current and voltage from the panel and the properties of interest are the output power and temperature. It is, however, not possible to perform a simulation where the current and voltage are the only known parameters, since most coefficients used in the model vary with temperature. Estimations have therefore been done on how the temperature difference across the module vary with the incoming current. The relationship between the solar irradiation and the output current and voltage from the PV panel has been gathered from the I-V curve, and all these parameters have been weighed together to simulated the total temperature change of the air stream. This has been done for heating and cooling mode using eight TE modules connected to the PV panel.

Figure 21 shows the expected temperature change of the air stream for the entire climate panel, including the change achieved by cooling the PV cells. As can be seen in the figure it is theoretically possible to achieve a temperature increase of the air stream of 15°C at a solar irradiance of 1000 W/m^2 in heating mode. In cooling mode the maximum temperature decrease is reached at a low solar irradiance, which is only about -0.5°C. In other words the panel can be expected to work rather well in winter time, whilst being quite insufficient in summer.

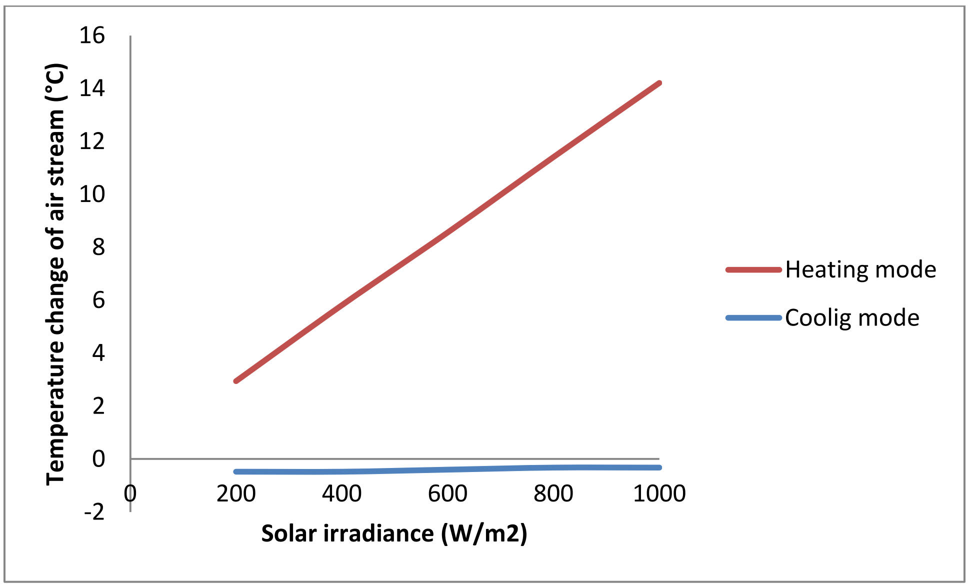

Figure 21. Overall estimation of the maximum achieved temperature change of an air stream with flow rate 35 l/s with solar irradiance for heating and cooling.

6. Experimental testing

6.1 Method and material

The following experiments have been carried out with TE modules of the model QC-71-1.4-3.7M from QuickCool. The temperature has been measured using thermoelectric wires connected to a PC-logger 2100 from Intab. Each thermoelectric wire consist of a thermocouple which, when connected to a logger, record the temperature at the junction. A voltage is created in the thermocouple as a result of the temperature difference between the junction and the connection point. The voltage level is translated by the software and expressed as temperature with an accuracy of 0.1°C. The logger is used along with the software Easy View by Intab and the input voltage was 50 mV T/C °C (9.29 V at 200°C). Measurements were taken with an interval of 1 s.

6.2 TE module testing

Test 1 - Function of the TE module

Experimental set up

The set up for this first experiment consisted of two metal bars taped together, each with 5 mm of insulation. The TE module was placed between the bars in direct contact with the metal and the insulation surrounding it (see figure 22 left). The temperature was measured on the hot and cold side of the TE module, on the backside of the bar in contact with the module. In a later step the heat transfer to the fins with no insulation between them was performed in order to evaluate the effect of using insulation to prevent heat transfer. In this case two aluminum sheets were put together holding the TE module in between. Temperature sensors were used to measure the temperature at the hot and the cold side of the module as well as at the fin in direct contact with the module (figure 22 right).

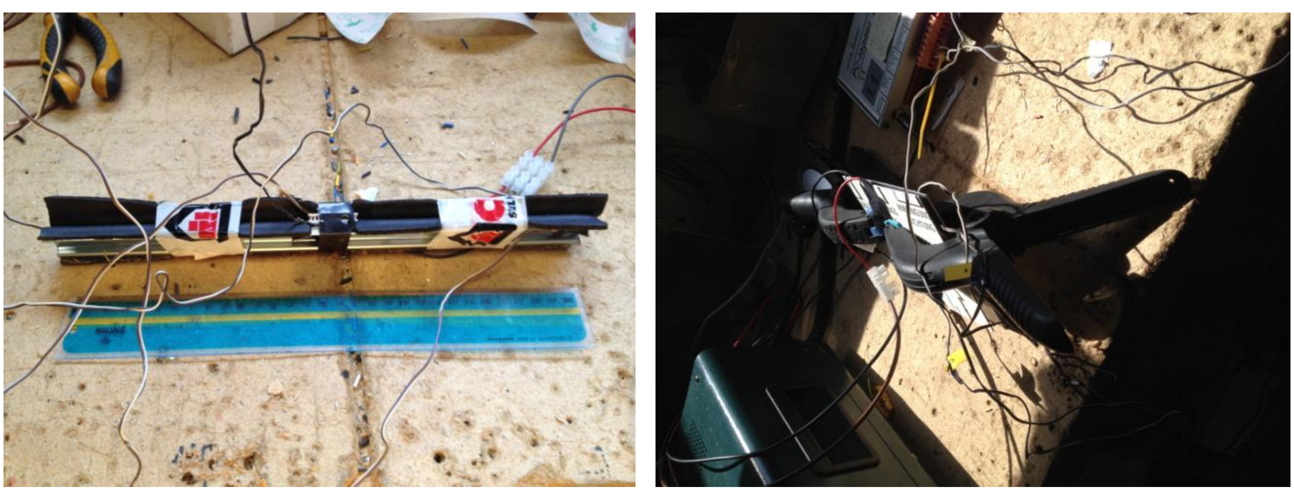

Figure 22. Experimental set up test 1: left with insulation, right without insulation.

Result

Three tests were performed using an input voltage of 1 V, 4 V and 8 V, which roughly corresponded to a current of 0.4 A, 1.3 A and 1.8 A. The general trend noticed was that the temperature of the hot and the cold side changed drastically during the first 5 minutes and that the temperature levels evened out and stabilized after about 15 minutes. The hot side temperature was larger with a higher input current. The temperature difference between the hot and the cold side increased at first and stabilized as the temperature evened out. The temperature at the cold and hot side of the TE module for different incoming currents, with time, is shown in figure 23-24.

Plotting all the curves together as in figure 23-24 it becomes obvious that the input current has a large effect on the temperature levels. If the input voltage is put at the maximum value of 8 V, corresponding to a current of 1.8 A, the temperature rises over 100°C on both the hot and the cold side. At this input it takes longer time for the temperature levels to stabilize and there is no recognizable dip in the cold side temperature. This input would be favorable for heating. Only an input current of 0.4 A manages to give a current level which keeps the cold side temperature below ambient of 20°C. If the module is to be used for cooling the input current must therefore be kept low.

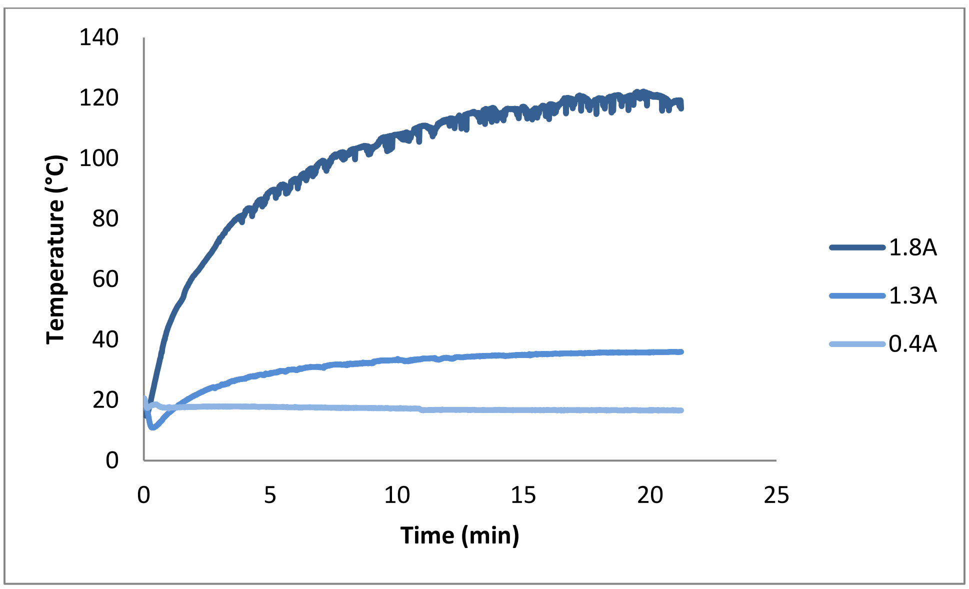

Figure 23. Temperature at cold side of TE module for three different currents.

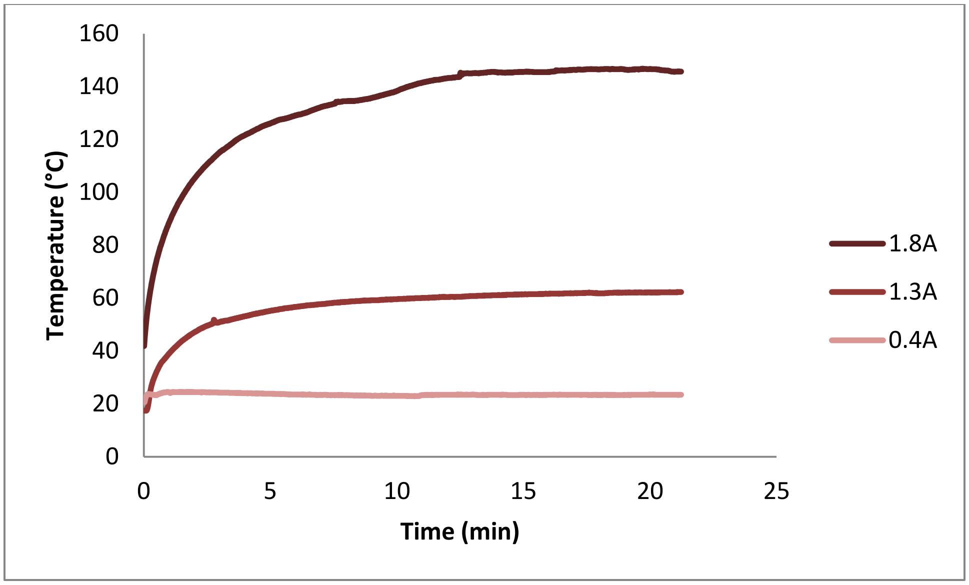

Figure 24. Temperature at hot side of TE module for three different currents.

