



# EIT KIC InnoEnergy Master's Programme

## Renewable Energy - RENE

**MSc Thesis**

**Technical and economic analysis of a novel asymmetric  
PVT hybrid solar collector**

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**Session: September 2013**



Escola Tècnica Superior  
d'Enginyeria Industrial de Barcelona

UNIVERSITAT POLITÈCNICA DE CATALUNYA

*MSc RENE is a cooperation between*

Universitat Politècnica de Catalunya, Spain | KTH-Royal Institute of Technology, Sweden  
Instituto Superior Técnico, Portugal | École Polytechnique (ParisTech), France



## Abstract

PVT collectors produce both electricity and heat from the same area. A novel design for concentrating asymmetric PVT collector has been tested. By flowing the water inside the collector increases the electrical efficiency and produce hot water.

For characterizing the new prototype, a test set-up was constructed in Älvkarleby at Solarus AB laboratory and in University of Darlana, Sweden to evaluate the electrical and thermal parameters. The results are discussed and an electrical and thermal performance analysis have been done with the Solarus PVT collector. The electrical efficiency has been observed with cell and receiver temperature.

A thermal comparison is established between two different climates. One special prototype has been made for this thesis work with two different selective surface. The thermal efficiency respectively at zero reduced temperature for these two types of selective surfaces were 0.65 and 0.64, the U-value was  $8.366 \text{ W/m}^2\text{°C}$  for the trough with Solkote selective coating and  $8.606 \text{ W/m}^2\text{°C}$  for the trough with Q loss selective surface coating. The annual thermal output of these two selective surfaces has been calculated for two different geographic locations, Dhaka, Bangladesh and Älvkarleby, Sweden.

An economic analysis has been performed of the Solarus collector for matured (subsidy free) and early adopter (with subsidy) market. The total cost with internal rate of return (IRR) has been calculated for different number of Solarus collector in Sweden. The potential customer and market have been identified.



## Acknowledgements

First and foremost the author is grateful to ALLAH.

The author would like to thank KIC-Innoenergy program. Without the KIC-Innoenergy initiative, I would never had the opportunity to study in Europe. I would like to thank our program coordinator (RenE) prof. Enrique Velo for his continuous support and encouragement.

The author is intensely grateful to his supervisor at UPC, Prof. Sergio Busquets, for his excellent guidance and encouragement throughout the study. I would also like to give a special thanks to my industrial supervisor at Solarus, Mr. João Santos Leite Cima Gomes to give me an opportunity to work with him. He has been an enormous support, in both practical and thesis-related affairs. The author is glad to have had the opportunity to meet and work with both these people.

Special thanks to Solarus team for giving an opportunity to work on their prototype and for being supportive. I would like to thank Beat, Andrea, Karina, Tony, Henrick and others.

The author owe much gratitude to Dr. Matts Rönnelid for taking him to Dalarna University, and for the opportunity to use the laboratory there. Author also wish to thank Dr. Björn Karlsson, Emmanouil Psimopoulos, Evan Justin, Jihad Haddi, Linkesh Diwan, and Luís Ferreira, for their advice and assistance.

The author wish to express his thanks to his family who has been giving support all the way of his life, his friends and somebody very special.

Finally, I would like to extend my thanks to all persons who encouraged or helped me during my work.

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## 1 Introduction

A hybrid Photovoltaic/thermal (PVT) is a combined PV panel with thermal collector which able to produce electricity and heat. It offers the same advantages of PV and Thermal collector with these advantages:

- Generates higher electricity output than a standard PV panel.
- Maximizes available roof space.
- Lower installation costs.

The concept of photovoltaic/thermal (PVT) gives an opportunity to increase the overall efficiency of a PV module through the use of excessive heat. The water flows inside the receiver which helps to reduce the temperature of the PV module. This cooling effect enhances the overall efficiency of the system.

Photovoltaic electricity comes from the conversion of sunlight into electricity in semiconductor materials, such as silicon which is covered with a thin metallic layer. These photosensitive materials have the property of releasing their electrons under the influence of external energy. This is the photovoltaic effect. The energy is supplied by photons (light components) that offend the electrons and release them, inducing an electric current.

The solar radiations which are coming from the sun, and succeeded to penetrate the glass to the absorber, without any reflection from the glass are absorbed, the absorber heats a network of copper pipes water circulates. This technology which we call a solar collector, it produces hot water or heat. All devices that act as solar collectors are increasingly integrated into the sustainable architecture projects. [3]

The prototype for this work combines between these two technologies, also the concentration of the irradiance. It is a low concentrating PV/Thermal (PVT) collector. This type of collector has mainly one aim is to reduce the price of electricity, by reducing the PV area, increasing the electrical efficiency and compensate by the concentration of the light on this smaller area, which makes it more cost effective, because we get the same amount of electricity produced with lower PV cell area.

This thesis deals with a prototype under this reference CPC-PVT and CPC-T built in Solarus AB, Älvkarleby, Sweden. Their mission is to make it more attractive for customers, and more cost effective, by improving the both thermal and electrical performances and to increase the system's total energy output.

The work which will be done in this thesis, consist on first, the electrical and thermal performance of CPC-PVT and observe the performance with different parameters, heat losses and optical efficiency of this prototype which has two absorbers painted with two different paints, one called Solkote which is glossy, and the second is Q-loss which is mate. And also to study the economic aspects of the collectors.



## 1.1 Motivation

In concentrating solar systems, solar cell which are the most expensive part of solar, use very small space. Because in concentrating system the incident solar rays are concentrated in a small solar cell. Which reduces the cost of the solar panel significantly. And also it increases the electric power output.

By reducing the amount of high cost, the life cycle costs (carbon emission during manufacture and transport and other costs) per watt power also reduces. Therefore, it is important to focus on concentrating solar system.

Solarus AB is a Swedish SME that produces asymmetric concentrating roof-integrated solar collectors, known as CPCs (Compound Parabolic Collectors). The collectors are based on MaReCo (Maximum Reflector Collectors), which attempts to minimize the collector material with a concentrating design.

## 1.2 Company Description:

Solarus AB is a Swedish SME that produces asymmetric concentrating solar collectors. Solarus has a modular collector box in which different types of absorber can be inserted in order to create different products, such as the asymmetric concentrating PV/Thermal collector (PVT).

Solarus AB was founded by Niclas Stenlund and Stefan Larsson as a private limited company in Norrtälje, Sweden 2006.

“The company’s mission was the development, production and marketing of concentrated solar technology to the world market.” Solarus provides solar energy technology to professional users.



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Figure 1.1. Solarus Logo

Solarus is continuously searching for new ways of optimizing its solar collectors and regularly tests the performance of new prototypes. In this context, several partial modifications to the original collector were tested and a novel asymmetric concentrating PVT prototype is built and ready to be evaluated.

### 1.3 Objectives

The main aims for this thesis are to:

- Introduce the new technology.
- Comparing the performance of using different receiver paints in Solarus CPC- T collector.
- Analyzing the electrical performance of the PVT collector.
- To perform an economic analysis of the collector.



## 2. Theoretical Background

### 2.1 Historic development

Since a very long time the basic of solar heating has been known and used. In the 4<sup>th</sup> century BC the ancient Greeks use to heat their homes by the passive solar energy [21], in the 18<sup>th</sup> century there were some ideas how actively convert solar energy to heat, when the highest temperature could be achieved in a "hot box" was tested by scientists, the box was insulated with glass lid. Black painted metal tanks were used by people in the 19<sup>th</sup> century to as solar water heater; they use to put them on the roofs. However, as soon as the sun goes down the water inside these tanks cool down and this technique takes a long time to heat the water. In 1891 this technique with the "hot box" was combined with the black metal tanks, to give the first commercial solar water heater in the world by Clarence Kemp from Baltimore, USA [22]. These collectors were of a black metal tanks putting inside boxes and covered with glass lids, capturing the sunlight. A similar system to the solar systems used today was developed by 1909 William J. Bailey in 1909 [23], in this system the tank and the solar collector are separated to two units, here the tank is insulated with the possibility of placing it inside the house, keeping the water hot for longer time than the previous one. [6]

After some years, the market for solar thermal energy started to increase in the United States, but then failed as gas and electricity became available at low price. In the 1950's, 1960's and 1970's greater attention was paid to solar thermal energy in all countries of the world. Technology was introduced in Japan, where the market has grown very rapidly. Also in countries around the Mediterranean Sea, Australia and Greece, in these areas people started using solar water heater and the market last for a long time [4]. When the oil embargo took place, in 1973, and the prices of oil increased greatly, the solar water heater industry restart again in many places.

In the mid-1980s, the prices of oil became stable then, sales of solar collectors dropped [6].

During the time between 1981-1989, more than 100 PVT-liquid collectors were manufactured and installed by SunWatt, it is located in USA, did work on low-concentrating PVT and started the development in 1978 [7]. During the 80s, many projects started to appear in Europe [8].

## 2.2 Solar Irradiation

The term “solar energy” is mostly understood as the radiant energy emitted by the Sun and which is converted into electrical or thermal energy on earth.

Energy from the Sun is come from nuclear fusion reactions which happen in the deep core of the Sun (Fig. 2.1). The spectrum of the sun’s radiation and the one of a blackbody are similar, at approximately 5777 K, the spectrum’s emissivity is considered as equal to 1. The Sun radiation is dispatched in all directions and the radiation incident on the earth outside of the atmosphere is  $1367 \text{ W/m}^2$  [9], also called the solar constant. This is an annual average as the solar radiation varies slightly over the year (from  $1322 \text{ W/m}^2$  in July to  $1412 \text{ W/m}^2$  in December), because the earth is slightly elliptical orbit around the sun and variations in solar activity [9].The amount of solar radiation which reaches the earth is approximately  $1000 \text{ W/m}^2$  it is reduced as it passes through the atmosphere due to absorption of certain wavelengths by molecules in the atmosphere and diffusion by atmospheric pollutants.

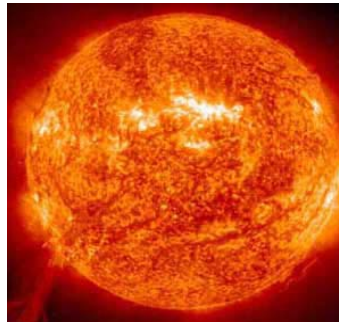
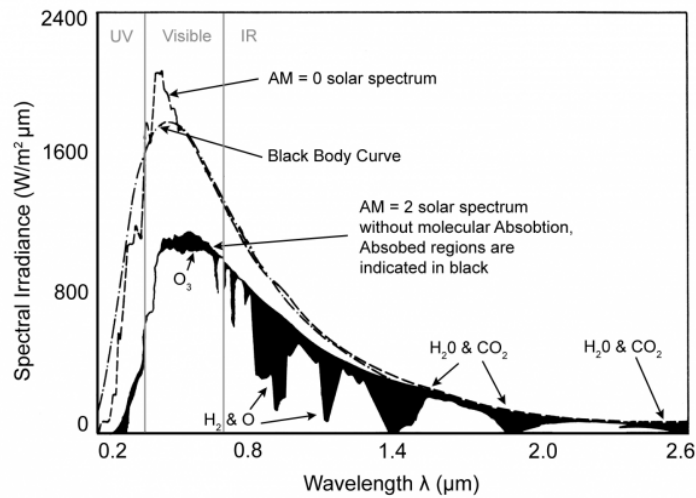


Figure 2.1: The Sun with continuous nuclear fusion reactions

Solar spectrum is the abbreviation of spectral distribution of electromagnetic radiation coming from the Sun, its wavelength extends from  $0.3 \mu\text{m}$  to  $3.0 \mu\text{m}$ , including visible light, ultraviolet and near infrared radiation. The absorbents of solar radiation by atmospheric gases and radiation from the sun before and after passing via the atmosphere are shown on figure 2.2.



Figure 2.2: The solar spectrum for a black body at 5777 K and the absorption bands of different wavelength



Lower irradiance to the ground at higher latitudes, because the angle of incidence of solar irradiance on the earth’s surface is higher. Solar radiation travel through longer distance in the atmosphere to reach higher latitude, which makes it losing more energy by absorbents and reflectance before reaching the earth, therefore the average irradiance at high latitude is lower than lower latitudes.

In Sweden, this amount of annual irradiance on a horizontal surface varies from 950 W/m<sup>2</sup> to 1000 W/m<sup>2</sup>, around Mediterranean sea it is between 1400 W/m<sup>2</sup> and 1800 W/m<sup>2</sup>, it could be over 2300 W/m<sup>2</sup> in some areas such as the desert of Africa, as shown in Figures 2.3 and 2.4 [10].

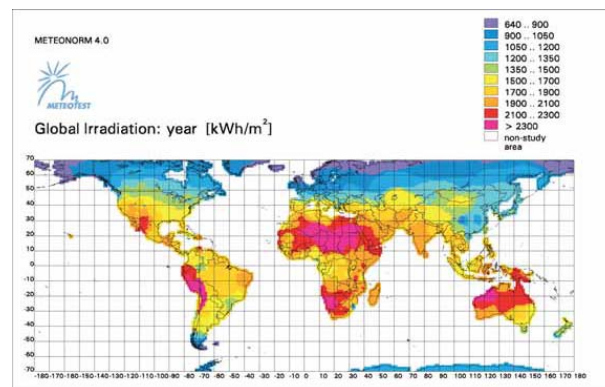


Figure 2.3: The annual global irradiation throughout the world, measured on a horizontal surface

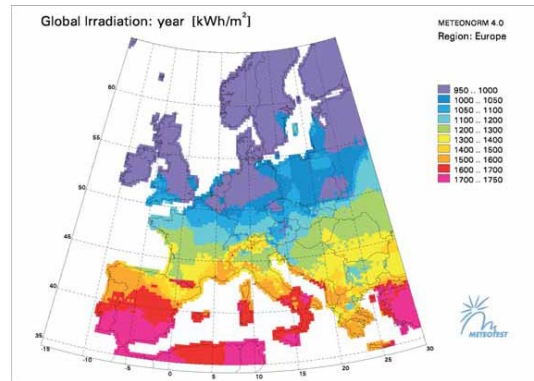


Figure 2.4: The annual global irradiation in Europe, measured on a horizontal surface

## 2.3 The Photovoltaic Effect

The photovoltaic effect is a phenomenon where electrons in a surface become excited by incident light and produce a potential difference between two surfaces. This effect happens naturally in surfaces, particularly metals. In most cases the effect is immediately cancelled by the excited electrons being conducted through the surface itself to neutralize the voltage.