The temperature levels measured correspond to a cooling power of between 0-3.5 W and a heating power of 0-4 W. The power output follows the same pattern as the temperature levels. The COP value reaches 0.27 for cooling and 0.32 for heating, at an incoming current of 1.8 A.

The effect of using insulation between the fins is displayed in figure 25. The same incoming currents were used for the two setups, one with insulation and the other without. The temperature was measured at the fin and the corresponding temperature levels in cooling mode is shown in the figure. As can be seen the temperature is much larger without insulation. If insulation is not used the heat transfer from the hot to the cold side becomes too large to keep the cold side at a temperature below the ambient. For an incoming current of 1.8 A the difference in temperature at the fin, with and without insulation, is around 18°C in cooling mode which is significant. The result for heating mode shows the same pattern. Prevention of heat transfer between the hot and the cold side is more important if the panel is to be used for cooling since the temperature quickly rises above the ambient. In heating mode it is not as important to keep up the temperature difference between the sides as long as the temperature is not high enough for the modules to overheat.

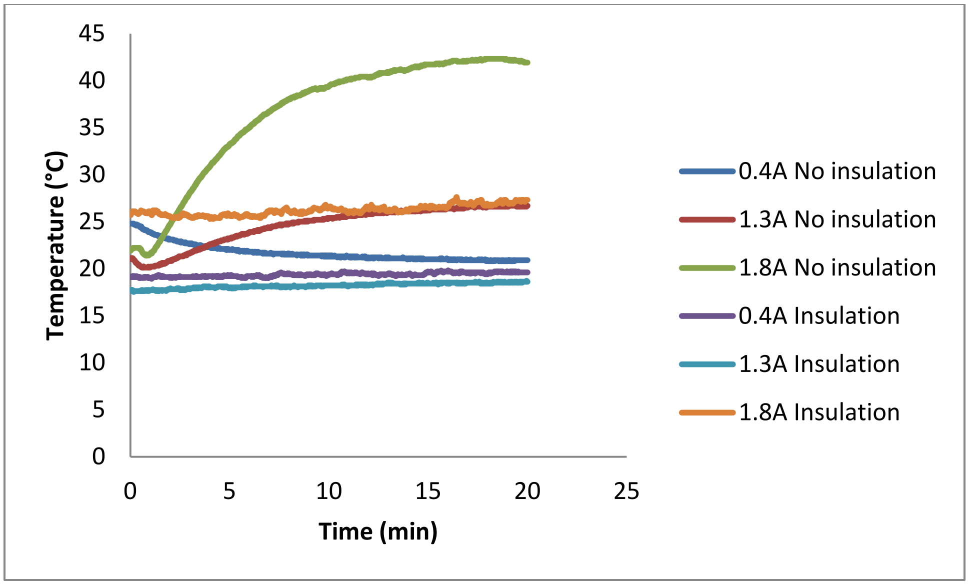

Figure 25. Difference in temperature at the fin in contact with the TE module with and without insulation between the fins at the cold side.

Test 2 – Cooling the fins with air

Experimental set up

In order to get an indication on the effect of cooling the fins with air a similar set up was used, but with longer bars. The two metal bars, 80 cm long, was taped together holding the TE module in between. Insulation was used to prevent heat transfer from the hot to the cold fin. The temperature was measured at the fin, at the spot where the fin was in direct contact with the module, at the hot and the cold side. Two tests were performed, one with air flow and one without. The airflow was induced using an air pressurizer with an unknown flow rate.

Result

Figure 26 shows the difference in temperature with and without air flow for both cooling and heating mode, at an incoming current of 1.5 A. As the figure shows a difference of about 5°C can be detected in heating mode, whereas the difference in cooling mode is around 2°C. It can be seen that the difference between the two modes increase as the temperature level stabilizes. It can also be seen that the initial dip of the temperature in cooling mode is prolonged as the fin is cooled. Based on this experiment it is hard to anticipate the effect of a larger air flow across a wider area. However, it seems like the heat is more effectively removed from the fin if there is a flow of air across the surface rather than stagnant air.

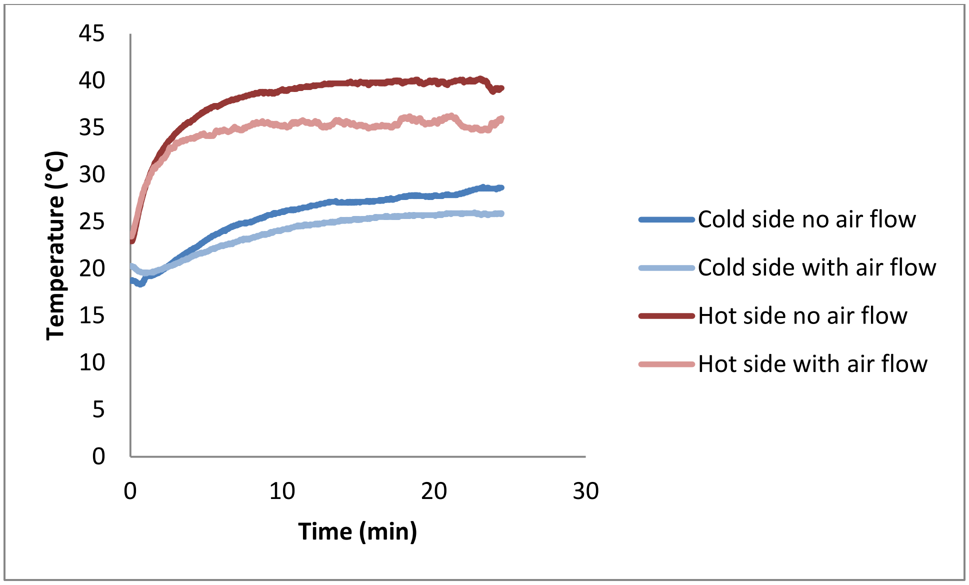

Figure 26. Temperature at fin in heating and cooling mode with and without air flow.

6.3 Prototype testing

The prototype tested in this chapter is designed as described in chapter 4. It consists of two aluminum sheets screwed together. The eight TE modules are in direct contact with each of the sheets, and cooling paste is added to increase the heat transfer. The fins are separated with 2 cm of insulation and the modules are laid out in two rows of four. Two connection set ups have been tested. Firstly the modules in each row are connected in parallel and the rows are in turn series connected. Secondly the modulus in each row are series connected the rows, in turn, are connected in parallel.

Figure 27. Picture of prototype wall. Two aluminum sheets are screwed together holding 8 TE modules in between them at each dent. The sheets are separated with insulation to prevent heat transfer between the hot and the cold side.

Test 3 – Parallel connection

Experimental set up

The set up consisted of the prototype described above. The prototype was standing up and the wires connected to the power supply with a maximum voltage of 13 V and a maximum current of 10 A. The temperature sensors were taped onto the sheets in the dents where the fin is in direct contact with the TE module. The temperature was measured for 60 min at both the hot and the cold side.

Result

Measurements were done for four different incoming currents between 2-8 A. For parallel connection the incoming current was about twice as high as the voltage. A current of 8 A corresponded with an input voltage to the prototype of 4 V. Figure 28-29 shows the temperature levels at different currents in cooling and heating mode. As can be seen the lowest temperature level in cooling mode is reached at a current of 6 A, which for this connection could be the optimum current. The temperature spread in cooling mode is only around 2°C and could be dependent on the ambient temperature for the different measurements. In heating mode the spread is a bit more significant. The highest temperature reached is 25°C, for an incoming current of 8 A. Worth noting is that the temperature in the room where these measurements were performed was around 17°C. It seems as though parallel connection caused a too low input to each module to get a large temperature increase and thereby a large power output.

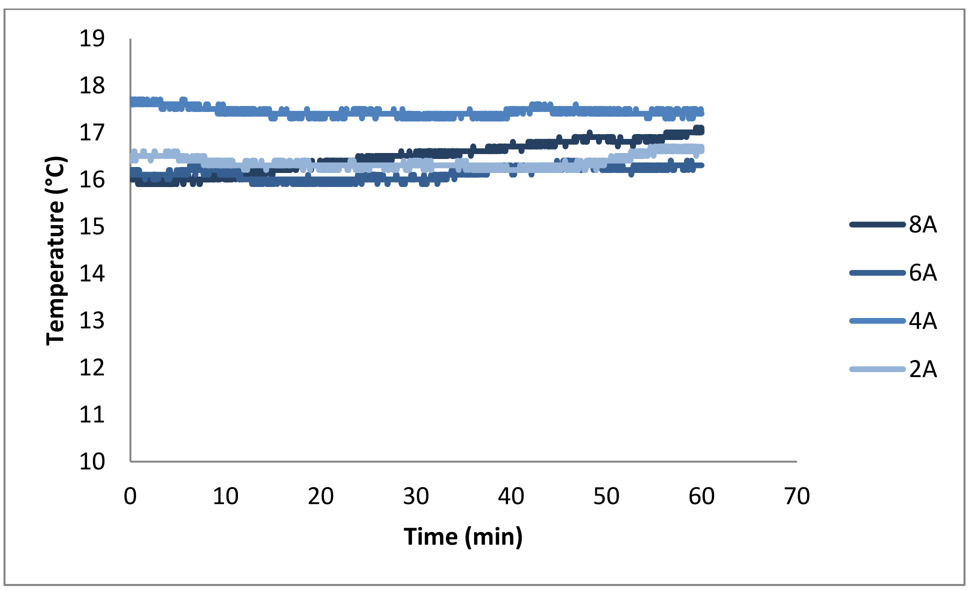

Figure 28. Temperature at the fin in contact with TE module on cold side for different incoming currents to the prototype

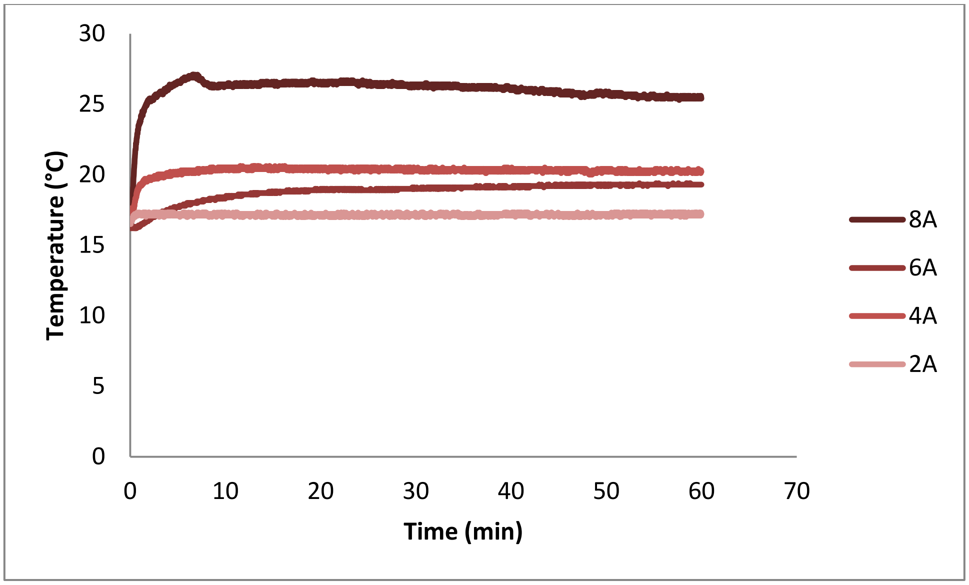

Figure 29. Temperature at the fin in contact with TE module on hot side for different incoming currents to the prototype

Test 4 – Series connection

Experimental set up

The same prototype was used for this experiment as for the previous, but with series connection instead. The panel was placed in the warehouse and connected to a power supply with a maximum voltage level of 30 V and a maximum current of 10 A. Due to the series connection a higher input voltage was required than when having parallel connection and a different power supplier was therefore used in this experiment. The measurements were done for a time period of 60 min and the temperature sensors were placed in the same spots as before.