In solar cells, two types of silicon crystal lattices, positive or 'P' type and negative or 'N' type are placed in contact. This creates P-N junction. When the lights reach the crystalline silicon, the hole from N-type semiconductor move to P-zone, and electron from P-zone move to N-zone, that formed the electric current from N-zone to P-zone, then formed the electric potential difference, that comes the electricity source.



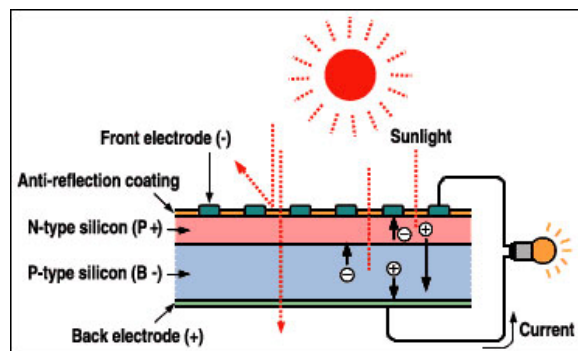


Figure 2.5: The basic working of Solar cell

Since the semiconductor is not a good conductor of electricity, the number of waste electron when passed P-N junction are high and flow in semiconductor as its large resistance.

The following statement from the Berkeley Science Review [28] explains the working principal of a solar cell:

Under normal circumstances, a semiconductor crystal behaves like an insulator and does not conduct electricity. But if sunlight is absorbed in the crystal, it becomes conductive, unleashing energized charge carriers that are free to roam. This charge is most easily collected if the semiconductor is chemically “doped,” meaning that impurities are intentionally added that donate additional charge carriers. A clever doping scheme positions positive and negative charge carriers in such a way that a useful current flows out of the solar cell in response to absorbed light [11].

Different doping agents are used to create the P (excess of holes) and N (excess of electrons) in the crystal lattice. When an electron in the P-N junction absorbs a photon, its energy increases and it jumps to the valance band of the silicon atom or may be freed in the crystal lattice. The valance band in the N side has a lower energy level than the valance band of the p side. So the electrons have a tendency to go towards N side of the P-N junction. This created potential difference between two sides of the crystals. When a load is connected between the N and P side, electrical current flows.

Photovoltaic cells are classified based on the type of crystal, the elements used for doping or their particular construction.



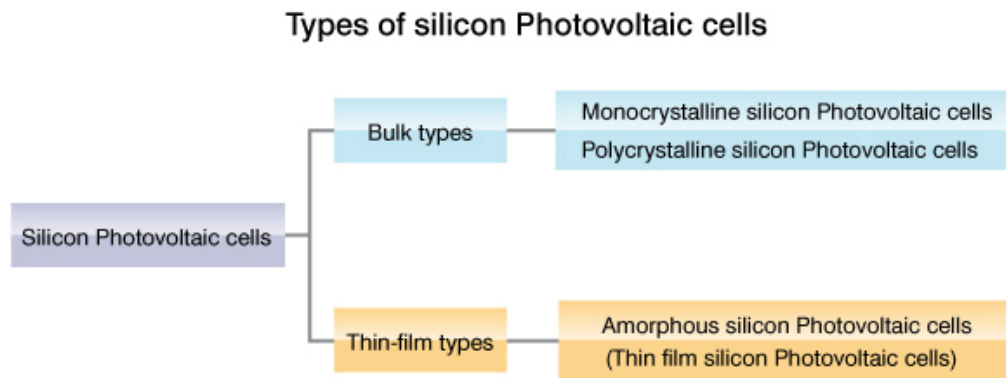


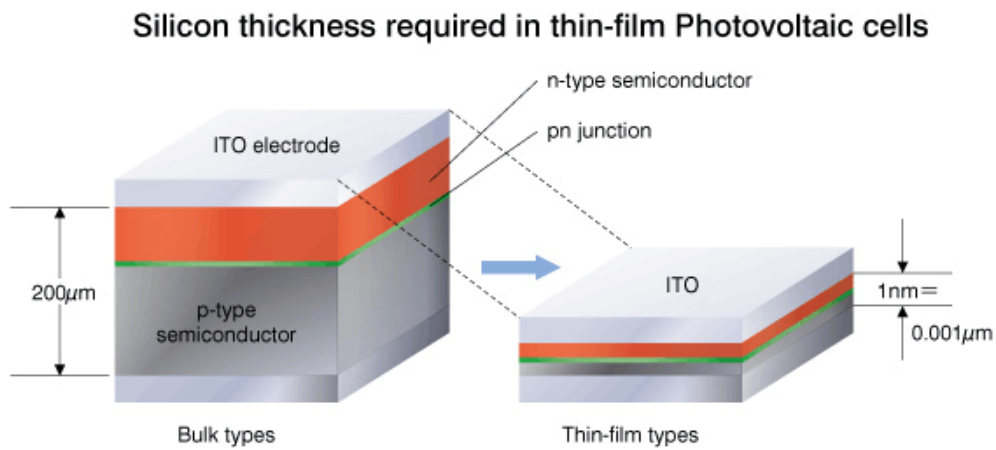
Figure 2.6: The types of photovoltaic cells

Monocrystalline silicon photovoltaic cells are the oldest form of photovoltaic system. Which have the highest conversion efficiency among all commercial photovoltaic cells today, but they require thinly sliced silicon of high purity and it's expensive to make thin slice. They need energy and capital investment to produce monocrystalline silicon, which boosts its price.

Polycrystalline silicon is composed of many smaller silicon grains of varied crystallographic orientation. This material can be synthesized easily by allowing liquid silicon to cool using a seed crystal of the desired crystal structure. Additionally, other methods for crystallizing amorphous silicon to form polysilicon exist such as high temperature chemical vapor deposition (CVD).

Thin-film silicon photovoltaic cells are photovoltaic cells produced by depositing silicon film onto substrate glass. While the cost is kept low because less silicon is used compared to crystalline types, conversion is less efficient than crystalline types. But efficiency can be improved by layering several cells and generating power from each one (multijunction); something that can only be done using thin-film types.






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Figure 2.7: Thin film photovoltaic cells

The short circuit current,  $I_{sc}$  occurs when the impedance is low. It is calculated when the voltage equals to 0.

$$I \text{ (at } V=0) = I_{sc} \quad (2.1)$$

The open circuit voltage,  $V_{oc}$  appears when there is no current passing through the cell.

$$V \text{ (at } I=0) = V_{oc} \quad (2.2)$$

Hence the power is calculated by:

$$P = I * V \quad (2.3)$$

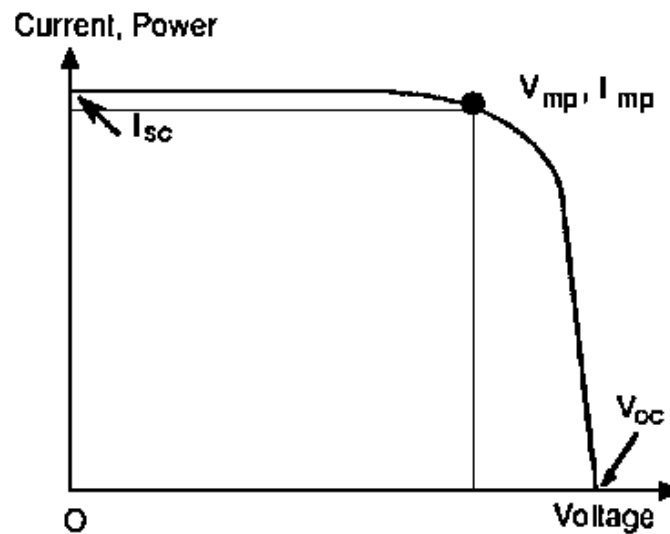


Figure 2.8: I-V curve

In figure 2.8, it illustrates the short circuit current and open circuit voltage. And also it shows the current and voltage at the maximum power point.

## 2.4 Literature study of PV/T

Recently a new technology to warm up water and heat appeared, this time it is not a new flat plate collector but it is a concentrator PV/T (photovoltaic/Thermal Hybrid), it has two functions more than the flat plate, concentrating solar radiation on the receiver, and cogenerate thermal and electrical output together. To investigate the thermal performance of concentrating PV/T, many sources were consulted during this thesis work. Many task to test and evaluate the thermal performance of this kind of collectors has been done, especially to look at the thermal efficiency, some of these research are outlined in this section.

To find out how the absorption happened in the absorber surface below the PV. A work which has been done by Cox and Raghuraman [12] shows that there was an increase in thermal efficiency, from 34% to 39% using a back contact gridding in combination with a separate absorber below the PV. Zondag et al. [13] found out that with the channel underneath transparent PV with a secondary absorber at the back, the thermal efficiency was 63% comparing to 60% for a PVT channel collector with the channel underneath opaque PV.



To increase the heat transfer from PV cells to absorber, a conventional PV-lamination was connected to a sheet-and-tube absorber to aluminium-oxide-filled two-component epoxy glue by De Vries [14]. It was known that the glue had a heat conductance of  $0.85 \text{ W/m K}$  due to the aluminium oxide, but in reality lower value was found, this caused a heat transfer coefficient of  $45 \text{ W/m}^2 \text{ K}$  between the cells and the absorber. Theoretical calculation showed that this thermal resistance reduced the annual average efficiency of his collector from 37% to 33%. Other report of Sudhakar and Sharon [15] showed that there was a really poor thermal contact between the PV-laminate and water; they found out that there was  $15^\circ\text{C}$  difference of temperature between them; this poor contact was assigned to the thermal resistance of the PV-laminate and the fact that tubes are tightened to the absorber. But in another work of Hendrie [16] the same results were found, large difference between the temperature of PV cells and water, here mean water temperature was  $28^\circ\text{C}$  while the cell temperature was  $63^\circ\text{C}$ , the difference in this work is that this large difference in temperature was ascribed to the fact of having a mechanical seal which left large air gaps between absorber and the tubes. Raghuraman [17] reports on a PVT-liquid system composed of solar cells that are glued directly to the thermal absorber plate with an insulating with a layer of electrical insulation to avoid the contact between them and the absorber plate, which could give some short circuit.

The PV-laminate consisting of a thick layer of silicone, with a thermal conductivity of  $0.2 \text{ W/m K}$  and a thickness of  $0.5 \text{ cm}$ , gave a heat transfer of  $40 \text{ W/m}^2 \text{ K}$ , found temperature difference of  $12^\circ\text{C}$  between the absorber and the PV-laminate because of the high thermal resistance of the silicon layer, therefore the thermal efficiency was reduced by more than 10%.

Many efforts have been done to improve the heat transfer from the absorber the liquid, such as the work of De Vries [14] which proposed to have a dual-flow PVT-collector, with water inlet above the PV and the water exit below the PV, plus an additional insulation which was an air layer between the PV-laminate and the water exit channel, in order to keep the PV cells as cool as possible, the design is shown in Fig 2.9. After simulating this system, it showed an improvement in the thermal efficiency because of the insulating air layer, the results showed, 66% as thermal efficiency and 8.5% electrical efficiency.

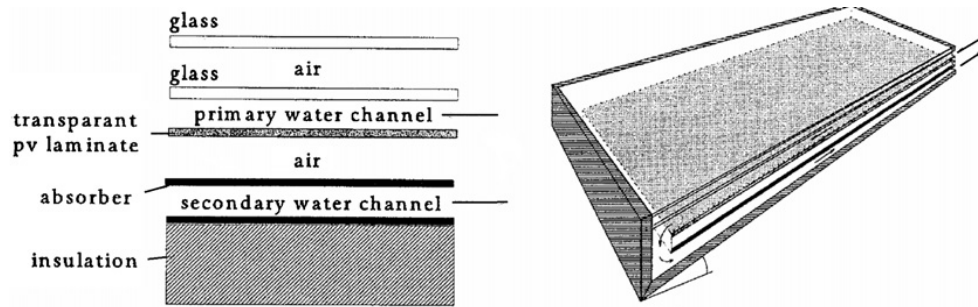


Figure 2.9: Two absorbers model of De Vries

The annual yield of PV/T system could be improved by 2% according to De Vries [14], if water channel are used in the bottom of PV cells, instead of a sheet-and-tube construction. Annual production could be even increased by another 6%, if water layer is over the laminate PVT instead of below. However, the average electrical efficiency was reduced from 6.6% to 6.2% due to the extra layer of glass.



### 3. Describing Solarus Collector:

#### 3.1 Solarus Concentrating Asymmetric Thermal Collector (CPC-T)

The length of the thermal receiver is 2.290 m and the height is 0.158 m. There are different types of thermal collector manufactured by Solarus AB. The mechanical configurations are almost alike with PVT collector (described in 3.2). Instead of putting solar cells on the absorber, selective surface can be introduced there. But it should be mentioned here that the stagnation temperature can go very high which can cause damage to the collector. The author had experienced with this kind of incident.

##### 3.1.1 Different Versions of the CPC-T

During this thesis work, I worked with two different types of thermal absorber. Both of the surfaces were selective. The main idea was to identify the best selective surface among them and suggest to the company considering different parameters. Selective surfaces are: 1) Solkote and 2) Q-loss.



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Figure 3.1: Solarus CPC-T collector with different selective surfaces

Solkote: It’s an optical coating specifically formulated for solar thermal applications. Its high temperature tolerance, resistance to moisture and UV degradation, and excellent optical qualities make it an ideal, low cost substitute for electro or vacuum deposited selective surfaces.

Technical Specification [30]:

Binder	100% Silicone polymer
Solvent	Xylene
Temperature Range	-73°C to +538°C
Storage Temperature	-45° C to +27°C
Specific Gravity	<1
Vapor Density	>1
Degradation	Unaffected by moisture, UV or elevated temperatures in glazed solar applications when correctly cured.

### 3.2 Solarus Concentrating Asymmetric Photovoltaic/Thermal Collector (CPC-PVT)

The modules manufactured and marketed by Solarus AB. This model has evolved from the MaReCo (Maximum Reflector Collector) design. This model came from Vattenfall’s solar energy research program. It has an asymmetric concentrator which means the receiver located to the side of the concentration trough rather than in the center. This gives a Compound Parabolic Concentrator (CPC) shape to ensure that reflected light reaches the receiver.