Result

The temperature was measured for four different incoming currents. In comparison to the parallel connection the voltage level was in this case higher than the current level. The incoming currents tested varied between 1-4 A which corresponded to a voltage level of between 4-20 V into the prototype. Figure 30-31 shows the temperature levels in cooling and heating mode for different incoming currents. In cooling mode the temperature is kept below the ambient for all currents. As can be seen the temperature dips initially and stables out for all currents but 4 A. For incoming current lower than this series connection seems to work well. In heating mode the maximum temperature of 45°C is reached for an incoming current of 4 A. For low incoming currents the temperature does not reach beyond the ambient. Compared to the previous experiment series connection seems gives a higher temperature level and is therefore preferable when heating is required.

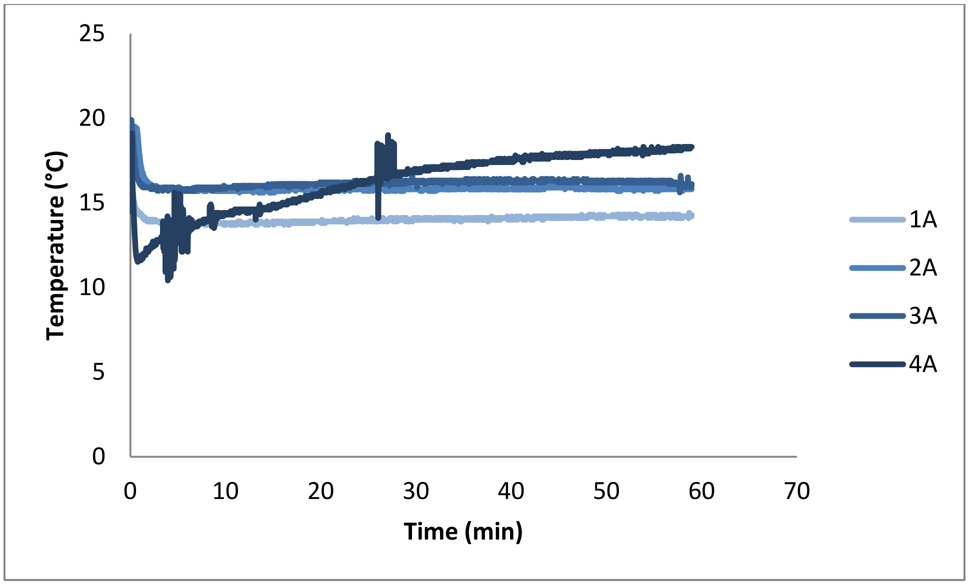

Figure 30. Temperature at fin in contact with TE module as function of time, for cooling mode at different incoming currents.

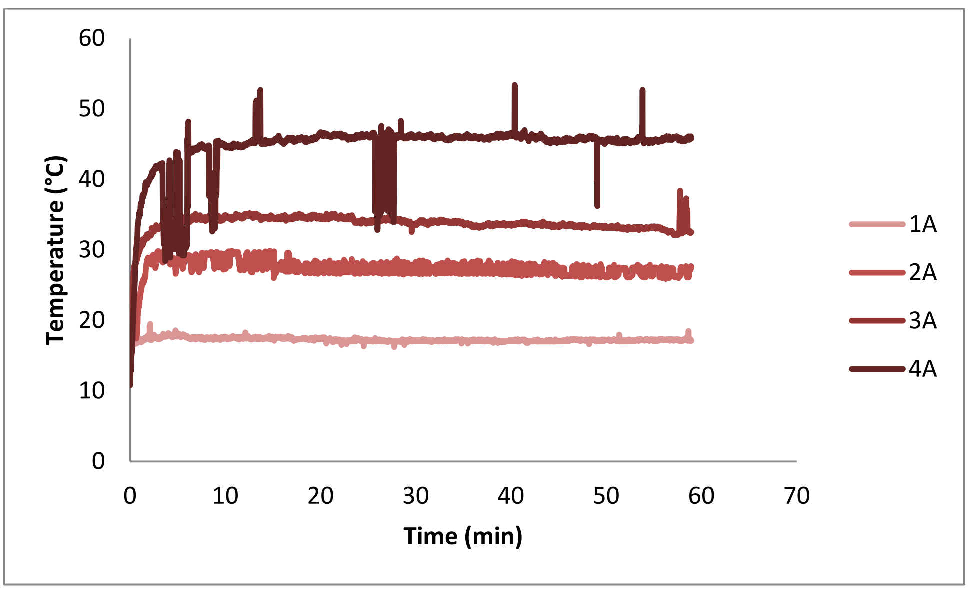

Figure 31. Temperature at fin in contact with TE module as function of time, for heating mode at different incoming currents.

Test 5 – connection to solar panel

Experimental set up

The prototype was placed in the workshop, same as before, and the wires attached to the PV panel through a window. The PV panel was placed vertically against the outside wall of the building in full sunlight. (A solar irradiance of 1000 W/m^2 is assumed.) The temperature measured at three points of the hot and the cold side respectively: in the dent where the fin is in direct contact with the TE module, in the middle of the rows 15 cm from each TE module and at the edge of the sheet 15 cm from one TE module. The measurement went on for 1.5 h in the afternoon.

Result

The temperature levels at the hot and the cold side for parallel and aeries connection is displayed in figure 32-33. The output from the PV panel before it was connected to the prototype was 35 V and 8 A. When looking at the figures it becomes obvious that the temperature level becomes much larger with series connection than with parallel. For parallel connection the temperature of the fin differs only slightly from the temperature in the room. In other words the TE modules barely produce any heating or cooling at all. The temperature level across the fin is quite even when parallel connection is used. With series connection there is a great temperature difference across the fin, and it will take longer time for it to even out. With series connection the temperature at the fin can become up to 90°C, which is good for heating mode. However, the cold side temperature becomes rather large as well, around 40°C, which means no cooling is possible at this level of solar irradiance. In general terms parallel connection is better in cooling mode and series connection in heating mode.

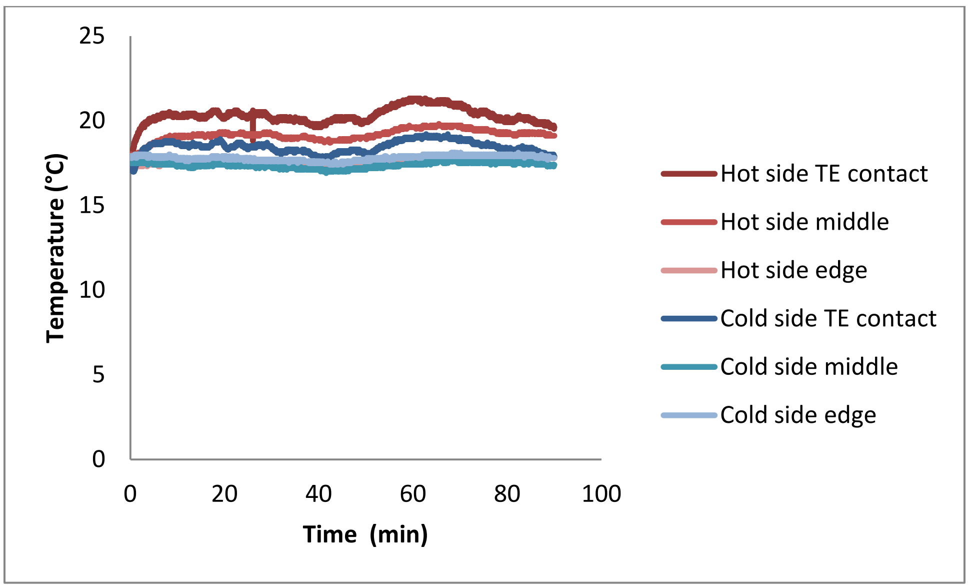

Figure 32. Temperature spread across the fin in heating and cooling mode for parallel connection. Prototype connected to V panel with output 35 V and 8 A.

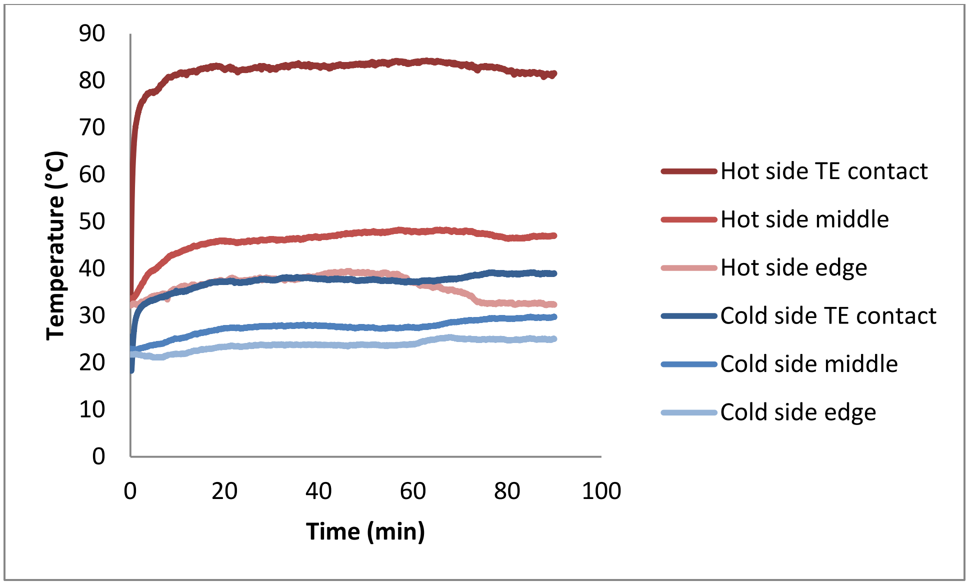

Figure 33. Temperature spread across the fin in heating and cooling mode for series connection. Prototype connected to V panel with output 35 V and 8 A.

6.3 Summary of practical experiments

Due to lack of time, limited resources and breakdown of equipment the number of practical tests performed were not as extensive as planned. There was no time to practically test the heat transfer from the fins to the air or to test the performance variation of the PV panel with air cooling. There are, however, some points of interest worth noticing in the result presented in the previous, which are listed below.

- **Fast response and stabilization of the TE modules** – The response of the TE module is instantaneous. As soon as the module is connected to the power source the temperature of the hot side rises rapidly and the cold side declines. The temperature difference across the module stabilized within minutes.
- **Insulation is important** – There is a large heat transfer between the hot and the cold side of the TE module, especially at high currents. The temperature of the cold side was kept lower when insulation was used and taking measures to prevent heat transfer seems to be extremely important to keep the cold side below the ambient temperature.
- **Series connection gives a larger power output from the prototype** – It was shown that the power output from the prototype increased significantly as the modules were connected in series rather than in parallel. In heating mode the output and the temperature was much more favorable when series connection was used. When using parallel connection the temperature at the cold side was more easily kept below the ambient temperature. The input to each module was lower with this type of connection, which helped keep the temperature levels down.
- **Slow heat transfer across the fins** – The heat transfer across the fins was slow. Even though the temperature of the TE module stabilized quite quickly the heat took long time to spread across the fin. After one and a half hours of measurement there was still a large

temperature difference between the points of the fin in contact with the TE modules and the edges.

- **The contact between the TE module and the fin plays a big part in the function of the prototype** – Since the prototype is handmade the measurements are not exact and it has been hard to keep the same contact and pressure at all eight TE modules. The temperature levels at the fins in contact with the TE modules has varied greatly due to lack of contact and pressure at some points. It has been noted that the modules break more easily when the contact is bad. If the input current is high the temperature of the module can become over 150°C. If the heat transfer is not efficient enough the module will overheat and break. The manufacturer suggests a pressure of 15kg/cm^2, which is quite large. It has not been possible to measure the pressure used for these experiments but it can be assumed that this level has not been kept. The modules broke down due to overheating at several occasions. If the contact is improved the temperature of the module will go down and it will last longer. Good heat transfer also helps keeping the cold side at a low temperature. For future trials and when developing the final product it is important to work on maximizing the contact to get an even temperature level across the fin and make sure the modules last long.
- **Cooling is needed to keep the temperature down at the cold side** – It has been proven that even with large fins the heat transfer is not large enough to prevent the cold side from getting above the ambient temperature. Even with improved contact between the TE modules and the fins there should be additional heat removal, for instance by creating air circulation across the surface to make sure the cold side stays cool.

7. Analysis

7.1 Potential energy saving

Estimation of the annual energy output

In order to determine the energy output from the panel, the amount of heat transferred from the panel to the air has to be estimated. As described before the panel consist of two sub-systems; the PV cells and the thermoelectric wall. The power output from each of these systems can be determined separately and added together to get the total power output from the panel for different solar irradiances. The result is presented below. The calculations of the values presented in the tables are given in appendix 11.5.

PV panel

Q for different solar irradiances in shown in table 4 below. This result is based on simulated values only, since there has been no time to perform practical tests measuring the output temperature. The thermal efficiency has been put to 30% for all solar irradiance. In reality this value vary with temperature the same as the electrical efficiency, but since no specific values have been available for the PV panel used this estimated value is based on previously performed experiments within this area. The power output decrease with decreasing solar irradiance and temperature.

Table 4. Heat power transferred to air stream from PV panel for different solar irradiances.

G (W/m^2)	η_{th}	ΔT (K)	Q (W)
1000	0.30	13.9	489
800	0.30	11.1	391
600	0.30	8.3	293
400	0.30	5.6	196
200	0.30	2.8	98

TE wall

The amount of heat transferred to the air stream flowing passed the wall with the TE modules has been determined in cooling and heating mode for both parallel and series connection. The input has been fitted to a certain solar irradiance using the I-V curve. This estimation is very rough and the result presented should be seen as an indication of how the power output vary with solar irradiance only. For heating mode an outdoor temperature of -5°C has been used. The temperature of the air reaching the wall is the outdoor temperature plus the temperature change achieved by the PV cells at that particular solar irradiance, which is displayed in table 4. In cooling mode the ambient temperature is put equal to the outdoor temperature of 25°C. Input data and calculations can be found in appendix 11.5. The result is based on the temperature levels measured at the fins for different incoming currents. The highest level of heating or cooling measured is that where the fin is in direct contact with the TE module and the lowest is that at the edge of the fin. The result presented below is based on a mean of these two measure points. Table 5-6 present the outcome temperature of the air stream and the corresponding heat power for parallel and series connection respectively. Table 7 presents the COP value corresponding to the output heating and cooling power.

Looking at table 5-6 it can be seen that the cooling power is higher when parallel connection is used and heating power is higher when series connection is used. The negative value of the cooling power for 1000 W/m² in series connection means that there is no cooling power at all but the air is instead heated. Looking at the temperatures this is confirmed as well. Comparing the temperature levels at the wall and of the air stream it can be seen that almost all heat is transferred, since the temperatures are almost the same. Due to losses on the way the expected result would be a higher temperature of the air stream than at the fin in cooling mode and a lower temperature in heating mode. The fact that this is not always the case shows that there are some flaws in the model. The values should therefore be seen more as an indication of the outcome rather than exact values.

Table 5. Output temperature and heating/cooling power of the air stream for parallel connection.

G (W/m²)	Tc measured (°C)	Th measured (°C)	Tc air	Th air	Qc air (W)	Qh air (W)
1000	18.0	20.5	17.0	23.2	280	502
800	17.0	21.5	16.3	19.2	307	451
600	17.3	19.8	18.0	18.7	245	543
400	17.0	19.0	17.1	18.7	279	640
200	16.8	17.0	16.9	16.9	288	670

Table 6. Output temperature and heating/cooling power of the air stream for series connection.

G (W/m²)	Tc measured (°C)	Th measured (°C)	Tc air	Th air	Qc air (W)	Qh air (W)
1000	31.0	56.5	31.0	56.4	-212	1666
800	24.5	47.0	24.5	46.8	16.4	1431
600	18.5	35.5	18.5	35.3	227	900
400	17.5	27.5	17.6	27.3	262	939
200	15.5	23.5	15.1	23.3	297	848

The result presented in tables 5-6 is displayed graphically in figure 34-35. The first figure shows the temperature of the air stream in heating and cooling mode for parallel and series connection. As can be seen the temperature is larger for series connection in both heating and cooling mode. The difference between the two modes is also larger for series connection. When parallel connection is used the temperature of the air stream stays below the outdoor temperature of 25°C that is assumed in summer. I order not to take in air warmer than the indoor temperature, this connection is to be preferred in summer. In winter series connection would be recommended instead, since it manages to heat up the incoming air stream. The higher the temperature of the incoming air the less heating is required by the existing heating system.

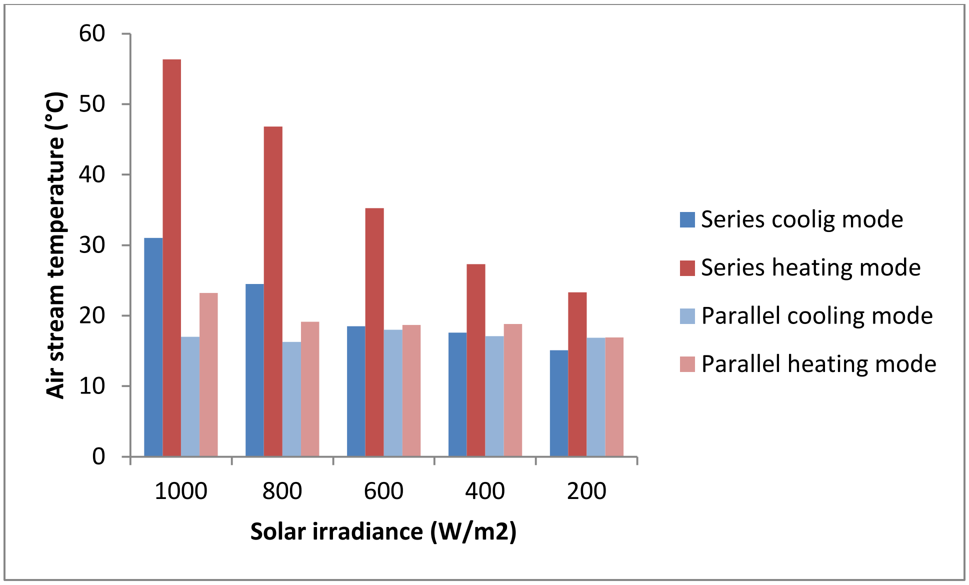

Figure 34. Temperature of air stream at different solar irradiances for parallel and series connection.

Figure 35 displays the power output corresponding to the temperature levels in figure 34. As can be seen the total power output is larger for series connection than for parallel. Looking only at cooling power the output is larger when parallel connection is used. For a solar irradiance of 1000 W/m^2 the cooling power is negative in series connection meaning there is heating of the air instead of cooling.

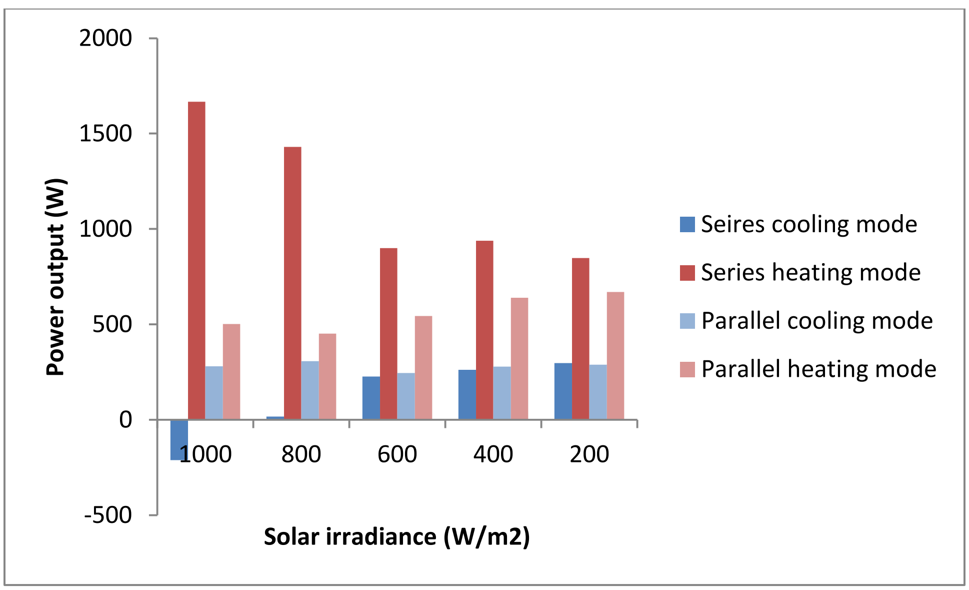

Figure 35. Power output from climate panel at different solar irradiances for parallel and series connection.

Table 7 shows the COP value corresponding to the heating and cooling power presented in the previous two tables. The result shows that the COP for the heating/cooling power of the air stream is much larger than that of the TE modules. The reason for this is that the heat transfer from the fins to the air is determined using a much larger area than that of a single module. The output heating and cooling power is based on the mean temperature of the fin, meaning the average temperature between the hottest and coldest part of the fin. The corresponding heating/cooling power of the air stream is determined sing an area of 0.91 m^2, which is assumed to be the area from which heat can be transferred from the TE wall to the air stream. The area of a single module is 0.0009 m^2, which is considerably smaller. Therefore the amount of heat in the air is much larger and the maximum heating power of a single TE module which is around 20 W.