This asymmetric design is basically suited for thermal applications in northern and southern climates, and was designed to provide maximum thermal heat in the winter. This is achieved because of the unique acceptance angle of the modules.



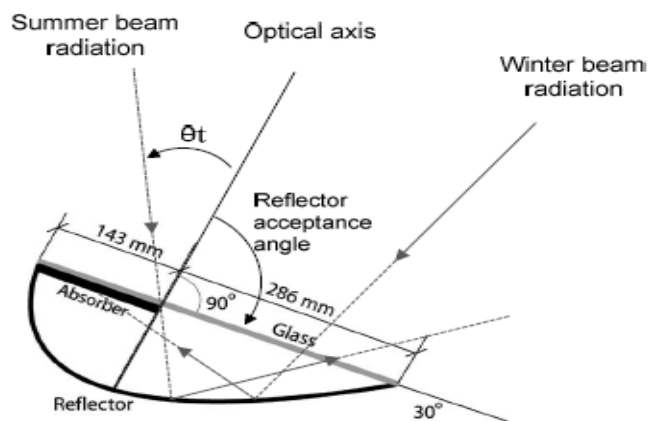


Figure 3.2: Basic geometry of Solarus PVT Collector

The radiation is concentrated onto an aluminium thermal absorber on which PV cells have been laminated. The cells were laminated on both the upper and the lower side of the absorber. The front side works like a standard PV module without concentration while the backside receives solar radiation from a parabolic reflector.

Even though the concentration factor of the collector is low, equal to 1.5, the PV cells can still reach high temperatures. This will reduce the electric production and cooling is required in order to maintain electrical efficiency.

The cooling process is carried out by running water inside the thermal absorber. By using the heat generated in the absorber, the PV/T collector produces electricity and thermal heat. The PV/T system consists of a photovoltaic module, thermal absorber, compound reflector (parabolic and circular), glazed protection and supporting structure. The reflector material is made of anodized aluminium with a solar reflection of approximately 95% [1]. The optical axis for the reflector geometry is normal to the glass of the collector. The glass cover of the collector made of low iron glass with solar transmittance of 0.9 at normal incidence angle.

Both the front side and the backside of the receiver consist of two PV strings each. Each string consists of 38 PV cells. The total number of PV cells per receiver is thus 152 cells. The total area of PV cells on a receiver was approximately 0.58 m<sup>2</sup> and the active glazed area was approximately 0.87 m<sup>2</sup> per receiver. Active glazed area was defined as the glazed area where the incident radiation can contribute to electricity production, i.e. the area on top of the cells and the area on top of the reflector in front of the cells, excluding edges, spaces between cells and parts where there was no reflector [2].



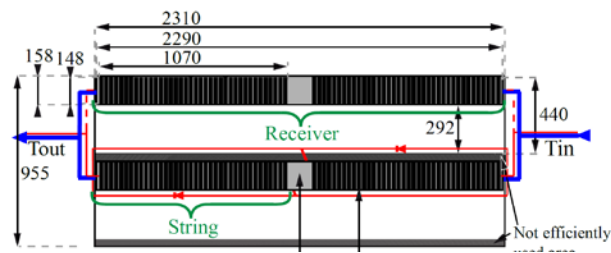


Figure 3.3: Cell configuration of Solarus PV/T collector

The total size of the collector is 2.31 m by 0.955 m. The active height of the reflector is 0.292 m. The parts of the collector which are excluded by the active glazed area are indicated in the figure 3.2. The total active height of the trough is 0.44 m, i.e. the sum of the active reflector height and the height of the PV cells.

### 3.2.1 Different Versions of the CPC-PVT

#### Version 10(old):

The Solarus Hybrid version 10 was put into production in 2012. It has a modular design, consisting of a single collector tray and frame, in which different receivers may be mounted to produce PV, T or PVT collectors. It has high  $F$  values. ( $F$  values indicate uneven distribution of heat, which means inefficient heat transfers).





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Figure 3.4: The Solarus V10 PVT collector

The receiver has PV cells in both sides. The V10 receiver has cell size of 158 mm. The reflective end gables were used in the old receiver. The receiver core has eight parallel narrow pipes with air space between the pipes and the diameter is around 5 mm. It has also inadequate electrical isolation between PV strings and the receiver core. Each side of the receiver bus bars and bypass diodes are connected and two strings of cells (38 cells each) are attached in parallel. The cells are fixed to the receiver by embedding them in clear silicone gel. The finished receiver contains 152 PV cells in four strings connected in parallel.

#### **Version 11(New):**

The version 11 collectors were put into production in year 2013. It has a modular design with more options than version 10. The transparent end gables were used in the new receiver to reduce the shading effect. The receiver core has eight narrow pipes with no air space between the pipes. The glass is held in an aluminium frame which has been re-designed in the new version with a different way to attach to the body. The V11 has new method for attaching water hosepipes which make

connected a pipe extremely simple. The hosepipes have a special end which is inserted into the receiver and locked in place with a clip, sealed with two 'O' rings.

The collector has 152 cells in four series strings, each string connected in parallel, two per side. And the electric configurations are almost same as V10.



Figure 3.5: The Solarus V11 PVT collector



## 4. Experimental Setup:

The collector prototypes were measured both indoors and outdoors.

The electricity was measured using an IV tracer connected to a laptop. Data was retrieved from the IV tracer using software designed by Christian Gruffman from FinsunInresol. This software is able to perform both single and continuous automatic measurements. In the indoor measurement only the single measurement function was used while for the outdoor measurements both functions were utilized. The IV tracer draws an IV-curve based on 100 values at different currents and voltages, while the software retrieves this data and records the values of  $I_{mp}$ ,  $I_{sc}$ ,  $V_{mp}$ ,  $V_{oc}$ ,  $P_{max}$ , FF and cell efficiency. The electricity produced by the cells was not being continuously extracted during the measurements which may lead to cell overheating and consequent power reduction due to cell temperature dependence.

### 4.1 Indoor test:

The indoor solar simulator was designed to simulate solar radiation and consists of two rows of 8 halogen light bulbs each with 1000W of power. As in many solar simulators, the light distribution is the drawback, since it is far from perfect and it depends strongly on the position of the cells within the simulator. During the testing of strings, one IV tracer has been connected which helped to observe the I-V curve of the string. A laptop has been connected with the I-V tracer to see the value of the parameters of the strings. The laptop has special excel program which shows the I-V curve.



Figure 4.1: Solar simulator used for the indoor measurements

## 4.2 Outdoor test:

Due to practical reasons such as equipment availability but also to optimize time and maximize testing time under good solar conditions, the collector was measured in 2 outdoor locations: Darlana University and at Solarus AB.

The outdoor set-up consisted in a tilt adjustable wooden stand where the collector was facing to the sun. The collector was  $44^\circ$  tilted to the surface. The selected tilt was the best for maximizing output for the location and the time of the year in which the measurements took place, March, April and May of 2013. Location was Älvkarleby, Sweden.



Figure 4.2: The solarus collector stand for outdoor measurements

The test rig used in Solarus AB was developed by FinsunInresol AB. The rig was designed to connect to the thermal collector in a closed loop, and feed a constant temperature independent of the return temperature. It consisted of a control unit, feed water pump, a flow meter, mixing tank, heating apparatus, and a plate heat exchanger to dump the heat from the solar collector. The pump used in the device is a Wilo Start RS 25/7, with a three stage speed switch. It can supply a maximum flow volume of 1.4 liters/second, with a maximum delivery head of 7 meters. The pump was connected in series with a flow meter, which sends 5760 pulses/liter flow. The test rig can circulate water or glycol in the collectors. For the tests in the winter, Tyfocor LS was used to fill



the system. This fluid provides anti-freeze protection down to  $-28^{\circ}\text{C}$ , and is compatible with a wide variety of materials. It has several temperature sensors to check the temperature of the fluid in different points. The data logger records all the temperature data and flow rate of the fluid. The pumps have been used to change the flow rate of the fluid. And the heat exchanger helps to cool down the hot fluid which comes from the collector outlet end.

The **MELACS** (Micro Energy Logger and Control System) is a versatile device built around PIC16F micro controller. It is designed and manufactured by Inresol AB, and is used as the controller circuit in the Finsun Solar Thermal Test Rig and other devices. A MELACS was used as standalone data logger to read data from thermal sensors and the reference cell. It accepts 8 analogue voltage inputs in the range  $\pm 3.3\text{ V}$  with a resolution of  $0.8\text{ mV}$ . It has additionally 8 digital I/O ports and also a MicroSD card slot.

The solar radiation was measured utilizing one calibrated reference solar cell. The output voltage is  $28.7\text{ mV}$  when exposed to  $1000\text{ W/m}^2$  solar radiation. The reference cell had two outputs: one is for data and other one is for temperature correction. The reference solar cell was connected to a data logger which had a display to monitor the readings. It had a micro-memory chip to store the data.

The LM 35 temperature sensors have been used to measure the ambient, inlet and outlet temperature. The measurement range is  $-55^{\circ}\text{C}$  to  $+150^{\circ}\text{C}$  and accuracy is  $\pm 0.5^{\circ}\text{C}$  at  $25^{\circ}\text{C}$  by Texas Instruments. Before using those temperature sensors, it was necessary to calibrate the temperature sensors. After calibrating the temperature sensors the necessary offset and scaling have been selected to put in the melacs logger. These were placed carefully on copper pipe outside of the collector and copper paste was used to ensure a good thermal connection.

The hosepipes have been used to flow the fluid from the test rig to the collector inlet-outlet side. In the inlet and outlet side two LM 35 temperature sensors were attached with copper paste. The pipes were well insulated to avoid losing heat to the environment.

The bushings of the pipe were made perfectly according to the dimension of the collector inlet-outlet pipe. To make the bushings well tight with the receivers inlet-outlet sides, 'O' rings have been used.

The system had glycol to avoid the freezing problem. The density and specific heat of glycol are  $1045\text{ kg/m}^3$  (at  $0^{\circ}\text{C}$ ) and  $3.625\text{ kJ/kg}\cdot\text{K}$  respectively.

To observe the electrical performance of the cell, the wire have been connected with the IV tracer and a laptop which has been connected with IV tracer shows the I-V curve and values of necessary parameters at six minutes interval. The IV Tracer is a device custom made for Solarus AB. It interfaces with computer via the serial cable and a custom Excel macro sheet logs data. Each IV curve is saved as a separate CSV file.

## **5. Testing and Analyzing the Solarus Collector V11.**

### **5.1 Methodology**

The collector was mounted in an outdoor test rig at the Solarus factory, and tested between March 25<sup>th</sup> and April 3<sup>rd</sup>, 2013. The testing methodology



was followed from L.R. Bernardo et al. (2011) [18] and Bernardo Ricardo et al. (2013). [20]

## 5.2 Placement

The collector was mounted in the outdoor testing laboratory at Solarus AB, Älvkarleby, Sweden (geo-coordinates: 60°33'58.9644" North, 17°26'43.5984" East), at an angle of 44° to the horizontal, facing due South. The laboratory was located in a section of the factory parking lot and due to the winter season the floor was covered with thick ice which has given a significant portion of the diffuse light, reflected from snow surface. So the collector's tilt has been chosen carefully to reduce the diffuse light.

## 5.3 Parameters

Table 5.1: Measured Parameters:

Parameter	Device	Comments
$V_{oc}, V_{mp}, I_{sc}, I_{mp}, P_{max}$	Net Book	Electrical performances were found from I-V curve which is generated by I-V tracer.
$T_{in}, T_{out}, T_a$	MELACS	Data showed in degrees.(every six minutes)
$S_c$	MELACS	Incident solar radiation was measured in every six minutes.(Unit:[W/m <sup>2</sup> ])
$\eta$	Thermal Test Rig	The unit is [l/h] and measure every minute

## 5.4 Limitations

The evaluation of this collector was limited by a number of factors. The significant factors are:

**Pyranometers:** The quality of the pyranometers was not good enough at the company. So it was recommended to use a reference cell, which



measured only the irradiance in the plane of the collector. Thus accurate measurements of the beam and diffuse irradiance are not available.

**Malfunctions:** Some instruments were unreliable, for example the data logger on the flow meter stopped accepting new values, and had to be re-set daily. And also the test rig was not regulating the temperature automatically so it needed manual command. The data from temperature sensors seemed to oscillate.

**Weather Conditions:** Due to extreme cold, water had to be replaced by glycol in the test rig and in the system. The filling process of glycol in the system was not very accurate, there was water left inside. This reduces the accuracy of the thermal measurements. Last but not least, the lack of clear days for measuring was complicated matters.

## 5.5 Calculations

### 5.5.1 Specific Heat and Density of Glycol

The MELACS and IV Tracer were giving all the necessary parameters needed to analyze and conclude the data. But in order to be very precise and taking into account the limitations it had, further calculation was necessary.

The density and specific heat of Tyfocor was varying over the range of temperatures experienced during measurements. In the calculation of thermal power, linear approximations of the density curve were made and the information from the manufacturer was followed,

$$\rho_{Tyfocor}(T) = \rho_0 + \frac{d\rho}{dT} * (T - T_0) \quad (5.1)$$



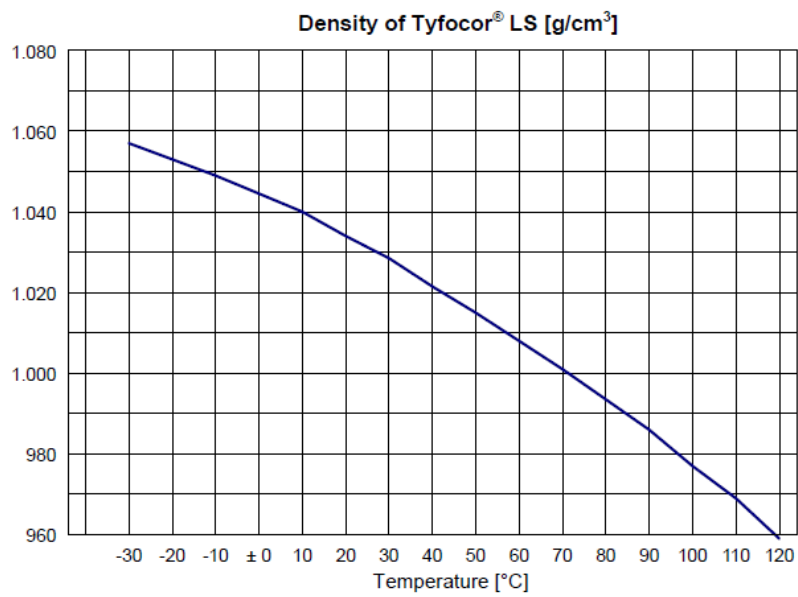


Figure 5.1 Linear Density curve of Tyfocor glycol

By setting  $T_0 = 273$  K and the using data from the manufacturer company, I found  $\rho_0 = 1045$  kg/m<sup>3</sup>. Using a linear approximation of the density curve,  $\frac{d\rho}{dT} = -0.7273$  kg/m<sup>3</sup>K.

The specific heat also needed to calculate due to the disturbances.

$$C_{P,Tyfocor}(T) = C_{P,0} + \frac{dC_P}{dT} * (T - T_0) \quad (5.2)$$

In this case, the specific heat is around,  $C_{P,0} = 3.52$ kJ/kgK and  $\frac{dC_P}{dT} = 0.004$  kJkgK<sup>2</sup>.

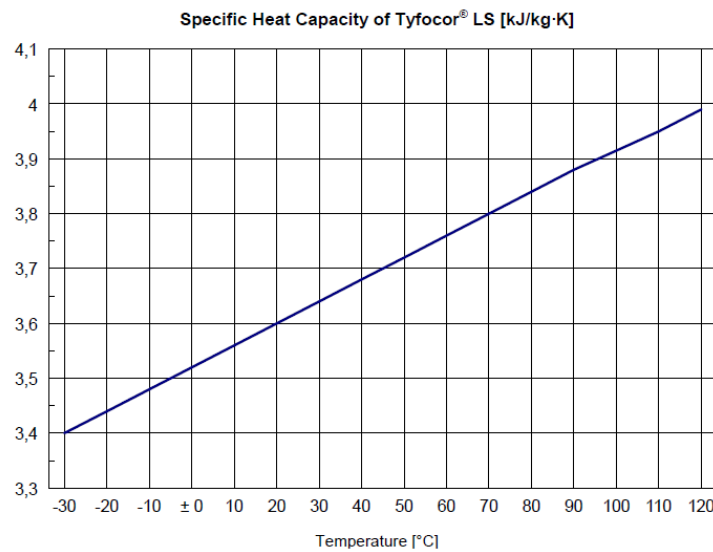


Figure 5.2 Linear Specific heat curve of Tyfocor glycol

### 5.5.2 Electrical Power

The expression of thermal power is:

$$P_{el} = V * I \tag{5.3}$$

### 5.5.3 Thermal Power

The expression for thermal power as: [19]

$$P_{th} = \rho \dot{V} C_p \Delta T \tag{5.4}$$

Where,  $\dot{V}$  is the flow rate in m<sup>3</sup> per second, and  $\Delta T = (T_{in} - T_{out})$ .

According to the Bernardo Ricardo et al. (2013), [20], the power indicated by the IV Tracer was subtracted from the measured thermal power to find the actual thermal power. This step is necessary as the IV Tracer applies no real electrical load on the collector, meaning that the portion of power that would have gone through an electric circuit is transformed into heat.



Therefore, the expression for total output power is:

$$P_t = \rho \dot{V} C_p \Delta T \quad (5.5)$$

And the thermal power is determined by:

$$P_{th} = P_T - P_{el} \quad (5.6)$$

The uncertainty in the temperature difference is found  $\pm 0.7^\circ\text{C}$ .

### 5.5.4 Efficiency

Not all of the incident solar radiation coming from the sun is absorbed by the absorber; there are some optical losses, such as, reflection of the glass and reflection between the cover and the absorber. From the absorber the heat is transferred to the liquid trough conduction and convection, but not all the heat is transferred because also the absorber has its own losses, mainly through radiation and convection, also conductive heat losses, insulation of the piping is important.

Irradiance which is successfully absorbed by the absorber is reduced by the heat losses. As described by Equation 5.7.

$$q = S_{UL}(T_a - T_{amb}) \quad (5.7)$$

Where,  
 $T_a$ : Temperature of the absorber  
 $T_{amb}$ : Temperature of the ambient air  
 $U_L$ : Heat loss coefficient  
 $S$ : Absorbed radiation;

## 5.6 Results

### 5.6.1 Electrical Performance:

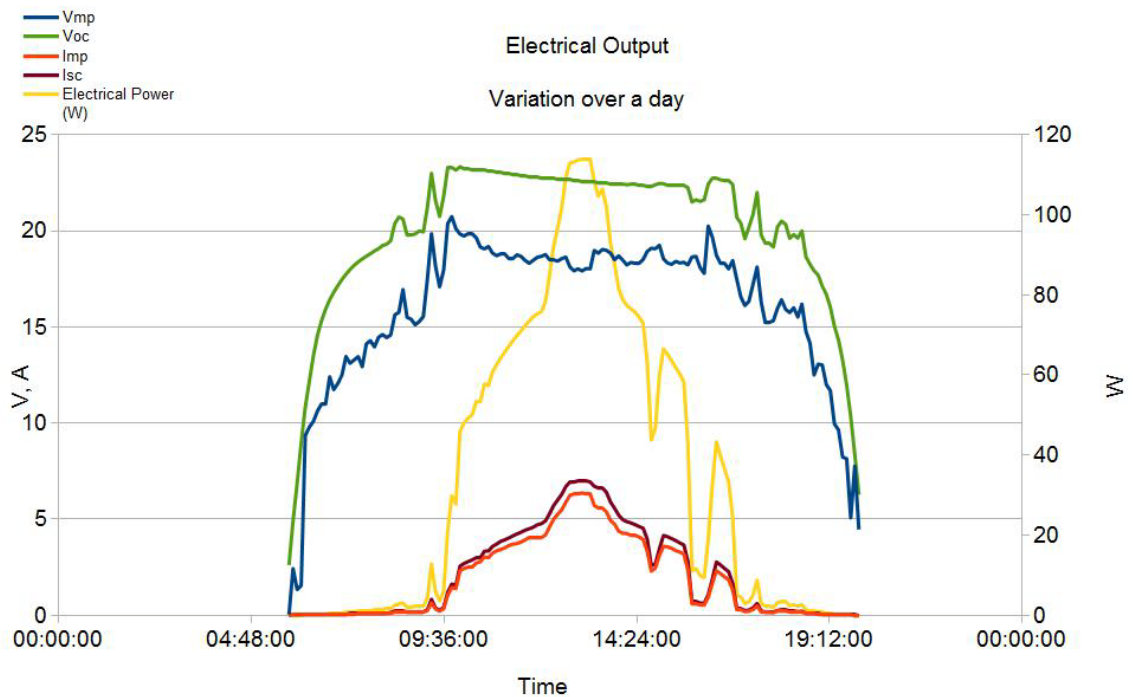


Figure 5.3 Electrical Output of Solarus PVT V11 collector on 1<sup>st</sup> April'2013.

In the figure 5.3, it is showing the electrical output across the day. It illustrates that at the noon when the solar irradiation is high then we get higher electricity. It has some abrupt changes due to cloud and shading. The maximum electrical power was around 110W. It should be mentioned that here in this experiment only on trough has been tested. And one collector has two troughs. The X-axis is showing the time.

### 5.6.2 Thermal Performance:

The thermal performances have measured which the collector was giving electricity. In the figure 5.4, the inlet, outlet and ambient temperature are showing. The fluctuations in thermal



power are because of the irradiance variation and also due to defects on temperature sensors. The maximum thermal power was around 300W.

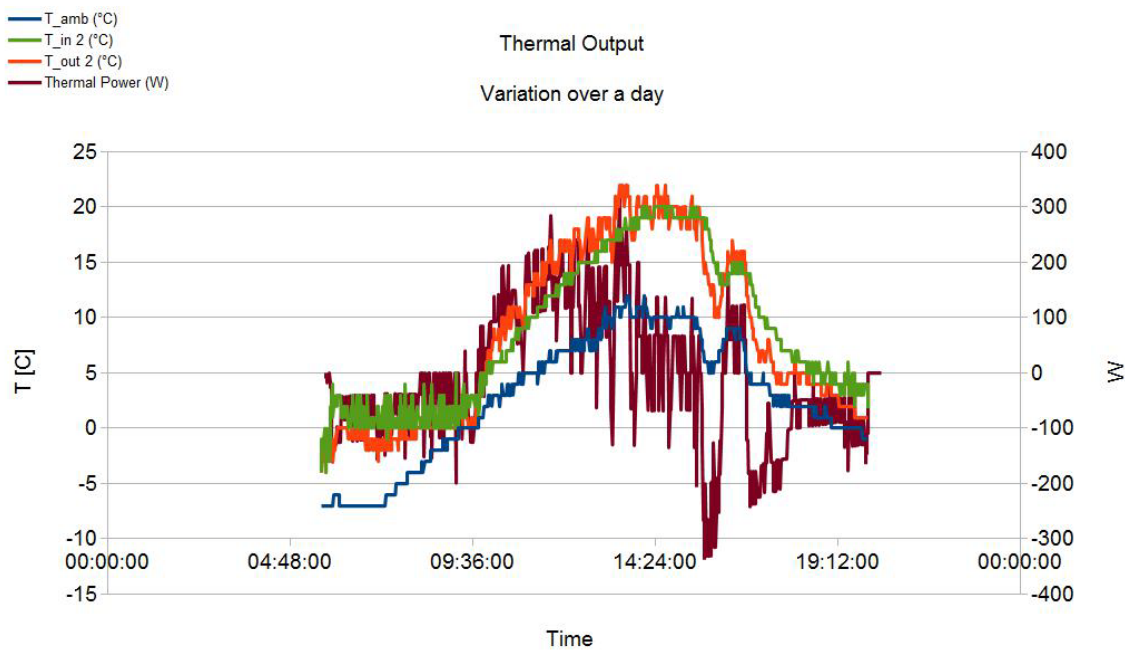


Figure 5.4 Thermal output of Solarus PVT V11 collector on 1<sup>st</sup> April'2013

### 5.6.3 Overall Performance:

In order to see the overall collector performance, both the thermal and electrical performances have been analyzed together. In the figure 5.5, this gives the overall performance of the collector.

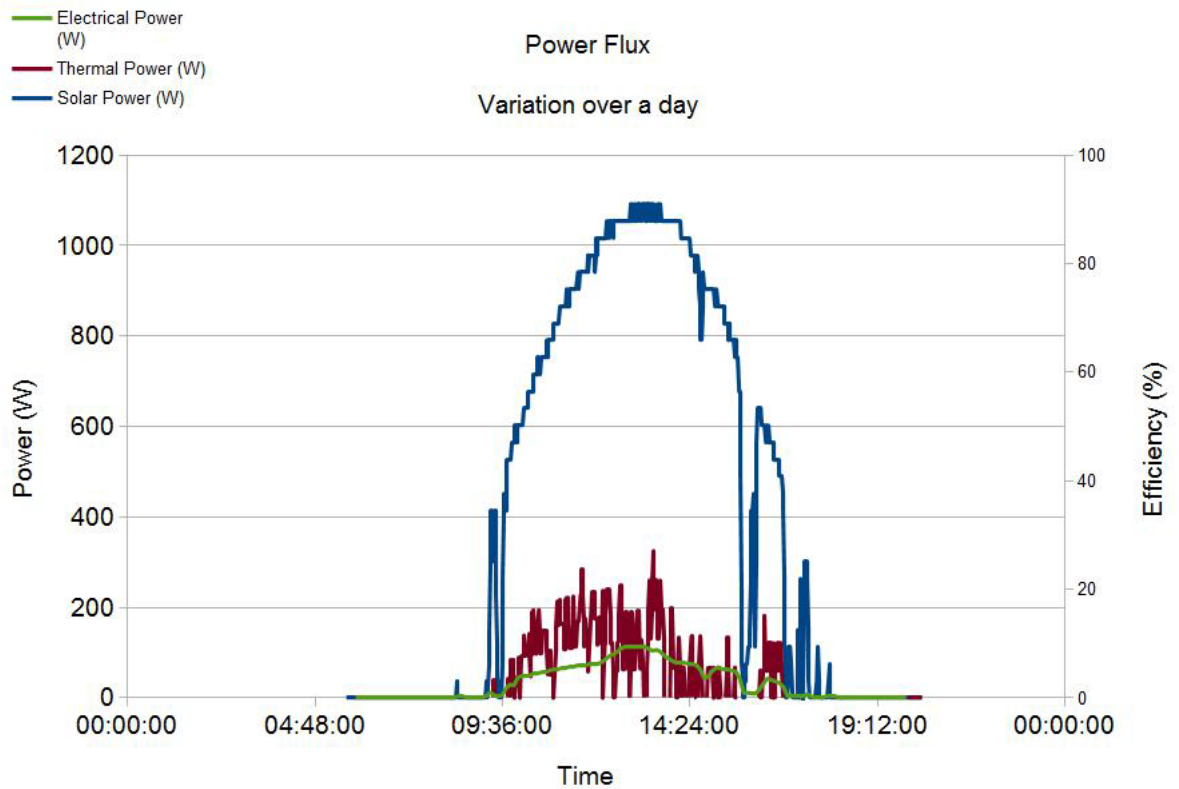


Figure 5.5 Power flux (electrical and thermal both) of Solarus PVT Collector on 1<sup>st</sup> April. The abrupt changes especially in thermal power are because of the device failure, bad weather, or shading from trees.

### 5.6.4 Cell efficiency Vs Cell temperature

The changes in photovoltaic cell efficiency with cell temperature have been showing in figure 5.6. Cell electric efficiency is different from overall electric efficiency, as it is calculated based on the solar irradiance input to the cell area, whereas overall electric efficiency is based on the entire collector. The cell electric efficiency gives a better estimate of the operating conditions of the silicon cells in the receiver.