As table 7 shows the largest COP achieved by a single TE module occurs at low solar insulation. At low insulation the input current is low, and the COP is maximized for low currents. When studying the COP of the air stream it can be seen that the same pattern occurs here. At low solar insulation the COP reaches the highest values. The COP for heating is larger than COP for cooling in both parallel and series connection. The conclusion is therefore that the TE wall is more efficient for heating air than cooling air. For cooling mode the COP is larger with parallel connection and for heating mode it is larger with series connection. Even if the values should not be taken too serious it can be seen that the TE wall has potential of COP values in the same order, or larger, than regular heat pumps.

Table 7. COP of TE modules and of heat transfer to air stream for parallel and series connection.

G	COPc TE	COPh TE	COPc air parallel	COPh air parallel	COPc air series	COPh air series
1000	0.18	1.14	1.12	2.02	-	6.72
800	0.11	0.86	1.62	2.39	0.09	7.59
600	0.21	0.92	1.81	4.02	1.68	6.67
400	0.43	1.31	3.19	7.31	2.99	10.7
200	0.85	4.27	6.26	14.6	6.46	18.4

As series connection seems to be the best solution for heating, this type of connection has been chosen to investigate further. For most part of the year the panel will be used in heating mode, and since the power output in cooling mode does not differ significantly between the two connection this choice seems reasonable. The total power output for the entire climate panel, including the PV cells, is shown in table 8 for different solar irradiance.

Table 8. Heat power transferred to air stream from the PV panel and the TE wall together, for different solar irradiances.

G (W/m^2)	Qc	Qh
1000	-213	2155
800	16.4	1822
600	227	1193
400	262	1135
200	297	946

In order to determine the total energy output of the climate panel for the entire year the power output for each irradiance needs to be multiplied with the amount of hours per year this intensity occurs. No data has been found showing the amount of hours per year for each irradiance. However, the Swedish Meteorological and Hydrological Institute (SMHI) provides information on the number of sun hours per day and month at different locations. The values used are those for Växsjö, which is the city closest located to Teckomatorp with available data (SMHI, 2007). The global irradiance for each month is given, and using these values along with the sun hours the mean irradiance for each day of a specific month has been calculated. The global irradiance is the direct irradiance towards the panel. SMHI also provides information on the diffusive irradiance, but it has been assumed that this cannot be absorbed by the monocrystalline PV panel. It has been determined that the panel is put in cooling mode for the summer months June-August and in heating mode the rest of the year. The total energy output for each year is shown in table 9 below. **Over the year the energy output from the panel is around 1300 kWh.**

Table 9. Calculation of yearly energy output from the entire climate panel.

Month	Solar time (h/day)	Global irradiance (kWh/m^2*day)[1]	G (W/m^2)	Mode	Q (kW)	Energy output (kWh/day)	Energy output (kWh/month)
January	1	0.5	500	Heating	1.16	1.16	36.0
February	2	1	500	Heating	1.16	2.32	65.0
March	3.5	2	570	Heating	1.18	4.13	128
April	5.5	3.5	636	Heating	1.31	7.21	216
May	7.5	5	666	Heating	1.40	10.5	325
June	7	5	714	Cooling	0.11	0.77	23.9
July	7.5	5	666	Cooling	0.16	1.20	36.0
August	6.5	4	615	Cooling	0.21	1.37	42.5
September	4.5	2.5	555	Heating	1.18	5.31	159
October	2.5	2.5	1000	Heating	2.20	5.50	171
November	1.5	1.5	1000	Heating	2.20	3.30	99.0
December	1	0.5	500	Heating	1.16	1.16	36.0
Whole year total							**1 337**

[1] Values for Växsjö Sweden (SMHI, 2007)

7.2 Economic evaluation

The economic gain from installing the climate panel depend on the annual energy usage and what type of heating system is used in the building to which it is applied. A "typical Swedish house" is said to have an annual energy consumption of 25 000 kWh per year (Energimyndigheten, 2002). Of these 5 000 kWh is household electricity, 5 000 kWh is for hot water production and the remaining 15 000 kWh is used for heating. The climate panel provides around 1300 kWh per year, which is equivalent to 5% of the total energy need and 9% of the heating. The amount of money saved depend on what type of heating system is installed in the building, which also determines the pay-pack time. Table 10 shows the estimated production cost for the panel. The pay-back time is simply estimated as the production cost divided by the annual saving. The amount of money saved per year and the pay-back time for different heating systems is displayed in table 11.

Table 10. Cost for material and production of climate panel.

Part	Cost
PV panel	1 500
Peltier elements	2 000
Aluminum fins	1 000
Insulation	200
Wires	100
Additional materials (screws etc.)	50
Work	800
Total	**5 650**

Since the cost of the panel is roughly estimated, a production cost of 5 000 SEK has been used to determine the pay-back time. The annual energy saving calculated in the previous chapter took into account both the heating and the cooling power. In Sweden, however, cooling systems are not commonly used in single family houses. Heating systems are running when necessary but even if cooling will help increase the indoor comfort it will not decrease the energy usage. When comparing the climate panel to common heating systems, as shown in table 11, the cooling power has therefore been excluded. The annual energy saving achieved by the panel is therefore closer to 1 200 kWh.

Table 11. Money saved per year in SEK for different heating solutions.

Heating system	Price[2] (SEK/kWh)	Annual Cost Heating (SEK)	Saving (SEK)	Pay-back time
Electrical Heating	1.20	18 000	**1 440**	**3.5**
Oil	1.40	21 000	**1 680**	**3.0**
Gas	0.90	13 500	**1 080**	**4.6**
District heating	0.80	1 000	**960**	**5.2**
Bio Fuel	0.70	10 500	**840**	**6.0**
Typical Heat pump	0.40	6 000	**480**	**10.4**
ETK5000	0.44	6 600	**528**	**9.5**

As table 11 shows the saving and pay-back time vary with the type of fuel replaced. Compared to a heat pump with a heat factor of 3 the economical gain is low and the pay-back time long. The pay-back time for an air-to-air heat pump is generally 3-5 years (Vattenfall, 2014), and in comparison to that this system is a worthy investment for the top four heating systems in table 11.

An important factor to consider when evaluating the economic viability of the system is the investment cost. A large investment is demanded to replace a heating system with another. If there is a shortage of capital it could therefore be worth to add a system like the climate panel to the current heating systems to lower the energy usage and annual cost, rather than investing in a new heating system.

The pay-back time of the climate panel for three different scenarios is displayed graphically in figure 36. (The calculations behind the graph can be found in appendix 11.6) As said before it is assumed that the temperature level at the fin, from which heat is transferred to the air, is the mean temperature between the hottest and coolest spot. The “High level” spot is that where the fin is in direct contact with the TE module. The “Low level” spot is at the edge of the fin. Depending which temperature is assumed across the panel the outcome varies and thereby the economic gain and pay-back time. As the figure shows the pay-back time varies greatly depending on which temperature level has been used in the calculation. If the low level is used the pay-back time becomes too large for the panel to be competitive with commercial heating systems. If the high level is used, on the other hand, the pay-back time becomes good enough for the panel to compete with even the most efficient heating systems. The conclusion is that, in order to make the climate panel economically viable, effort should be spent on making sure there is a fast and even temperature spread across the fins. This will maximize the heat transfer to the air and thereby the power output.

[2] Energimyndigheten, 2013

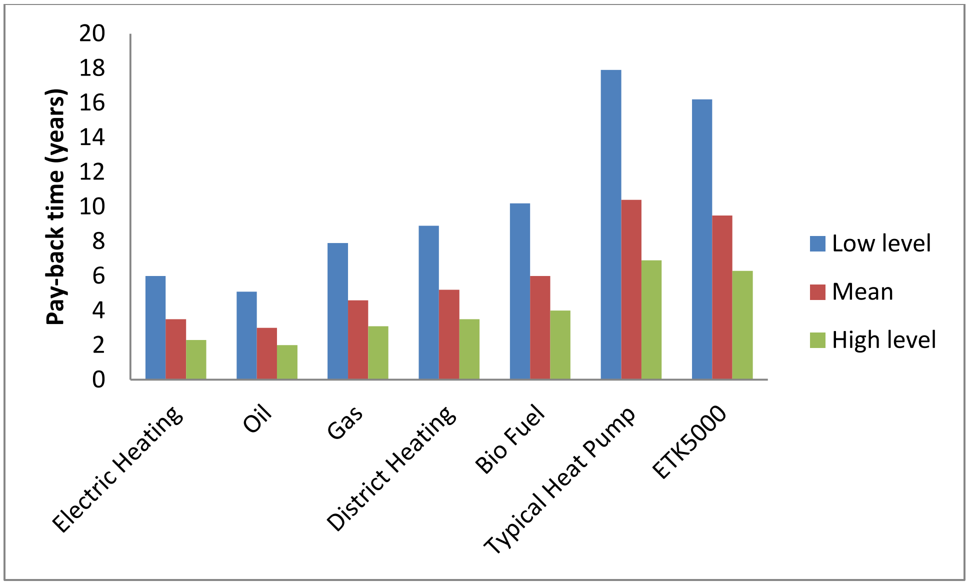

Figure 36. Pay-back time of climate panel compared to common Swedish heating systems. "Low level" means the temperature at the edge has been used for the calculations, "High level" means that the temperature where the fin is in contact with the TE module has been used and "Mean" means the average between the two has been used.

8. Discussion and Evaluation

8.1 Evaluation of the result

The first impression when studying the result of the analysis is that the climate panel has good potential. A quick way to evaluate the viability of the result is to compare the yearly energy output with that of PV panel. The annual energy output from a PV panel used in Sweden is said to be roughly between 100-150 kWh/m^2 (Energimyndigheten, 2011). The PV panel used in this project is about 1.6 m^2 and the yearly output should therefore be somewhere around 240 kWh. Compared to the energy output of the climate panel this corresponds to a COP value for the panel of around 5. This is agreeable with the result presented in table 7. As stated earlier this value is probably a bit too optimistic, but since this product is not yet fully developed and further testing is needed it could be used as a theoretical benchmark for future prototypes.

Considering the fact that the calculations are based on the test results of the initial prototype there is great room for improvements. When used along with commercial heating systems they pay-back time is short enough to make the climate panel a worthy investment. It needs to be remembered, however, that it cannot be used as a replacement of the existing heating system but simply as a complement. Compared to conventional air-to-air heat pumps this solution has a longer pay-back time, but a lower initial investment. A typical air heat pump has an investment cost of 15 000-30 000 SEK and a yearly output of around 10 000 kWh (Vattenfall, 2014). In comparison the investment of a climate panel is lower but so is the annual output. In order to make the product more competitive it needs to either be improved to increase the output or made cheaper. A third possibility is of course to use it as a separate solution rather than using it as a complement to existing heating systems. This possibility is discussed in future chapters. Another important detail to remember is that the air flow through the panel is assumed to be caused by the rate at which air is sucked out of the house through the exhaust air heat pump system. If the panel is used along with ETK500 the air flow will be induced by the heat pumps system. If used along with any of the other heating systems compared to there might not be any proper ventilation in the house and an additional fan may be needed to create the air flow. Therefore the system, as it is designed in this project, cannot be used directly along with all of the heating systems compared to.