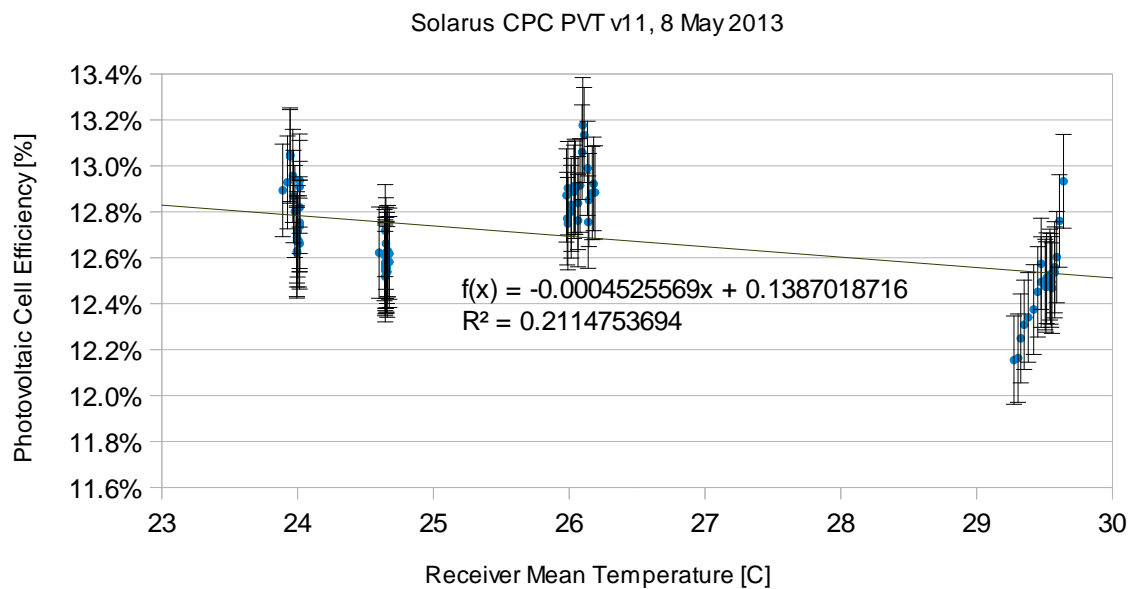


Figure 5.6 Photovoltaic cell efficiency Vs Receiver mean Temperature for collector V11 at the Dalarna University Solar Laboratory.

The collector was tracked to the sun in a vertical axis between each measurement, and the flow rate was varied from 15 l/h to 90 l/h in five even steps to control the mean cell temperature.

### 5.6.5 Electrical efficiency Vs Cell Temperature

The average electrical performance of a trough has been shown in the figure 5.7. It can be compared with other photovoltaic panels in order to observe the efficiency. At standard conditions (25 °C and 1000 W/m<sup>2</sup>), the cells were operating at an efficiency of ~12.7 %. Though the manufacturer's datasheet states that the efficiency around 18.8% [34]. This is because of the glazing and reflection losses in the collector.



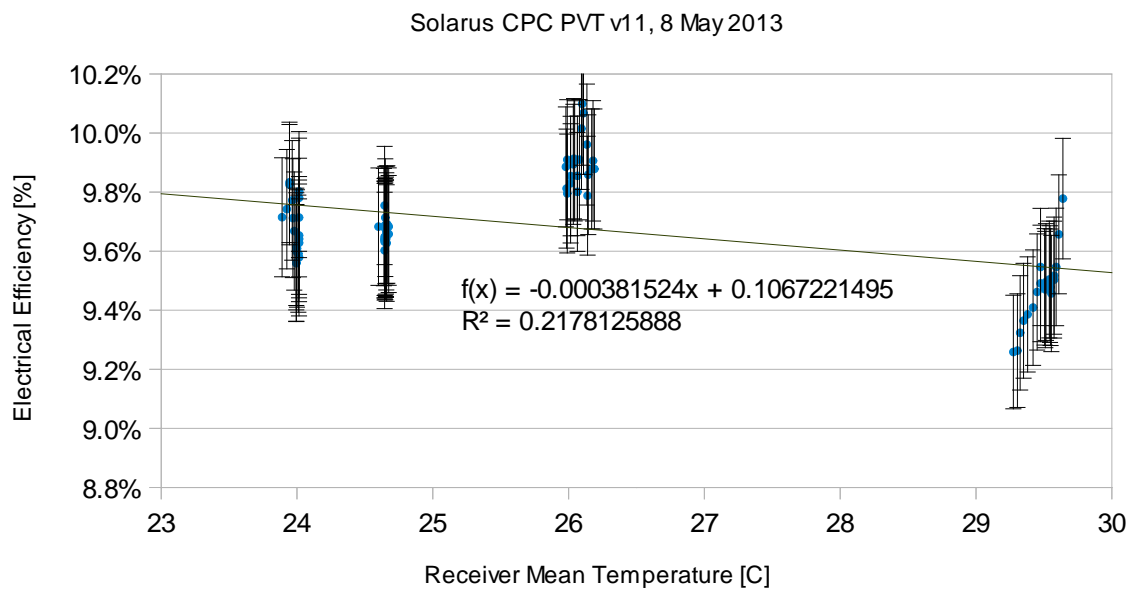


Figure 5.7 Electrical Efficiency (based on trough aperture area) Vs Cell Temperature for collector V11 at the Dalarna University Solar Laboratory.

### 5.6.6 Thermal efficiency Vs Reduced Temperature

The main cause of reducing efficiency in thermal collector is that the receiver loses heat by radiation. The reduced temperature is a proportional constant which in proportion to the collector heat loss. In figure 5.8, it shows how the receiver behaves as a thermal absorber.



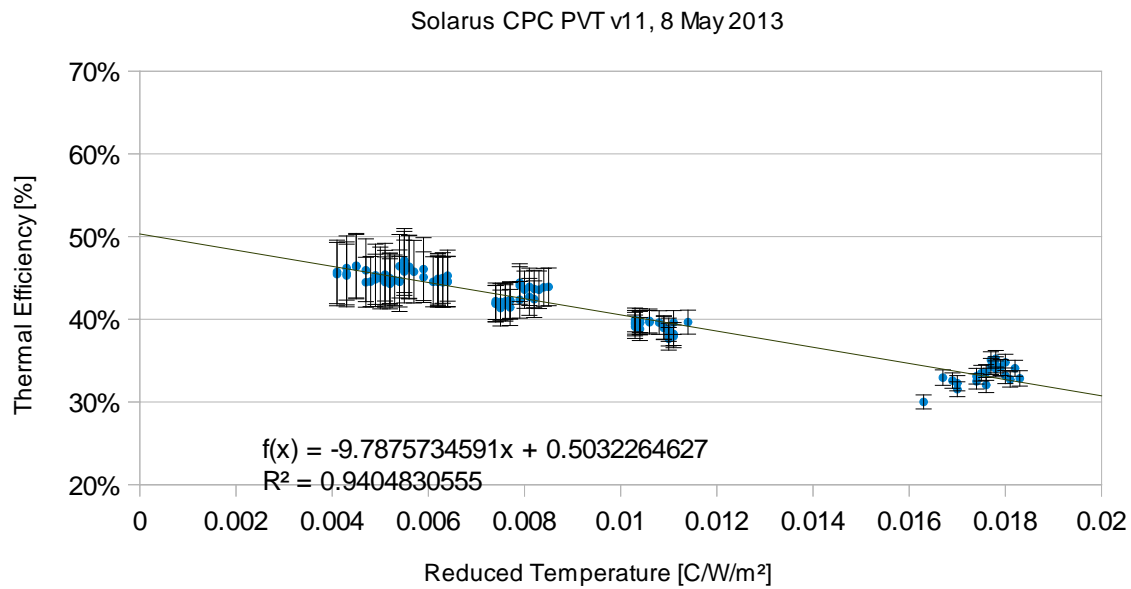


Figure 5.8 Thermal efficiency Vs reduced temperature for collector V11 at the Dalarna University Solar Laboratory.

When the reduced temperature is zero (0), it means there is no loss. At higher temperature the losses from the collector increases significantly [36].

## 6. Collector efficiency

The thermal performance of solar collector is defined from its optical properties. Not all of the incident solar radiation coming from the sun is absorbed by the absorber; there are some optical losses, such as, reflection of the glass and reflexes between the cover and the absorber. Only what remain from solar radiation after the optical losses is absorbed by the absorber. From the absorber the heat is transferred to the liquid through conduction and convection, but not all the heat is transferred because also the absorber has its own losses, mainly through radiation and convection, also conductive heat losses, insulation of the piping and collector is important.

Irradiance which is successfully absorbed by the absorber is reduced by the heat losses. As described by Equation 6.1.

$$q = S - U_L(T_p - T_a) \quad (6.1)$$

$T_p$       Temperature of the absorber plate

$T_a$       Temperature of the ambient air

$U_L$       Heat loss coefficient (insulation capacity of the collector in (W/m<sup>2</sup>K))

$S$         Absorbed radiation

### 6.1 Irradiance

The hemispherical solar irradiation  $G_T$  on a tilted solar collector, is the global solar irradiation (diffuse and beam) on the collector.

The ratio of the power to the irradiance gives the instantaneous efficiency of a solar collector. As shown in Equation 6.2.

$$\eta = \frac{q}{G_T} \quad (6.2)$$

### 6.2 Optical losses

The losses of solar radiation which happens due to absorption and reflection in the cover (glass) and the absorber, these losses are described by the optical



efficiency of the collector. Also optical losses in the reflector must be taking into account in the case of concentrating collectors.

### 6.2.1 Optical losses in the glass cover

The irradiation coming on the absorber is reduced, because some of this irradiation is lost by reflection and absorption in the glass. At normal incidence, a flat clear glass with 4 mm thickness has a transmittance of approximately 83%. An increase of the transmittance of glass material has been developed, by reducing iron content and anti-reflection treatment. The reduced iron content glass has a transmittance of approximately 90%. The common used glass is the antireflection treated glass with a transmittance up to 95% [31].

### 6.2.2 Optical losses in reflectors

The optical losses are different from reflector to other depending on the material. Many studies have been done on aluminium and steel, These studies showed that the steel material can last longer time than the aluminium, especially when it comes to outdoors, but higher reflectance for the aluminium of 90% and 65% for Steel, but aluminium reflectors which are anodized have proved to be long-term stable [31].

### 6.2.3 Absorbed energy from solar radiation

The absorbed energy,  $S$ , shown in Equation 6.3, is the global irradiance in the collector  $G_T$  (beam and diffuse) after being reduced by the optical losses. The optical losses are described by the term  $(\tau\alpha)_n$ , this term includes also the multiple reflexes between the absorber and the cover.

$$S = G_T(\tau\alpha)_n \quad (6.3)$$

The temperature of the absorber is higher than the temperature of the liquid inside the absorber, this different in temperature due to heat losses is expressed by the collector efficiency factor,  $F'$ , this factor depends on the temperature, it includes different heat resistances which happens in the absorber,  $F'$  influences the heat losses and the energy absorbed. The Equation 6.1 of the power,  $q$ , becomes as in Equation 6.4, if the factor  $F'$  is taken into account. In the equation 6.4,  $(T_p - T_a)$  is replaced by the difference between the ambient temperature,  $T_a$ , and the mean temperature of the liquid inside the absorber,  $T_m$ . this expression is the most common, since  $T_m$  is easy to measure, by measuring the inlet and outlet of the

fluid temperature, and calculating the average temperature between,  $T_{in}$  and  $T_{out}$ , as in Equation 6.5. (Perers, 2012).

$$q = G_T F' (\tau \alpha)_n - F' U_L (T_m - T_a) \quad (6.4)$$

$$T_m = (T_{in} + T_{out}) / 2 \quad (6.5)$$

The term  $F' (\tau \alpha)_n$  is the optical efficiency and referred as  $\eta_0$ , therefore the power can be expressed as in Equation 6.6, for more simplification.

$$q = \eta_0 G_T - F' U_L (T_m - T_a) \quad (6.6)$$

#### 6.2.4 Thermal heat losses from the collector

Thermal heat losses from the solar collector happen through the back, the top and the edges of the collector, the heat loss coefficient is  $F' U_L$ , the heat losses from the collector are the difference between the mean temperature of the liquid in the collector,  $T_m$  and the temperature of the surroundings time the heat loss coefficient, as  $F' U_L (T_m - T_a)$ .

#### 6.2.5 Evaluation of thermal performance

Measurements of the temperature inlet and outlet of the liquid in the collector, the ambient temperature, hemispherical radiation in the collector plane and the flow rate, allow us to evaluate the thermal performance of solar collectors, according to the European Standard (EN 12975). The overall efficiency is defined as in Equation 6.7, with  $C_p$  is the specific heat capacity,  $A_c$  is the aperture area of the collector and  $\dot{m}$  is the mass flow rate. The specific heat capacity of the water varies with water temperature; therefore it should take into an account the mean temperature of the liquid in the collector.

$$\eta = C_p \dot{m} (T_{out} - T_{in}) / G_T A_c \quad (6.7)$$

The thermal performance measurements make the calculation of the optical efficiency  $\eta_0$  of the solar collector possible, by rearranging the Equation 6.7 in Equation 6.8.



$$\eta_0 = qF'U_L(T_m - T_a)/G_T \quad (6.8)$$

## **7. Testing Thermal Collector with different selective surfaces and comparing between two different surfaces**

### **7.1 Measurement set-up**

This part describes the measurement set ups, techniques and equipment used for these measurements. They were mainly done outdoors in the field trials at the Solar Energy Research Centre (SERC).

### 7.1.1 Measurements using the test rig

The evaluation of the concentrating collectors has been done from outdoor measurements using a test rig. The thermal measurements were done between the 6<sup>th</sup> and the 8<sup>th</sup> of May 2013 for the T collector, and between the 23<sup>rd</sup> and 30<sup>th</sup> of May for the PV/T collector, both measurements took place at Solar Energy Research Centre (SERC), Borlänge, Sweden.

The collectors were facing the south during the measurements with a fix tilt of 45° (Figure 7.1). Global and diffuse irradiation were measured by the two pyranometers, they were mounted on the collector plane, with a static shading ring was mounted in front of the pyranometer which was measuring the diffuse irradiation, as shown in Figure 7.2.



Figure 7.1: Picture shows how the PV-T and the T-collectors were installed

Figure 7.2: The two pyranometers for measuring the global and diffuse irradiation, mounted in the collector plane





The inlet and outlet temperatures of the collector were measured with Pt 100 sensors as shown in Figure 7.3. Flow rates were measured by the two inductive flow meters, a data logger stores data every 10 seconds during the evaluation period.



Figure 7.3: Collector inlet side with Pt 100 sensors inside

### 7.1.2 Measurements of irradiance

The measurements of the hemispherical and diffuse solar irradiance have been done with two Pyranometers, with a shading ring for the Pyranometer which measures diffuse irradiance. The beam irradiance is the difference between the hemispherical (Global) and diffuse radiation; The Pyranometers were calibrated and placed in the collector plane.



### 7.1.3 Temperature measurements

If we want to delete disturbances from the collector thermal capacitance to the efficiency and measured thermal output, the inlet temperature to the solar collector must be constant. This is very important since our collector requires low flow rate. Pt 100 sensors, a thermopile and temperature sensor of microchip type (LM35) have been used to measure the temperature during different measurements, in our case the temperature measurements were done by the Pt 100, for the inlet, outlet and the ambient temperature were calculated based on the measurements of  $T_{out}$  and  $T_{in}$ .

### 7.1.4 The solar collector test rig

The test rig was built to test the thermal performance of different solar thermal collectors, such as, CPC, vacuum tubes, etc.

The test rig facilitates our stationary collector testing with good repeatability of the measurements.



Figure 7.4: The solar collector test rig.

The test rig is constructed in order to make the connection of different solar collectors simple and easy to the inlet and outlet pipes. One of the main aims of



the system design is to give a good control of the inlet temperature, and to keep the temperature to the collector, as constant as possible during the measurements time.

The test rig is able to test two collectors in the same time, has two cooling circuit to cool down the hot water delivered by the collectors, the first circuit uses the borehole the second uses the Chiller. Only one of these two circuits is used for both collectors in the same time. After the water has passed one of these two coolers, it passes through a 15kW electric heater; by operating this electric heater we can adjust the inlet temperature. The adjustment of the flow rate is done manually from the flow rate display, which is located just before the outlet pipes on the test rig.

## 7.2 Measurement results

The thermal low-concentrated collector has two troughs, the absorber of each trough is painted with different selective surface coatings, one is glossy and the other is mate. The aim of this part is to:

- Compare both troughs to each other, by comparing the two parameters (intercept and slope) of the thermal efficiency plot.
- Find out how one trough effects on the other.
- Compare the annual energy output of each trough.

### 7.2.1 The effect of one trough on the other

Before the two collector troughs with different selective surface coatings are compared, the trough which has to be compared originally it was planned to do measurements on a solar thermal low-concentrating collector to see if the two troughs identical in geometry and material properties, to show the same performance. Although identical, there is a risk that the heat losses from the lower trough will heat up the upper trough through convection, and therefore reducing the heat losses from the upper trough. There is no air exchange between the two troughs and therefore it is assumed that the heat losses from the front side will be equal. Eventually there will be an air movement from both sides of the lower trough by convection through the air to the upper trough, which will reduce the heat losses from the upper trough. Another phenomenon could be tested is the air between the trough on the back side of the collectors heated, which affects the heat losses from the two troughs differently.

Two thermometers were placed under each trough to see the difference in temperature, if really there are more losses in one trough comparing to the other.

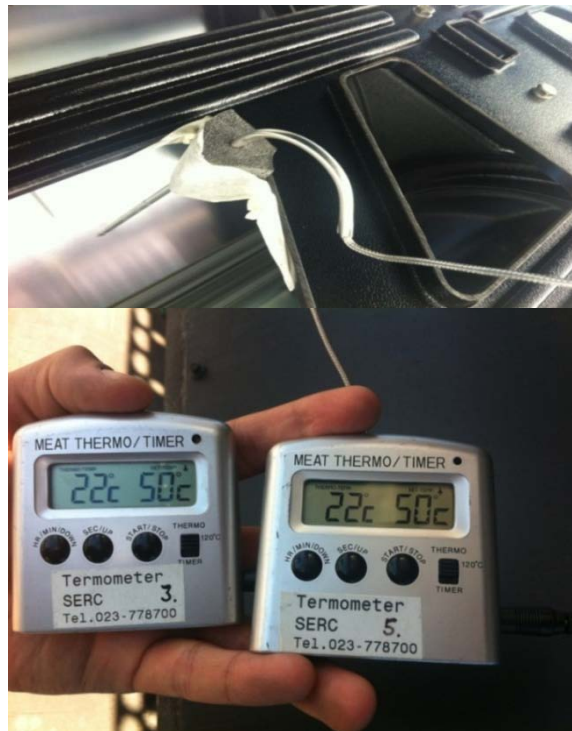


Figure 7.5: It shows the temperature reading of the two trough.

We measured the two temperatures of the both troughs, we found the same temperature, and therefore it can be assumed that any heat loss between the troughs mainly depends on the different absorber paints.

### 7.2.2 Thermal efficiency of the T collector

This evaluation has been done to show the difference in performance between the two troughs, which belong to the same solar collector. The solar collector was mounted facing south. The first is painted with mate (Q Loss) and the second is painted with a glossy paint (Solokote), this evaluation will show which paint performs better, Therefore we had to vary the flow rate for different values, from 20 to 90/h with a step of 10, in order to have different DT/G with different



efficiencies, for both troughs and plot the efficiency curve, as shown on the Figure 7.6, in order to define the optical efficiency and the heat losses.

The inlet and outlet water temperatures were measured using Pt 100, at an average hemispherical irradiance of  $935 \text{ W/m}^2$  with varied water inlet temperature from  $37^\circ\text{C}$  to  $25^\circ\text{C}$ , which decreased with increasing the flow rate, the ambient temperature was almost constant at  $16^\circ\text{C}$ , with a variation of  $1^\circ\text{C}$  during the test and the hot water reached to a maximum temperature of  $53^\circ\text{C}$ . The standard efficiency curves of the two troughs and its results are shown in Figure 7.6 and in Table 7.1.

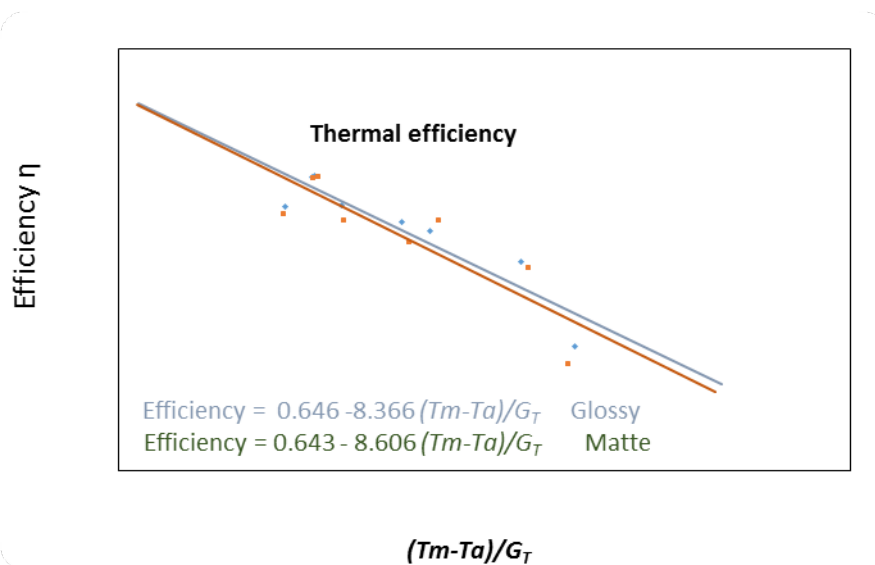


Figure 7.6: The Standard efficiency curves of the two troughs as a function of  $DT/G$ . The heat loss coefficient  $F'_{UL}$  value is the slope of the graph and the intercept of the graph with the Y-axis is the optical efficiency,  $\eta_0$ .

Table 7-1: The optical efficiencies and heat losses of the two troughs are derived from the efficiency graph and represented in this table.

Trough	Heat losses $F'U_L$ [W/m <sup>2</sup> °C]	Optical efficiency $\eta_o$ [-]
Glossy(Solkote)	<b>8.366</b>	<b>0.646</b>
Mate(Q loss)	<b>8.606</b>	<b>0.643</b>

The thermal efficiencies for both troughs with different painted absorber were found from the Equation 6.8 and based on the Gross area of each trough. Areas of both troughs are equal. The intercept of each line with the Y-axis defines the optical efficiency  $\eta_o$  of each trough and the lines' slopes define their heat losses, these values are presented on the Table 7.1.

The heat loss coefficient of the trough with Glossy painted absorber as the slope of the line showed is  $F'U_L = 8.37$  W/m<sup>2</sup>°C. The intercept  $F'\eta_o$  of the line with the Y-axis is 0.646, which represent an optical efficiency of about 65%. The trough with mate painted absorber has a slightly higher heat loss coefficient with  $F'U_L = 8.61$ W/m<sup>2</sup>°C, and slightly lower optical efficiency of 0.643 which represent almost 64%.

The two values of heat loss coefficient for the two troughs are quite high, if we compare them to the value which Solarus company report on their technical specification for this collector, because according to (Solarus AB, 2013) this collector has a heat loss coefficient of only 1.9 W/m<sup>2</sup>°C, while the value which was found after the measurements is about 4 times higher. The high amount of heat loss coefficient will be discussed later in the discussion.

There are some clear differences between the parameters, of both troughs, According to (Perers, 2012)[32] only the operating conditions would decide which one should be used, and the range of values of  $DT/G_T$  that we are expecting in an application, to heat a pool for example, no need for a high difference in temperature between the ambient and the absorber, in the other extreme case,



when we make steam to turn a turbine we need a significant difference in the temperature at high efficiency for large values of  $DT/G_T$ .

The two troughs have to be evaluated on their performance per year, to be able to compare them and find out which one is the best, in term of annual energy output, that's what will be presented in the next part.

## Annual energy output

### *Annual heat production in Älvkarleby Sweden*

According to (Martin, Oscar. 2004) [33], the efficiency describes the ratio between the useful and the supplied energy in a system, for example in solar collectors, this ratio is the heat produced to the incident solar radiation.

The efficiency of solar collector is related to many factors, depending on the selection of materials and the operating conditions. To compare two collectors it is not sufficient to just compare the efficiency at one absorber temperature and therefore we will compare the expected annual output in order to comment on their efficiencies and feasibilities.

To define the output of a solar collector is a complex process. Therefore, Björn Karlsson has developed a Method for simplifying the theoretical determination of the energy exchange from a solar collector. "*Karlsson formula*" can be used to calculate energy exchange with equal conditions for solar collectors at various temperatures.

The formula of *Karlsson* which easily calculates the useful energy per unit area is:

$$Q_u = G_T F' (\tau \alpha)_n - F' U_L (T_m - T_a) * t \quad (\text{KWh/m}^2/\text{year}) \quad (7.1)$$

$Q_u$	Annual heat production
$G_T$	Global annual radiation on a tilted surface
$t$	Number of hours when $G_T > 200 \text{W/m}^2$
$T_m$	Mean fluid temperature inside the absorber
$F'$	Heat transfer factor

Approximate annual production will be defined, for both troughs to be able to compare them. In order to start calculating, we need the optical efficiency and the

heat loss factor, which we already got from our measurements. If we assume that the heat transfer factor  $F'$  is equal to 1, this means that the mean temperature of the fluid inside the absorber is equal to the absorber temperature. [34]

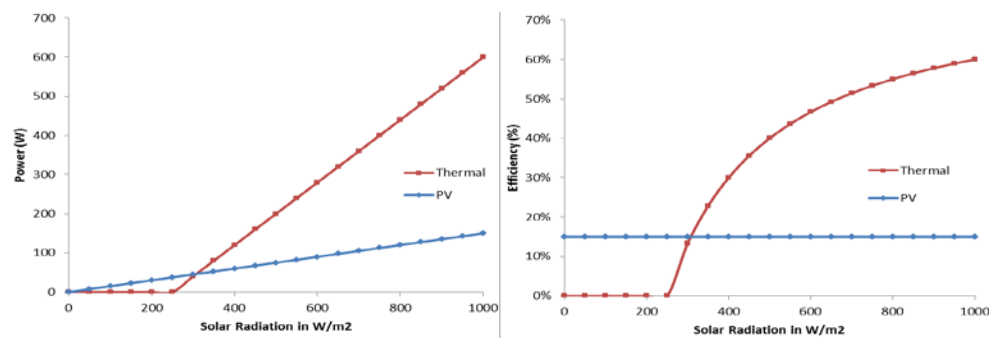


Figure 7.7: The effect of solar radiation in both the power and efficiency of both PV panels and solar thermal collectors

According to our experiment we found that a solar collector starts delivering some heat, when the irradiance is above approximately 200 W/m<sup>2</sup>. Another main purpose of showing the figure 7.7 is that the efficiency of a PV panel is independent of the solar radiation and the same does not happen in the solar thermal collectors. To calculate the annual output of this collector and to have a clear view on its annual output for both troughs, we should calculate it under two climates. One is a cold climate as Älvkarleby and the other will be hotter such as Dhaka, Bangladesh.

The annual solar radiation for the central Sweden is 800 kWh/m<sup>2</sup>/year [36], for the southern of Sweden this value is 1000kWh/ m<sup>2</sup>/year [36], here we choose to look at central Sweden where values for Älvkarleby are given as the total annual hours of sunshine when  $G_T > 200$  W/m<sup>2</sup>, with an average sunshine total hours of 1270

Table 7-2: The annual energy output of the collector. The collector is facing the south; 45° is the tilt angle. The annual energy output was calculated for 3 different mean fluid temperatures for the location of central Sweden, Älvkarleby.

and an ambient temperature during operation of 13°C. [33]



Trough type	Global annual radiation on a tilted surface [kWh/m <sup>2</sup> ]	Number of hours when GT>200W/m <sup>2</sup> , [h]	Ta [°C]	Annual heat production (kJ) for different mean fluid temperature		
				30°C	40°C	50°C
Trough with Glossy painted absorber, F'(τα) <sub>n</sub> =0.646 and F'U <sub>L</sub> =8.366	800	1270	13	475	370	263
Trough with Matte painted absorber, F'(τα) <sub>n</sub> =0.643 and F'U <sub>L</sub> =8.606	800	1270	13	467	358	249

If we compare different output from one trough at different mean temperature of the fluid, we find out that for 30°C, 40°C and 50°C respectively we have 475, 370 and 263 kWh/m<sup>2</sup>/year, so for higher mean fluid temperature we have lower heat output, because of the increase in the heat losses, as the Equation 7.1 shows.