Before drawing any final conclusions regarding the climate panel it is worth stopping for a minute to regard to reliability of the result. Firstly the expected heating caused by the PV cells cannot be evaluated, since the result is based on simulations only. The actual temperature increase of an air stream cooling the PV cells has not been tested practically. Previous studies on air cooled PV panels look into the possibility to increase the electrical output by reducing the temperature of the PV cells. The result presented in these studies, such as (Tonui J.K Tripanagnostopulos Y. , 2006), show only the change in temperature of the PV panel and not in the air stream. These results do, however, show temperature changes of between 10-15°C which correlated to the result of the simulations in chapter 5. The change in electrical output has not been considered in this study, but could have a slight effect on the input current and thereby the power output of the TE modules. Further factors that have not been taken into consideration is that fact that the values used are given for optimum conditions where the panel is tilted 45° and facing south. To simplify the installation the climate panel will be paced vertically and attached to the house wall, which may lower the output of the panel.

Looking at the output of the TE wall it can be concluded that the result of the analysis vary greatly from that of the initial theoretical simulation. The reason, as said before is that the theoretical model used for the simulations did not include conduction, whereas the analysis did. Since no practical experiments were performed using an air stream there is no way of estimating the efficiency of the heat transfer from the fins to the air. The temperature change of the air stream in the simulation showed a maximum of 1°C increase in heating mode and 0.5°C decrease in cooling mode. The analysis showed a decrease of between 5-10°C in cooling mode and an increase of up to 50°C in heating mode. In reality the air stream temperature can be assumed to lay somewhere in between the simulated result and that of the analysis. Other experiences, such as the ones performed by Le Pierrés et al and M. Gillott, show results similar to the ones presented in this report. In the French study (Le Pierrés et al, 2008) the temperature of an air stream with similar flow rate was measured to 17°C in cooling mode and 46°C in heating mode, which is close to the result achieved here. The annual saving in this study was about 1 200 kWh, which is similar to the result of the analysis. This value was, however, achieved using 40 TE modules and a PV area of 11 m^2. Compared to that the result presented in this study seems a bit unreasonable. A lower annual output than the one presented is therefore to be expected in reality. One major difference between this study and the French is that they did not cool the PV cells, which explains the higher power output to some degree. The thermoelectric cooling device tested out by Gillott (Gillott M. et al, 2009) managed to cool the air 7°C using eight TE modules and a similar input current. The output heating and cooling powers of the TE module and the COP values in other studies, amongst Xu et al (Xu X. et al, 2005), are also similar to the result in this study. The conclusion is therefore that the results achieved is somewhat reasonable and in line with similar experiments performed by others.

8.2 Uncertainty factors

There are many factor which affect the outcome of this project. The most important ones are listed below.

- Incomplete mathematical model
- Lack of available values
- Lack of reliable equipment
- Handmade prototype

Firstly the simulations are based on a mathematical model put up by the author. This model is based on formulas gathered from a number of scientific articles. Though the research has been thorough, no experiments have been carried out using PV cells and Peltier elements in the same way as in this project or for the same purpose. Information regarding the function of the TE modules has been easy to find and the relationship between the optimum current and the COP can be considered reliable. The lack in the model is mainly connected to the heat transfer from the modules to the fins and further to the air. This process is described by formulas only found in one scientific article and is not fully adapted to this particular case. Since there has been no time to practically simulate an air flow and measure the temperature change one will have to rely on the simulated result only, which is not completely accurate. For the heat transfer from the PV panel to the air the model is a bit simpler and can be considered a bit more reliable. The fact that there has been no practical experiments performed on the PV panel alone makes this part uncertain since there has been no way to evaluate the result. As always when trying to describe reality with theory simplifications have been done. Also, optimum conditions have been assumed, which will not always be the case in reality.

Another major uncertainty connected to the simulations is the lack of available information from the manufacturers. The model is based on a number of constants and properties specific for the products and materials used. Values for constants such as the Seebeck coefficient and the resistivity have been gathered from various scientific articles. These are connected to the semi-conductors used and can be considered fairly reliable. Some values are however connected to the specific product, such as the U-value for the PV panel. This information is not given by the manufacturers and is hard to get. The estimations done are therefore quite unreliable. Also it has been hard to read the graphs, such as the I-V curve, provided in the product information since these are very basically displayed.

During the experiments there has been a lot of trouble with the equipment, mainly the power supply. The equipment available is old and has broken down several times. It has been hard to get an accurate value of the incoming current and voltage to the prototype. Also there has been a difference in performance between different modules. The “best” result for each trial has been used assuming that with an optimum function this would represent the entire prototype. Some of the experiments have been done using whatever equipment was available in the workshop. Scraps of metal has been put together with tape and air pressurizes without known air flow or evenly applied pressures have been used. The exact material and property of the insulation is not known and several different types of insulation has been used throughout the tests. All these factors pose a threat to the accuracy of the results but it is hard to tell just how big the effect is. Another important uncertainty which may have an effect on the result is that the temperature in the workshop varies during the day. In the morning the ambient temperature can be as low as 15°C, and in the afternoon when the sun shines it can rise above 30°C. The conditions for the measurements have therefore not been the same and comparing the results is therefore not scientifically defendable.

The prototype used has been handmade. The dents in the aluminum sheet has been hammered by hand and the cutting has been done with inexact measurements. The wires inside the wall has not had the exact same length and it has been hard to make sure the modules are placed in direct contact with the fins. The result has shown that the contact between the fins and the TE modules is very important to get a good heat removal and prevent the modules from overheating. Therefore the human influence when constructing the prototype is a great uncertainty. If someone else were to try and build a similar prototype it is quite possible that the results achieved would differ a lot from the ones presented here.

8.3 Further testing and future prototypes

Further tests on current prototype

Due to lack of time the function of the prototype could not be fully investigated. Here are some suggestions on what further tests could be done on the current prototype to get a more reliable result.

- **Improve the contact between TE module and fin**
  - Try to improve the contact between TE module and fin to get an even heat transfer for all the modules and prevent the modules from breaking due to overheating.
- **Perform longer measurements**
  - Do measurements for longer periods of time to determine how long time it takes for the fin to get an even temperature
- **Try different connections**
  - Connect the modules in new ways to see if the output can be increased or the risk of breakdown decreases
- **Full day measurement with PV panel**
  - Connect the prototype to the PV panel for a full day to get a picture of how the temperature level vary with the sun during a full day – test in different month and with different solar irradiance
- **Create an air flow across the TE wall**
  - Create an air flow to measure the change in temperature level at the fin and the function of the TE module as more heat is removed
  - Measure the temperature change of the air flow at different flow rates to see how much heat is transferred from the fins to the air
- **Cool the PV panel**
  - Create an air flow across the PV panel and measure how the output and temperature of the panel changes when it is cooled
  - Measure the temperature change of the air flow across the PV panel

Future prototypes

In order to develop a finished product more testing is needed and further prototypes should be tried out. Given below are a few suggestions on how future prototypes could be designed in order to give a better result.

Use other types of TE modules

For eventual future prototypes other types of TE modules should be tested than the type used here. The model chosen for this particular prototype was the best considering the factors described in chapter 4, but other modules may prove to work better in practice. As a suggestion it would be interesting to compare the result using fewer and larger modules rather than having several small ones as in this case.

Use different types of fins

The fins used in the experiments performed have not been enough to achieve the necessary heat removal. For future prototypes different types of fins should be tried, for example rippled fins. Only using a sheet of metal to transfer the heat do not provide enough heat transfer to keep the cold side temperature at a level below the ambient. Better results could be achieved by improving the contact between the TE modules and the fins as well as increasing the pressure. Air circulation across the surface would also improve the heat removal.

As the analysis show the output varies greatly depending on what temperature level is used across the fins. During the experiments tested out the heat has not spread fast enough to create an even temperature level across the fin. For future prototypes work should be put into improving the temperature spread, perhaps by trying different materials for the fins or by reducing the amount of insulation used.

Use double connections

As it seems the power output and temperature level from the prototype is larger if series connection is used instead of parallel connection. In heating mode series connection is therefore preferable. The temperature level did, however, get too high to produced any significant cooling with this connection. In order to achieve a prototype which works well in both heating and cooling mode it could be worth considering the possibility of swopping between series and parallel connection. When building a future prototype it may be worth a try of including both parallel and series connection and with a switch between the two. This do include more components and the temperature gain achieved may not be enough to include the extra material, but as a prototype it might still be worth a try.

Add regulator

As this project has shown the temperature levels and thereby the heating and cooling power is dependent on the input current to each element. As the simulations showed the heating power increases with an increasing incoming current, whereas the cooling power has an optimum for a specific current. Rather than swopping between series and parallel connection it might be worth to install a current regulator that can control the incoming current from the PV panel to the prototype. With a lower incoming current the cooling power will increase. A regulator can also make sure that the incoming current and voltage does not exceed the maximum for each module. The prototype has been designed to manage the maximum output from the solar panel, but the practical experiments have shown that in full sunshine the input tends to be too large and when trying series connection several of the modules broke down. A regulator could keep the incoming levels below maximum and the gain in power could out way the increased cost on adding a regulator.

8.4 Designing the product

There are two possible ways of developing this product, as a complement to an existing heating system or as a separate solution. Depending on the usage of the products there are different ways to optimize the solution. Suggestions for how the product can be developed for each of the purposes are given below.

1. Complement to an existing heating system

As the results have shown the power output and efficiency of the system is higher in heating mode than cooling mode. If the panel is to be used as a complement to an existing heating system it needs to lower the annual energy cost. Every kilowatt hour of heat produced by the panel will decrease the energy needed by the existing heating system by one kilowatt hour. The energy which provides the panel is "free" since it is taken from the sun and not purchased from the grid. In order for the system to be effective, however, the COP value of the panel should be higher than that of the heating system. Normally there are losses when energy is converted to heat, for example in an oil boiler. If a heat pump is used the heat factor is instead higher than 100%, typically 3 kWh of heat is received form 1 kWh of electricity. If used along with a heat pump as the ETK5000 the COP value of the climate panel must be larger than the heat factor, otherwise it would be more effective to simply connect the PV panel directly to the heat pump. (This may not be technically possible, but installing solar panels would decrease the amount of electricity purchased to run the heat pump.) If using the climate panel along with an existing heating system it would be wise to focus on maximizing the heat power. Whatever cooling power follows is a gain in indoor comfort, but since the cooling power has no effect on the energy need the focus should be on maximizing the heating.

2. Used as a separate system

If the panel is to be used as a separate solution, for example in a summer house focus should be spend on optimizing the incoming current instead. Supposing the panel is not replacing or complementing another heating system, all heating and cooling power produced can be seen as a gain. By installing a regulator that controls the level of the incoming current the heating and cooling power can be optimized to maximize the indoor comfort. A battery could also be installed to collect the excess power produced by the PV panel and keep the system running as the sun sets. Such a system will become more expensive than a system which compliments an existing heating system. The alternative in this case would, however, be to invest in another heating system with a much higher cost. This type of system requires a bit more work in developing and finding the optimum points, but addresses a different market with less competition. Considering the fact that the product, as it is presently, only functions as the sun is shining it may fit better in houses with no specific heating requirements rather than trying to make it competitive with existing solutions.

8.5 Further applications

The objective for this project has been to evaluate the prototype in terms of an addition to an existing heating system used in a single family house in Sweden. Due to the weather conditions in Sweden heating is needed for most part of the year and the focus has therefore been to maximize the heating power. Generally TE modules are used for cooling purposes and it could be possible to used the product as a cooling device instead. A surplus to this is the fact that cooling is mostly needed when the sun shines the most, hence in summer. The climate panel could therefore be adapted to be used as a cooling device only, preferably countries with more sun hours than Sweden.

In that case it needs to be adapted and optimized, which lays beyond the boundaries of this project but it is certainly possible.

Another obvious gain with the panel is that it can be used in houses that lack electricity. There are still many living areas in the world without electricity. Installing a product such as the climate panel could help creating a comfortable indoor environment in these houses. The system could also further be developed to produce hot water. In areas where only cooling is needed the air cooling down the PV panel is useless. The PV cells could instead be cooled by water, which would be heated up. If stored properly it could be used as domestic hot water.

This project has studied the solution for a single family house. Larger panels could also be produced to provide building complexes or be placed on the roof to multi-family houses. The TE modules could then be build into the ventilation system of the house and be powered by PV panels placed on the roof. The design of such a system would differ from the design developed here, but it is a possibility worth looking into. The panel as it is could also be installed beneath the window of a single apartment. Thanks to the smaller living area and energy need of an apartment the panel may prove to be more economically viable.

9. Conclusion

The purpose of this project has been to investigate the possibility of designing a solar driven air-to-air heat pump by connecting Peltier elements to a PV panel, and evaluate its potential. After performing a theoretical and practical study the conclusion can be drawn that:

– Yes, it is indeed possible, and there is enough potential to extend the trials and develop the prototype into a heating system.

The results showed that, as the prototype is designed now, it is possible to save up to 1 300 kWh a year if adding the panel to an existing heating system. This corresponds to 9% of the heating and 5% of the total energy need for a "normal" Swedish house. Depending on the system used along with the pay-back time of the panel is between 3-10 years, which is in the range of other heating systems. It was proven that the output is larger in heating mode than cooling mode, which correlates with the need of a Swedish house. Two paths have been outlined for further development of the project. The first is to use the panel as a complement to an existing heating system. In this case the panel should be optimized to maximize the heating output. The more heat is being produced the more energy can be saved throughout the year. Another way to make the panel more competitive is to cut the cost. The second path is leading towards using the panel as a separate solution, for example in summer houses. In this case a regulator should be added to optimize the incoming current to provide the maximum heating and cooling power to improve the indoor climate when the house is in use. It is also possible to add a battery to power the panel when the sun is not up.

There are several advantages to the climate panel, if being developed into a full product. Compared to conventional air-to-air heat pumps the design contains no movable parts, which increases the lifetime and make it more sustainable. The panel is an environmentally friendly solution, sine it contains no transfer fluids and is powered by renewable electricity from the sun. Another advantage is that it is self sustained, which means it can be used in houses that are not connected to the electric grid. The investment cost is also relatively low compared to other heating systems. Amongst the disadvantages is the fact that the panel, as it is designed today, only works when the sun is out and can therefore not be used to provide a house where people live all year. Compared to other heating systems the total power output is low and costs need to be cut in order to make it a more worthy investment.

As stated earlier this project is the starting point to developing the final product, and there are a lot of things to be improved. Due to lack of time and equipment the results are not completely trustworthy, but should be seen as an indication of future potential instead. There are flaws in the theoretical model as well as the model for analyzing the test results. Therefore there is a broad span to the presented result, which needs to be tightened to fully evaluate the product. Future tests and improvements are needed to take this project to the next level, but considering the fact that no similar experiments have been done before the idea has proven to have great potential.

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11. Appendix

11.1 Nomenclature

Coefficient	Unit	Description
Energy and Electricity		
W	J	Work (Energy)
P	W	Power
I	A	Current
V	V	Voltage
R	Ω	Resistance
q_{el}		Electric charge
Q	J	Heat (Energy transferred)
T	K	Temperature
t	s	Time
η	%	Carnot efficiency
TE elements		
N		Number of TE elements
α	V/K	Seebeck coefficient
π	J/A	Peltier coefficient
T_H	K	Hot side temperature
T_C	K	Cold side temperature
ΔT	K	Temperature difference (T_H-T_c)
T_m	K	Mean temperature
Q_c	J	Cold side heat transfer
Q_H	J	Hot side heat transfer
ρ	Ω m	Resistivity
K	W/m*K	Thermal conductivity
Z	K	Figure of merit
g	m (m^2/m)	Geometry factor (area/length)
I_{opt}	A	Optimum current (for maximum COP)
COP_{max}		Maximum COP
PV panels		
η_{pv}	%	Electrical efficiency of PV cell
η_{ref}	%	Efficiency at T_{ref}
η_{th}	%	Thermal efficiency
η_0	%	Thermal efficiency for T_{in}=T_{amb}
β	/K	Efficiency temperature coefficient
T_{pv}	K	Operating temperature
T_{ref}	K	Reference temperature

		(25°C)
A_a	m^2	Area of PV module
G	W/m^2	Solar irradiance
F_R	-	Heat removal factor
τ	-	Transmissivity
α_a	-	Absorptivity
Air flow		
T_{house}	K	Temperature into house
T_{out}	K	Temperature out from panel
T_{in1}	K	Temperature in at front of panel
T_{in2}	K	Temperature in at back of panel
T_p	K	Temperature after passing PV cells
A_{TE}	m^2	Area of thermoelectric element
q	W/m^2	Heat flux
h_c	W/m^2*K	Convective heat transfer coefficient cold side - air
h_h	W/m^2*K	Convective heat transfer coefficient hot side - air
$C_{p, air}$	J/K*kg	Air specific heat
m_{air}	kg/s	Mass flow ventilation air

11.2 Swedish laws and regulations on indoor comfort

Energy efficiency regulations

The regulations regarding energy efficiency in buildings define maximum levels for three different climate zones in Sweden (BFS 2013:14). The maximum heat transfer 0.40 W/m^2*K is the same for all three zones but the accepted energy usage vary due to different outdoor temperatures. The specific energy usage for buildings are limited to:

- 13 kWh/m^2 *year for zone 1 (North) , 110 kWh/m^2 *year for zone 2 (Middle) and 90 kWh/m^2 *year for zone 3 (South) – for buildings not using electric heating
- 95 kWh/m^2 *year for zone 1 (North) , 75 kWh/m^2 *year for zone 2 (Middle) and 55 kWh/m^2 *year for zone 3 (South) – for buildings using electric heating

Regulations regarding dampness in indoor air

According to the chapter 22 §28 of the Swedish Environmental Code the requirements for indoor air quality in buildings, with regards to moisture, are (BFS 2013:14):

- No excessive condensation should be seen at windows for an outdoor temperature of -5°C or lower.
- The moisture content in the air should not regularly exceed 3 g/m^3 air.
- The relative moisture content at 21°C should not exceed 45%, which is equivalent to 7 g water/ kg dry air.

Regulations regarding indoor temperature

Legislation regarding indoor temperature is stated in chapter 26 §19 of the Environmental Code and include living spaces such as kitchen and bathroom, as well as other spaces where people reside more than temporarily. "Thermo climate" is defined as factors which affect a person's heat exchange with the environment. Measurement should include evaluation of air temperature, air movement and floor temperature. The indoor temperature should not:

- Be less than 18°C in living and working areas
- Be less than 20°C in service homes or schools
- Be less than 16°C or higher than 27°C at the floor

Regulations regarding heating

The heating systems should be designed so that the indoor temperature do not decrease drastically for extreme outdoor temperatures. A heating system should be designed so that:

- The indoor temperature decrease is maximum 3°C for an extreme outdoor temperature occurring once every 20 years.

Regulations regarding ventilation

Recommendation for carrying out chapter 9 §3 and chapter 26 §22 of the Swedish Environmental Code regarding air quality and ventilation. For residential areas the requirements are (BFS 2013:14):

- The air exchange rate should not fall below 0.5 room volume per hour.
- The outflow of air should be above 0.35 l/s*m^2 or 4 l/s*person.
- The outflow of air from rooms with many people should be 7 l/s*person.
- The air flow within a room should not exceed 0.15 l/s to not cause uncomfortable draughts.
- CO_2 levels should stay below 1000 ppm.
- The difference in absolute moisture between outdoor and indoor air should not exceed 3 g/m^3.

According to energy efficiency rules the maximum fan power for dimensioned air flows cannot exceed the following values:

- 2.0 kW/m^3*s for inlet-exhaust systems with heat recovery
- 1.5 kW/m^3*s for inlet-exhaust systems without heat recovery
- 1.0 kW/m^3*s for exhaust air systems with heat recovery
- 0.6 kW/m^3*s for exhaust air

11.3 Decision basis to finding the proper TE module for the prototype

Table 12. Table presenting the output heating and cooling powers of different TE modules along with the two available PV panels. The result has been used as a foundation for deciding which type of TE module should be used in the prototype. The models are sorted after heating output.

Model	Number of elements	Connection	P=Imax*Umax (W)	Qc (W)	Qh (W)	ec	eh	
PE-127-14-25-S	4	2Sx2P	245	154	399	0.77	2.00	
QC-71-1.4-3.7M	8	4Sx2P	243	154	397	0.77	2.00	
QC-127-1.4-8.5MD	2	2S	248	148	396	0.74	2.00	
PF127-10-13	4	2Sx2P	245	150	395	0.75	2.00	
PF127-10-20	6	2Sx3P	245	149	394	0.75	2.00	
QC-63-1.4-8.5M	4	4S	245	148	393	0.74	2.00	
QC-31-1.4-8.5M	8	8S	245	144	389	0.72	1.94	
HT3-12-F2-3030	6	2Sx3P	242	144	386	0.72	1.93	
QC-17-1.0-3.9M	30	15Sx2P	234	147	381	0.74	1.91	
CP1.0-127-05	6	2Sx3P	240	134	375	0.67	1.87	
QC-127-1.0-3.9M	4	2Sx2P	228	146	374	0.73	1.87	
QC-241-1.4-8.5M	1	1S	235	135	370	0.68	1.85	
QC-63-1.0-3.9M	8	4Sx2P	225	144	369	0.72	1.84	
QC-127-1.4-3.7MS	4	2Sx2P	229	138	367	0.69	1.83	
HT4-12-F2-3030	4	2Sx2P	225	132	357	0.66	1.78	
QC-241-1.0-3.9M	2	2P	216	138	354	0.69	1.77	
PE-017-05-15-S	126	9Sx14P	212	139	350	0.69	1.75	
QC-31-1.4-3.7M	16	8Sx2P	213	134	348	0.67	1.74	
HT4-12-F2-4040	4	2Sx2P	213	128	341	0.64	1.71	
PE-071-10-13-S	6	3Sx2P	206	127	333	0.64	1.67	
TEC1-12706	2	2S	197	126	323	0.63	1.62	
QC-71-1.4-6.0M	4	4S	197	124	321	0.62	1.60	
PE-065-05-15-S	30	3Sx10P	194	126	320	0.63	1.60	
CP1.4-71-10	6	3Sx2P	201	112	313	0.56	1.57	
PE-127-14-15-S	2	2S	188	119	307	0.59	1.54	
PF127-14-15	2	2S	188	117	306	0.59	1.53	
PE-031-10-15-S	14	7Sx2P	181	113	294	0.57	1.47	
BN202113	2	2S	144	144	288	0.72	1.44	
TEC1-1703	30	15Sx2P	171	117	288	0.59	1.44	DK
CP1.4-127-06	2	2S	185	103	288	0.51	1.44	
QC-127-1.4-6.0M	2	2S	175	110	285	0.55	1.42	
QC-63-1.4-6.0M	4	4S	173	111	284	0.55	1.42	
TEC1-12705	2	2S	163	114	277	0.57	1.39	

QC-35-1.4-6.0M	7	7S	168	107	275	0.54	1.38	
HT6-12-F2-4040	2	2S	173	102	275	0.51	1.38	
PE-071-14-15-S	3	3S	158	100	258	0.50	1.29	
CP1.4-71-06	3	3S	155	86	241	0.43	1.20	
PE-127-10-13-S	2	2Sx2P	122	76	198	0.38	0.99	
BN202112	2	2Sx2P	96	96	192	0.48	0.96	DK
PE-017-05-15-S	37	37S	62	41	103	0.20	0.51	
PE-065-05-15-S	9	9S	58	38	96	0.19	0.48	

11.4 Input used for the simulations in chapter 5

PV cells

The expected power output of the PV cells for varying solar irradiance is given by the I-V curve (figure 14), which is provided by the manufacturer. The model is based o the equations in chapter 4 and the input is presented below.