Now if we compare the difference in the output of the two types of paint. We have the three mean fluid temperatures, for 30°C, 40°C and 50°C respectively 3%, 5% and 10% higher yearly heat output for the Glossy (Solkote) paint.

To confirm our results and make them more credible we will calculate the difference in yearly energy output for both troughs, in a hot climate, therefore we choose Dhaka, Bangladesh.

#### *Annual heat production in Dhaka, Bangladesh*

Dhaka (latitude 23.7°N) has a tropical wet and dry climate according to the Köppen climate classification [10]. The temperature fluctuations are low, with an ambient temperature 25°C.

To calculate the annual energy output in Dhaka, as we did for Älvkarleby, we are going to use Karlsson formula. It was hard to find data for Dhaka contrary to Älvkarleby; data was taken from [35]. Therefore we had to use software called Meteonorm.

#### *Data for Dhaka using Meteonorm*



We simulated the location of Dhaka, in order to get the annual solar radiation and the total of annual hours of sunshine when  $G_T > 200 \text{ W/m}^2$ . After

Simulation we found yearly global radiation on the tilted angle of  $1582 \text{ kWh/m}^2/\text{year}$ . Concerning the annual hours of sunshine when  $G_T > 200 \text{ W/m}^2$  we got this graph below.

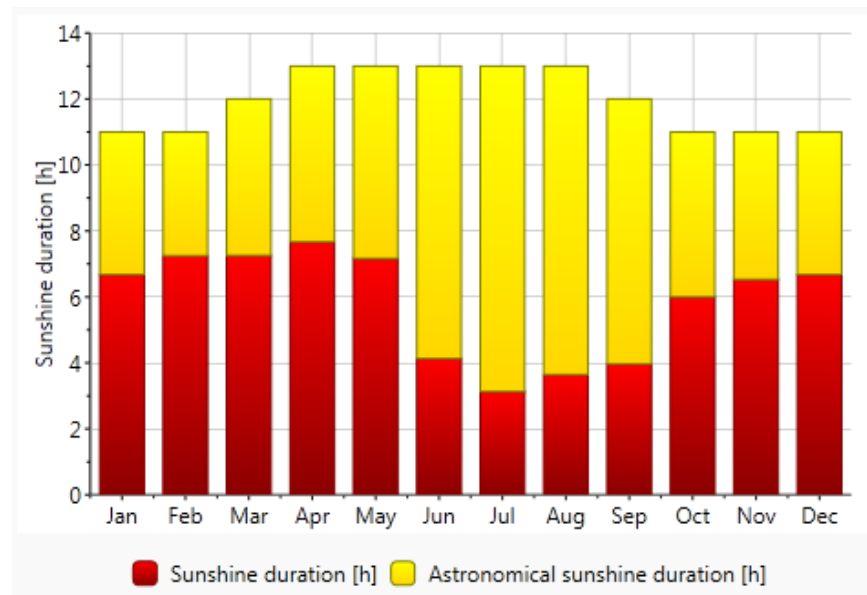


Figure 7.8: Sunshine duration for the location of Dhaka,

We calculated the annual hours of sunshine for Dhaka based on this graph. We assumed that the number of hours given by the sunshine duration are these hours when  $G_T > 200 \text{ W/m}^2$  to be checked later if it is the right number. So for Dhaka we got 2065 hours [35].

Data from [33] are valid, but we have some doubts about the data of Dhaka. These doubts are concluded in this question, do the yearly global radiation and yearly sunshine hours include radiation and sunshine hours, when  $G_T < 200 \text{ W/m}^2$ ? An answer for our question will be as a simulation of Älvkarleby city. If we get the same data as the one given by [33], it means that the data of Dhaka is correct.

Data for Älvkarleby city is not available on Meteonorm; therefore we decided to take the data of the nearest place. Borlänge is the nearest city to Älvkarleby, city, with available data.



### Data of Borlänge using Meteonorm

Borlänge is a city at a latitude of 60.433 [°N] and longitude of 15.5 [°E]. After simulation of this city we got 1180 kWh/m<sup>2</sup> for the yearly global radiation on the tilted angle. If we compare this value (1180 kWh/m<sup>2</sup>) of the yearly radiation found on Meteonorm, to the one from (Martin, Oscar, 2004) of 800kWh/m<sup>2</sup>, which doesn't include the radiation when  $G_T < 200 \text{ W/m}^2$ . We found out that they are different. If we assume that for both locations we have the same yearly radiation on tilted angle, even that they are slightly different. We could say that the yearly radiation from Meteonorm include the radiation when  $G_T < 200 \text{ W/m}^2$ . This amount of radiation represents 33%, So for Dhaka, the yearly radiation on tilted angle, instead of 1582 kWh/m<sup>2</sup> it becomes 1060 kWh/m<sup>2</sup>, after taking off the 33% of radiation when  $G_T < 200 \text{ W/m}^2$ .

We want to answer our second question about the yearly sunshine hours when  $G_T < 200 \text{ W/m}^2$ . As we did before we will calculate it for Borlänge, then compare it to the one for Älvkarleby, if it is almost the same, we will conclude that the yearly sunshine hours of Dhaka are correct, if not we will use the rule of thumb.

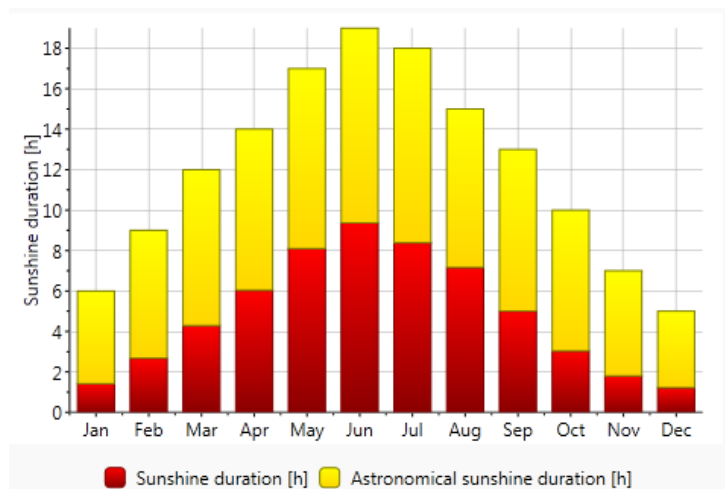


Figure 7.9: Sunshine duration for the location of Borlänge, Sweden

From the graph, it has been found an average of yearly sunshine hours of 1680 hours. If we compare the number of hours found on Meeonorm for Borlänge, to the one from [33] for Älvkarleby. We find out that the hours found on Meeonorm are 25% higher. Our explanation for this difference, is that the hours of sunshine given by Meeonorm includes the hours when  $G_T < 200 \text{ W/m}^2$ . As an answer for our question, we should take off 25% off from the hours which were found for Dhaka, so instead of 2150 hours we must use 1612.5 hours to calculate the yearly energy output.

We should mention that the Temperature ambient given by Meeonorm is including the temperature during nights and the time when  $G_T < 200 \text{ W/m}^2$ . We want the temperature ambient of only the time when we produce heat. Therefore and assuming some approximation between the ambient from Meeonorm and the temperature ambient of Älvkarleby, we assume that the Temperature ambient in Dhaka is about  $25^\circ\text{C}$ .

Table 7-3: the annual energy output of the collector. The collector is facing the south;  $30^\circ\text{C}$  is the tilt angle. The annual energy output was calculated for 3 different mean fluid temperatures for the location of Dhaka, Bangladesh.

Trough type	Global annual radiation on a tilted surface [ $\text{kWh/m}^2$ ]	Number of hours when $G_T > 200 \text{ W/m}^2$ , [h]	Ta [ $^\circ\text{C}$ ]	Annual heat production (kJ) for different mean fluid temperature		
				$30^\circ\text{C}$	$40^\circ\text{C}$	$50^\circ\text{C}$
Trough with Glossy painted absorber, $F'(\tau\alpha)_n = 0.646$ and $F'U_L = 8.366$	1060	1612.5	25	1036	901	767
Trough with Mate painted absorber, $F'(\tau\alpha)_n = 0.643$ and $F'U_L = 8.606$	1060	1612.5	25	1029	890	752



We decided to see how this collector would perform in a hot climate. Since we tried it in a cold climate before, in order to see if there will be any different in the performance for both type of paints. As we made for the location of Älvkerleby, the annual heat production in Dhaka was calculated for three mean fluid temperatures, 30°C, 40°C and 50°C.

Now assume that they are installed in Dhaka, very less difference between the two types of paint, for the three fluids mean temperatures.

#### *Meteonorm*

Meteotest has performed extensive research activities in cooperation with universities and the industry. Meteonorm is a product by Meteotest which resulted from research activities that started in the early 80s.

Meteonorm is a comprehensive meteorological reference, incorporating a catalogue of meteorological data and calculation procedures for solar applications and system design at any desired location in the world. It is based on over 25 years of experience in the development of meteorological databases for energy applications.

## **8. Economic aspects of Solarus PVT Collector**

## 8.1 Basic features and market

Solar energy is currently experiencing a rapid rate of deployment in two parallel markets: Electricity (PV and CSP) and heat (solar thermal collectors). Solarus has an aim for addressing both these two markets by the main feature of its technology: Solar co-generation of heating/cooling and electricity.

Although this idea is not new, the Solarus technology is taking the performance of solar co-generation to a new level. The present state of technology rests on a solid foundation of more than two decades of industry and government supported R&D in Sweden, where the long-term focus has been to reach the level of cost efficiency needed in order to be competitive in utility/wholesale market electricity generation.

The very generous levels of state support for solar energy (e.g. feed-in tariffs, tradable green certificates etc) in various local markets offer great business opportunities for both suppliers and buyers and has been a major driver for rapid deployment. However, too generous support systems have proven to lack political stability, which in combination with rapid growth of supply capacity has recently had severe impact on parts of the solar industry.

Rather than aiming for short-term profits from heavily subsidized markets, Solarus has been focusing on cost efficiency by developing a disruptive technology aimed to simultaneously cover the need for thermal (heating/cooling) and electrical energy for customers, a market largely remaining to be exploited. The outcome is a product portfolio that offers great ability to compete in existing solar energy markets but is even better exploited when defining a new market for co-generation.

## 8.2 Basic features, uniqueness

The existing product line of Solarus consists of two products: A thermal (T) module and a photovoltaic-thermal (PVT) hybrid module.

The unique features of Solarus are in general:

- High total energy yield (PVT)
- High temperature/exergy with low losses (T)
- In combination with storage and cooling technology, T and PVT together could be tailor made for system solutions covering a maximum share of the customer's demand for heat, electricity and cooling.
- Light-weight, self-bearing construction
- Product assembly optimized for efficient logistics – flat packages
- Modular design – same reflector box for T and PVT



- Materials selected with high consideration taken to both sustainability and cost
- Small plant foot-prints for heating/cooling+electricity concepts – ideal for commercial customers
- Concentrating technology offers high optical efficiency and low losses – in particular beneficial at high temperatures
- Seasonal yield more evened out over the year compared to flat plate technology.

### 8.3 Typical applications, examples

In the market segment of commercial/industrial customers, the Solarus products are suitable for several different applications. In this chapter, some typical applications are illustrated. All applications assume a system of 400 modules.

The goal is to be competitive on a subsidy free solar energy market. However, the pathway to low production costs goes via production capacity build up with a higher initial unit cost. To illustrate the effect during capacity ramp up, two scenarios for unit costs and revenue assumptions are shown: One scenario with high unit cost (during capacity build up) and revenues from subsidized markets (called “Early adopters” below) and one scenario with low unit cost and revenues from un-subsidized markets (called “Mature market” below). Consequently, 500 €/module and 250 €/module respectively for the PVT and 400 €/module and 200 €/module respectively for the T have been used. For electricity revenues, 200 €/MWh and 100 €/MWh have been used.

#### 8.3.1 PVT for electricity and low-grade heating

System description: 100 PVT modules producing electricity, cooled by water to 50 °C.

Table 8-1: PVT system generating electricity and heat

<b>Assumptions</b>		
<b>Number of modules</b>	<b>100</b>	<b>units</b>
<b>Operating Temperature</b>	<b>50</b>	<b>°C</b>
<b>Geographical Location</b>	<b>Sweden</b>	
<b>Annual yield, Electricity</b>	<b>203</b>	<b>kWh/m<sup>2</sup>/yr</b>
<b>Annual yield, Heat</b>	<b>905</b>	<b>kWh/m<sup>2</sup>/yr</b>
<b>O&amp;M cost</b>	<b>8</b>	<b>€/module/yr</b>

Table 8-2: Model and Outcome

	Early Adopters	Mature Market	
Price – Electricity	200	100	€/MWh
Price- Heat	50	50	€/MWh
Specific cost- Installed	3.2	1.9	€/W
Investments	80000	47500	€
Produced Electricity	45	45	MWh/yr
Produced Heat	190	190	MWh/yr
IRR	29%	41%	

### 8.3.2 T for process heat

System description: 100 T modules, producing 50°C heat, assumed to have a higher value in “Early adopters” if replacing other, more expensive source of heat.

Table 8-3: T system generating domestic hot water

Assumptions		
Number of modules	100	units
Operating Temperature	50	°C
Geographical Location	Sweden	
Annual yield, Heat	905	kWh/m <sup>2</sup> /yr
O&M cost	6	€/module/yr

Table 8-4: Model and Outcome

	Early Adopters	Mature Market	
Price- Heat	75	50	€/MWh



<b>Investments</b>	<b>70000</b>	<b>42500</b>	<b>€</b>
<b>Produced Heat</b>	<b>199</b>	<b>199</b>	<b>MWh/yr</b>
<b>IRR</b>	<b>25%</b>	<b>27%</b>	

### 8.3.3 T+PVT for electricity, heating and cooling

System description: By dividing the allocated area on both PVT and T units, systems could be tailor made to customers in order to generate the desired proportion of heat, cooling and electricity. In the following case, 70 PVT and 30 T modules is assumed. The temperature in the PVT modules is 50 °C. This makes the PV efficiency high. The 50 °C water is transferred to the T modules, where temperature is further elevated to 80 °C. About a third of the heat energy is fed into a single-stage absorption chiller.

Table 8-5: PVT and T system generating electricity (heat and cooling)

Assumptions		
Number of PVT module	70	Units
Number of T module	30	Units
Operating temperature PVT	50	°C
Operating temperature T	80	°C
Annual yield electricity (PVT)	203	kWh/m <sup>2</sup> /yr
Annual yield heat (PVT)	905	kWh/m <sup>2</sup> /yr
Annual yield heat (T)	542	kWh/m <sup>2</sup> /yr
O&M Cost	10	€/module/yr

Table 8-6: Model and Outcome



	Early Adopters	Mature Market	
Price- Electricity	200	100	€/MWh
Price- Heat	50	50	€/MWh
Price- heat for cooling	23	23	€/MWh
Investment	85000	54000	€
Produced electricity	31	31	MWh/yr
Produced heat	121	121	MWh/yr
Produced cooling	54	54	Refr. Ton hours/yr
Avoided electrical consumption	13	13	MWh/yr
IRR	15%	20%	

### 8.3.4 Other possibilities

Apart from the described applications, there could be many variations, e.g. with purpose to increase the solar fraction (the extent to which a consumers' consumption is covered by solar energy). One way to elaborate with the solar fraction is to add thermal storage capacity.

## 8.4 Market development, general

Among the different energy generation technologies available, solar energy is currently the fastest growing and is also attracting most investment capital. Even though local markets have experienced turbulence, the aggregated, global market is steadily growing. Of the 257 bn\$ invested in renewable energy in 2011 [31], 147 bn\$ (57%) was spent on solar energy.

- Of the 147 bn\$ global investments in solar energy reached in 2011, 138 bn\$ was in assets:
  - 62 bn in utility scale projects / 76 bn in small scale (rooftop) projects
  - 117 bn in developed countries / 30 bn in developing countries



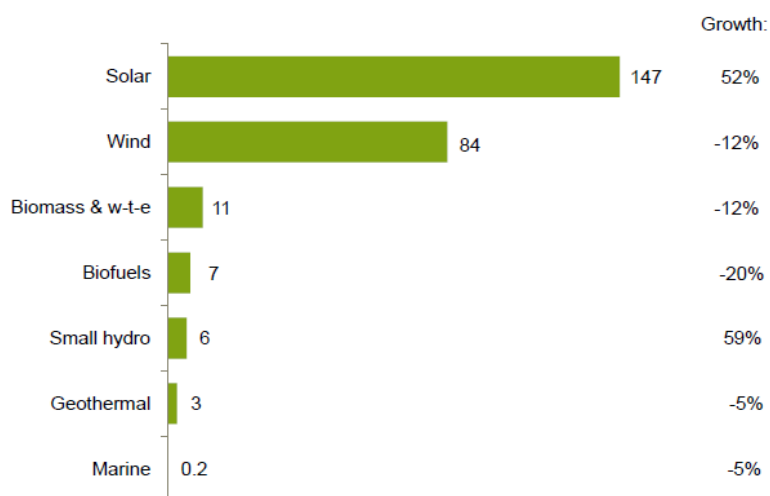


Figure 8.1: Global investments in renewable energy

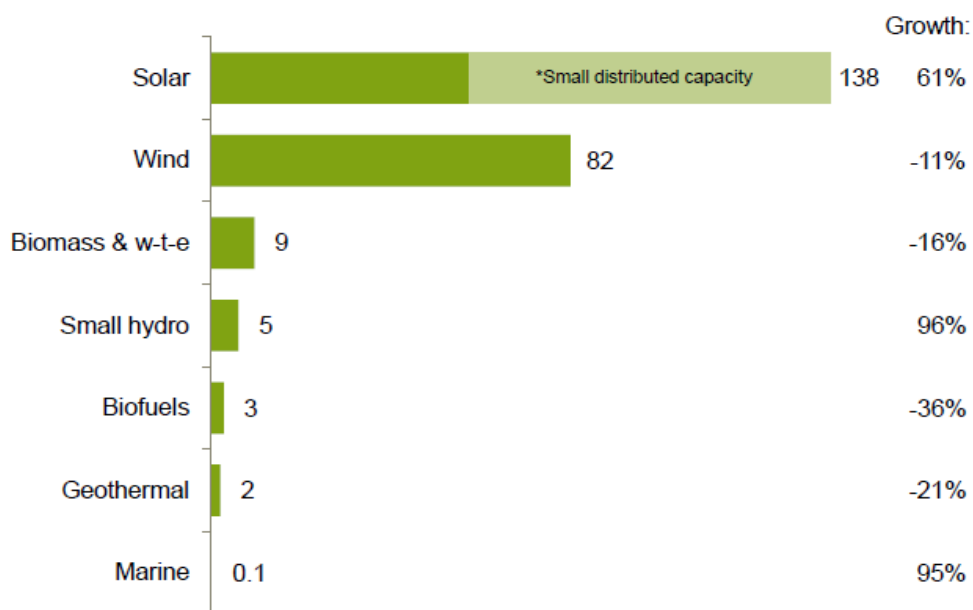


Figure 8.2: Global investments in asset finance of renewable

- Growth rate has been steady and aggressive for a decade, CAGR(Compound Annual Growth Rate) of 40%
- Countries:
  - US: 27.6 bn\$
  - China: 13.3 bn\$

- India: 4.7 bn\$
- Italy: 3.7 bn\$
- Segments (Bloomberg NEF estimate)
  - <20kW: 25% (residential)
  - >20kW, <1MW: 50% (small commercial)
  - >1MW: 25%
- Solar Thermal: China totally dominating
  - 42 GW<sub>th</sub> (60 M m<sup>2</sup>) worldwide in 2010
  - 81% China, 9.3% Europe, rest others

## 8.5 Market segmentation, potential

### 8.5.1 Countries

As mentioned previously, although the global market for solar energy is steadily growing, local markets are a lot more volatile. To a large extent, this volatility is caused by sudden changes in various subsidy schemes on local markets.

In order to be less exposed to subsidy schemes, and thereby also sudden changes thereof, Solarus is targeting competitiveness without subsidies. The three main parameters to consider for the different markets are:

- The local cost of energy for various customer segments
- The solar irradiation
- The LCOE of the solar technology to be applied

The following figure shows these three parameters combined. As LCOE is decreasing [33], which the trend is also clearly indicating by lower component, module and system cost, more markets come within reach.



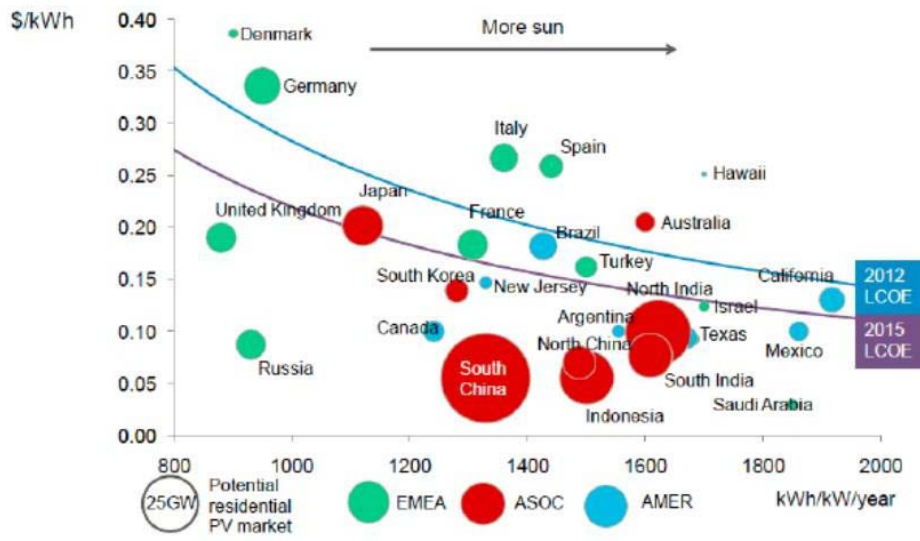


Figure 8.3: Estimated residential PV price parity in USD/kWh, (size of bubbles refers to market size) (BNEF, 2012a)

### 8.5.2 Customer segments

Being a somewhat disruptive in its characteristics, the Solarus technology will have a slightly different effect on different customer segments, implying that it might favor segments differently than conventional solar energy technology. A commonly used definition of segments is:

- Small residential
- Commercial/industrial
- Utility

Table 8-7: Some key characteristics of these segments

	<b>Small residential</b>	<b>Commercial/ industrial</b>	<b>Utility</b>
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System size	Small (<20 kW)	Medium (>20 kW;<1 MW)	Large(>1 MW)
Benefits of scale	Low	Medium	High
Alternative energy cost	High	Medium/high	Low
Value of generated heat	High	High	Low/medium
Market share of segment <sup>1</sup>	25%	50%	25%

For the **small residential** segment, Solarus technology could generate a value by its co-generation features. However, the benefits of scale are limited since installation costs for both electricity and heat will be added to the fairly small system. Solarus has taken this into consideration by simplifying installation. On the other hand, the price level for both electricity and heat in this segment is high so that systems built on Solarus technology still will be good business.

For the **commercial/industrial** segment, the co-generation feature will have most benefits. While the general alternative price level for the customer is still high in this segment, systems grow larger and thereby benefit from scale. The energy yield per roof top area is another key feature in sub-segments, meaning that due to the high total efficiency of the Solarus product, the limited roof top area of a customer will yield more solar energy than conventional technology, covering a larger share of the customer consumption.

For the **utility** segment, the economies of scale come into full force. However, large installations will inevitably require larger areas, which might locate these plants remotely. In these locations, off-take of heating/cooling will be less simple than in the commercial/industrial segment. Also wholesale market prices (excl distribution costs) are lower. Thereby, on a pure market competitiveness basis, economics will likely be challenging in the short term. Under current subsidy regimes in several markets, large plants focusing on electricity generation will be good business. The low module cost of Solarus in combination with low system costs implies that it is in this segment the competitive edge versus conventional PV technology is largest.

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<sup>1</sup> 2011 level, estimate by Bloomberg New Energy Finance



In conclusion the **commercial/industrial** segment, including multi-family housing is Solarus priority.

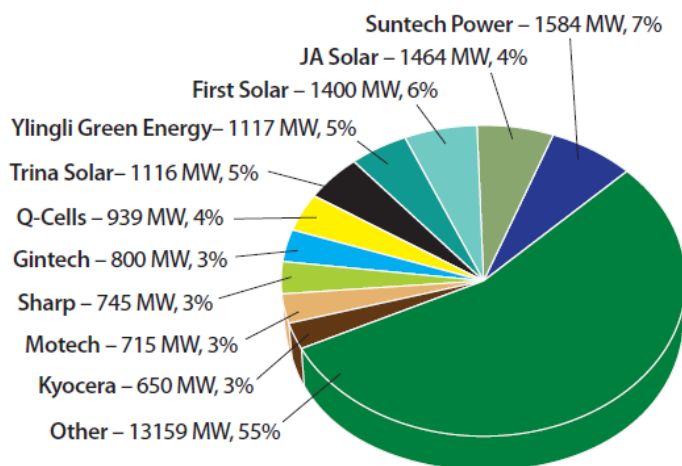


Figure 8.4: Top ten global PV producers in 2010, market share in % (DOE 2011)

## 9. Conclusion and Discussion

The daily performance curves of electrical, thermal and overall performances have been plotted in Figure 5.3, 5.4 and 5.5 respectively.

There are some losses and irregularities have found, and we have agreed that these losses are from uneven solar irradiation to the backside of the trough. So the configuration of the cells and also the concentrator has to be studied. The electricity carrying wires from the

collector to the load has some losses. In figure 5.6 and 5.7 it is showing that the two efficiencies are not same.

The thermal efficiency of the PVT collector has shown in Figure 5.8. The optical efficiency has been observed around 50% and it decreases as the temperature difference increases.

The amount of heat losses from the thermal collector is very high comparing to the value was declared by Solarus AB (2013). Either for the trough with glossy paint or with Mate the heat losses were almost 5 times higher than the value announced by Solarus which is  $1.9 \text{ W/m}^2\text{C}$ , while the values found respectively for the glossy and mate were  $8.366 \text{ W/m}^2\text{C}$  and  $8.606 \text{ W/m}^2\text{C}$ . The main reason of getting the higher heat loss is we have varied the flow rate instead of changing inlet temperature. Because it is fast to change the flow rate instead of changing inlet temperature.

The annual thermal output has been calculated in two locations (hot and cold climate) for the two types of selective surface coatings, we found that they were slightly different. In both climates the Q-loss coating has given slightly higher energy compare to Solkote. Although more experiment has to be done to decide finally. The U-value had found for both troughs were extremely high for a commercial product.

The target market and customer have been studied. The compatibility of the Solarus collector with the recent regulations has been discussed. The basic features and added value of the collector in order compete in the global have been identified. To be more specific, the electricity and heating cost, maintenance and other cost for specific geographic location have been calculated.

There are two markets have been analyzed. One is early adopters which have subsidy and other is mature which does not have any subsidy. Based on the markets, how Solarus collector will change in price and the investment required producing certain number of collector has been given. Internal rate of return (IRR) is very important parameter to evaluate the growth of the product in the market. It gives the idea of the profitability of the product. IRR has been shown for both markets.

In this thesis work, it has been studied about the global energy market and their segmentation (general and potential). In the customer segmentation section, the potential customer has been divided in three potential customers. These are small residential, commercial and utility.



## 10. Recommendation for Solarus

The receiver width can be increased to have more power production. But increasing the width of receiver might decrease the reaching light on the underside. So, it needs to do some experiment in order to get the optimum width.

The parabolic concentrator used by Solarus is strongly reflects light to one side of the receiver. In PVT, it is not desirable at a point. Because when the cell temperature increases the electricity production decreases (Figure). In thermal applications this is acceptable, even desirable to a degree as it provides higher temperatures.



Previous studies have included investigating the possible benefits from placing a light diffuser in the trough in such a way that the concentrated light is spread more evenly across the underside of the receiver. [37]

According to [38], low-concentration CPC collectors are less sensitive to scattering of the incident irradiance, and cheaper rolled aluminium reflectors can be a cost-effective and suitable material in these applications. Additionally, a lower-quality receiver may have the beneficial effect of spreading the reflected light more evenly across the photovoltaic cells.

The U value is found extremely high. Due to the high U value the efficiency is decreasing. The experimental U value from this thesis work is almost five times higher than the given value by Solarus AB. Therefore, it is required to change the receiver material and need more experimental test.

Solarus needs to do some extensive marketing of their product by introducing the added values and compatibility with the locations.





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