Table 13. Input used to simulate the temperature of the air stream cooling the PV cells.

Himin 250 W	
Aa (m^2)	1.63
m_{air} (kg/s)	0.035 [3]
Cp (J/kg*K)	1005
U (W/m^2*K)	7 [2]
η_0	0.3 [4]

TE modules

The model used for the TE simulations are the one presented in chapter 5. The TE module chosen for the simulation, as well as the practical experiments, was of the model QC-71-1.4-3.7M with properties described in table 3. For the simulation only one module is studied.

Table 14. Properties of TE module model QC-71-1.4-3.7M.

Bismuth-Telluride, Bi_2Te_3[5]	
α0 (V/K)	2 2224
α1 (V/K)	930.6
α2 (V/K)	6 2605
R0 (Ω/cm)	5112
R 1(Ω/cm)	163.4
R 2(Ω/cm)	0.6279
K0 (V/cm*K)	6 2605
K1 (V/cm*K)	-277.7
K2 (V/cm*K)	0.4131
QC-71-1.4-3.7M	
N	71
Qmax (W)	19.3
Imax (A)	3.7
Vmax (V)	8.2
Rmax (Ω)	2.22
Pmax (W) (Imax*Vmax)	30.34
ΔTmax (K)	72
Length (mm)	30
Width (mm)	30
Thickness (mm)	4.7
Geometry factor (mm)	0.03

[3] Boverket, 2013
[4] Tonui J.K Tripanagnostopulos Y. , 2006
[5] Riffat S.B Ma X, 2004

11.5 Calculations of values presented in chapter 7.1 table 5-7

PV panel

The thermal efficiency of the PV can be, as described in chapter 4, expressed as:

$$\eta_{th} = \frac{Q}{A_{pv} * G} = \frac{\dot{m} * C_p * \Delta T}{A_{pv} * G}$$

The temperature difference achieved across the PV cells depend on the solar insolation G. Since there has been no time to measure the temperature difference practically the simulated values will have to do in this case. The amount of heat transferred to the air, Q, can be expressed as:

$$Q = n_{th} * A_{pv} * G = \dot{m} * C_p * \Delta T$$

The values used are:

η_{th}: 0.30
A_{pv}=1.63 m^2

TE wall

The amount of heat transferred to the air passing the wall with the TE modules can be determined using the following two equations from chapter 4.

$$Q_C = A_{TE} * h_c * \left(T_{cfin} - T_{cm}\right) = \alpha * I * T_c - \frac{R}{g} * \frac{I^2}{2} - K * g * \Delta T$$

$$Q_H = A_{TE} * h_h * \left(T_{hm} - T_{hfin}\right) = \alpha * I * T_H + \frac{R}{g} * \frac{I^2}{2} - K * g * \Delta T$$

$$Q_{c-air} = \dot{m} * C_p * (T_{camb} - T_{cm}) \quad , \quad Q_{h-air} = \dot{m} * C_p * (T_{hm} - T_{hamb})$$

In this case practical measurements of the temperature change has been done. T_{cfin} and T_{hfin} stands for the hot and cold temperature which has been measured at the fin. To calculate the heat transfer to the air calculations have been done in two steps. Firstly the convective heat transfer from the elements to the fins and from the fins to the air has been taken into account using the equations in the first and second row. Qc and Qh have been calculated using the right side of the equations. Once these are received the left side of the equations has been used to determine T_{cair} and T_{hair}. These are the temperature of the air stream in cooling and heating mode caused by all eight TE modules. The area used is the area of the fin to which the heat is spread in a decent amount of time. This area has been determined to include all TE modules with an edge of 10 cm surrounding it. h_c and h_h are the convective heat transfer coefficients. The same value has been used for these constants, 305 W/m^2*K, which has been taken from Le Pierrés report where similar fins were used (Le Pierrés et al, 2007). Once the temperature of the air stream is known the heat transferred to the air has been determined using the equations in the third row. T_{camb} and T_{hamb} are the ambient temperatures. In cooling mode this is set to 25°C for all values and for heating mode it has been put to the outside temperature of -5°C plus the temperature increase caused by the PV panel.

Calculations have been performed for series and parallel connection and the highest and lowest measured temperatures have been used to get a span. The input is presented in table 15 below and the output temperature and heating power of the air stream for series and parallel connection in table 16-17.

Table 15. Input parameters used for all calculations.

G	I	V	Qc-simulated	Qh-simulated	Tc-amb	Th-amb
1000	8	31	1.3	11	25	8.9
800	6.5	29	1.3	11	25	6.1
600	5	27	1.7	9.3	25	3.3
400	3.5	25	2.1	7.5	25	0.6
200	2	23	1.9	4.9	25	-2.2

Table 16. Simulated temperature and heat power of air stream for series connection at different solar insulation.

G	Tc fin high	Th fin TE high	Tc fin low	Th fin low	Tc-air high	Th-air high	Tc-air low	Th-air low	Qc air high	Qh air high	Qc air low	Qh air low
1000	37	82	25	31	37	82	25	31	-423	2 560	-1.3	772
800	30	70	19	24	30	70	19	24	-177	2 236	210	625
600	18	47	19	24	18	47	19	24	245	1 528	209	272
400	16	34	19	21	16	34	19	21	314	1 167	210	710
200	16	28	17	19	16	28	17	19	315	1 057	280	638

Table 17. Simulated temperature and heat power of air stream for parallel connection at different solar insulation.

G	Tc fin high	Th fin high	Tc fin low	Th fin low	Tc-air high	Th-air high	Tc-air low	Th-air low	Qc air high	Qh air high	Qc air low	Qh air low
1000	18	20	18	21	16	26	18	21	315	590	245	414
800	18	26	16	17	17	21	16	17	298	530	315	372
600	17	22	18	18	18	20	18	18	244	578	245	508
400	17	20	17	18	17	20	17	18	279	675	279	604
200	17	17	17	17	16	17	17	17	297	670	279	670

11.6 Calculations for data presented in figure 36 chapter 7.2

Table 18. Power output in heating and cooling mode for low, high and mean temperature levels at the fin.

G (W/m²)	Qc low	Qh low	Qc mean	Qh mean	Qc high	Qh high
1000	-1.3	1261	-213	2 155	-423	3 049
800	210	1016	16.4	1 822	-177	2 627
600	209	565	227	1 193	245	1 821
400	210	906	262	1 135	314	1 363
200	280	736	297	946	315	1 155

Table 19. Annual energy output for low temperature level.

Month	Solar time (h/day)	Global irradiance (kWh/m²*day)[6]	G (W/m²)	Mode	Q (kW)	Energy output (kWh/day)	Energy output (kWh/month)
January	1	0.5	500	Heating	0.74	0.74	22.9
February	2	1	500	Heating	0.74	1.48	41.4
March	3.5	2	570	Heating	0.62	2.17	67.3
April	5.5	3.5	636	Heating	0.65	3.58	107
May	7.5	5	666	Heating	0.71	5.33	165
June	7	5	714	Cooling	0.21	1.47	45.6
July	7.5	5	666	Cooling	0.21	1.58	47.4
August	6.5	4	615	Cooling	0.21	1.37	42.5
September	4.5	2.5	555	Heating	0.82	3.69	111
October	2.5	2.5	1000	Heating	1.13	2.83	87.7
November	1.5	1.5	1000	Heating	1.13	1.70	51.0
December	1	0.5	500	Heating	0.74	0.74	22.9
Whole year total							**812**

[6] Values for Växsjö Sweden (SMHI, 2007)

Table 20. Annual energy output for mean temperature level.

Month	Solar time (h/day)	Global irradiance (kWh/m²*day)[7]	G (W/m²)	Mode	Q (kW)	Energy output (kWh/day)	Energy output (kWh/month)
January	1	0.5	500	Heating	1.16	1.16	36.0
February	2	1	500	Heating	1.16	2.32	65.0
March	3.5	2	570	Heating	1.18	4.13	128
April	5.5	3.5	636	Heating	1.31	7.21	216
May	7.5	5	666	Heating	1.40	10.5	325
June	7	5	714	Cooling	0.11	0.77	23.9
July	7.5	5	666	Cooling	0.16	1.20	36.0
August	6.5	4	615	Cooling	0.21	1.37	42.5
September	4.5	2.5	555	Heating	1.18	5.31	159
October	2.5	2.5	1000	Heating	2.2	5.5	171
November	1.5	1.5	1000	Heating	2.2	3.3	99.0
December	1	0.5	500	Heating	1.16	1.16	36.0
Whole year total							**1 337**

Table 21. Annual energy output for high temperature level.

Month	Solar time (h/day)	Global irradiance (kWh/m²*day)[8]	G (W/m²)	Mode	Q (kW)	Energy output (kWh/day)	Energy output (kWh/month)
January	1	0.5	500	Heating	1.59	1.59	49.3
February	2	1	500	Heating	1.59	3.18	89.0
March	3.5	2	570	Heating	1.75	6.13	190
April	5.5	3.5	636	Heating	1.97	10.8	324
May	7.5	5	666	Heating	2.09	15.7	487
June	7	5	714	Cooling	0.21	1.47	45.6

[7] Values for Växsjö Sweden (SMHI, 2007)
[8] Values for Växsjö Sweden (SMHI, 2007)

July	7.5	5	666	Cooling	0.22	1.65	49.5
August	6.5	4	615	Cooling	0.24	1.56	48.4
September	4.5	2.5	555	Heating	1.72	7.74	232
October	2.5	2.5	1000	Heating	3.05	7.63	237
November	1.5	1.5	1000	Heating	3.05	4.58	137
December	1	0.5	500	Heating	1.59	1.59	49.3
Whole year total							**1 938**

12. List of Attachments

1. Product specification HiminPV – HG240S/245S/250S/255S Monocrystalline Photovoltaic Module
2. Product Specification AmpleSun – Product ASF
3. Product information sheet ETK5000
4. Product specification QC-71-1.4-3.7M