Photovoltaic Cells Powering Cooling Systems

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DIVISION OF INNOVATION ENIGEERING | DEPARTMENT OF DESIGN SCIENCES
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MASTER THESIS

Photovoltaic Cells Powering Cooling Systems

How photovoltaic cells can be used to power cooling systems on small electronic products as a complement to the regular source of power.

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Abstract

This master thesis project was carried out at the Division of Innovation Engineering at Lund University and at Axis Communications AB in Lund. The thesis has investigated the possibility of using PV cells as a direct power source for small scale applications to meet the problems of heat management in electrical equipment. The investigation has been performed on a global level as well as on a local level as a case study. The case study was performed at Axis Communications AB where a prototype was to be designed as a proof of concept of a PV system directly powering a cooling system to prevent cameras from overheating. The prototype was to be designed as a solar protection cap with an integrated PV system. The PV system was to power two fans. The fans were integrated in the solar cap design with the aim to lower the temperature of the camera of interest, namely a fixed dome P32 camera.

The project aimed to find how the integrated PV system could be designed and with the case study to demonstrate how the PV system could power an active cooling system. The PV system was designed to optimize the power production at critical temperatures and irradiation. Dubai was the location in focus for the case study, where heat management of cameras is a problem.

The results consisted of a comparison between the cooling effects from the prototype and an existing solar cap solution without integrated active cooling. The results showed that the temperature of the camera with the prototype was lower than that of the camera with the existing solution under direct illumination. The project results can be used as an example of how an accessory product with an integrated PV cell system can power a desired application, in this case two fans that successfully lowers the camera temperature.

Keywords: Photovoltaic cells, Directly powering, Cameras, Cooling systems, Axis

Sammanfattning

Detta examensarbete har utförts på institutionen för Innovationsteknik på Lunds Tekniska Högskola och på Axis Communications AB i Lund. Denna uppsats har undersökt möjligheten att använda PV-celler som en direkt strömkälla för småskaliga applikationer för att möta problemen med värmehantering i elektrisk utrustning. Undersökningen har gjorts på en global nivå såväl som på lokal nivå i form av en fallstudie. Fallstudien utfördes på Axis Communications AB där en prototyp skulle utformas som ett proof of concept för ett PV-system som direkt driver ett kylsystem för att förhindra att kamerorna överhettas. Prototypen skulle utformas som en solskyddande keps med ett integrerat PV-system. PV-systemet skulle driva två fläktar. Fläktarna var integrerade i solskyddet med målet att sänka temperaturen hos kameran av intresse, som i detta projekt var en fixed dome P32 kamera.

Projektet syftade till att ta reda på hur det integrerade PV-systemet kunde utformas och med fallstudien demonstrera hur PV-systemet skulle kunna driva ett aktivt kylsystem. PV-systemet var utformat för att optimera energiproduktionen vid kritiska temperaturer och solinstrålning. Platsen i fokus för fallstudien var Dubai, där värmehantering av kameror är ett problem.

Resultaten bestod av en jämförelse mellan prototypens och den befintliga solkepsens kylningsförmåga. Resultaten visade att temperaturen hos kameran med prototypen var lägre än den hos kameran med den befintliga lösningen under direkt solinstrålning. Projektets resultat kan användas som ett exempel på hur en tillbehörsprodukt med ett integrerat PV-system kan driva en önskad applikation, i det här fallet två fläktar som klarar av att sänka kameratemperaturen.

Nyckelord: Photovoltaic cell, direkt strömförsörjning, Kameror, Kylsystem, Axis

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This master thesis project was carried out with the help of employees at Axis Communications AB as well as from Lund University. We would like to thank all the helpful people on Axis for the guidance and their valuable contributions to our project and everyone from Lund University who have supported us.

We would like to give a special thanks to Maiko Karlsson and Magnus Lundegård at Axis, who have been supervising us throughout the whole project and who have had a major part in making the project possible. We would also like to thank Freddie Olsson for all his help with the electrical set-up of the prototype. Our tests would not have been possible without his assistance. Moreover, we want to give a big thanks Jessica Wadin who has been our supervisor at Lund University. Thanks for guiding us and keeping us on the right track through the project and for the constructive and fast responses and feedback. We want to thank Henrik Davidsson at Energy Building Design at Lund University, who has been a huge support and has helped us with many important parts of the project. We would also like to thank Magnus Borgström at the Department of Solid State Physics at Lund University whom have given us useful information regarding photovoltaic cells.

We are very grateful for all the help, and for the opportunity of carrying out the project at Axis, which have been a valuable learning experience and it has been interesting and fun all the way.

Lund, January 2019

Louise Homle & Kajsa Wernerson

Table of contents

List of acronyms and abbreviations

GHI	global horizontal irradiation
DNI	direct normal irradiation
SE	sun elevation angle
PV cell	photovoltaic cell
PoE	power over ethernet
DHI	diffuse horizontal irradiation
PCB	Printed Circuit Board
CPU	Central Processing Unit

1 Introduction

This Master Thesis investigates the possibilities of utilizing the power from the sun to power cooling systems. The power from the sun is generated from Photovoltaic (PV) cells which then can run a cooling system inside a heat generating product placed outdoor. The project firstly investigated and researched the global trends and the existing issue within the area today and secondly, performed a case study.

The first part investigates the parameters in need of consideration when designing a PV system used for direct powering. The investigated parameters were later used in the case study when designing this kind of PV system for a specific product in a specific region. The region in focus for the case study is Dubai.

1.1 Problem Description

The global problem is overheated electronic components in need of an external power source to power a cooling system when exposed to irradiation and high ambient temperatures. The problem was observed by Axis Communications where cameras have had issues with overheating and where the cameras are in need of power for a cooling system.

1.2 Aims

The aim is to investigate and find the parameters in need of consideration when designing a PV system for direct powering. The goal of this project is to design an example of a product capable of protecting the P32 from direct sunlight as well as harvesting the solar energy to power an active cooling system using photovoltaic cells, which will be referred to as PV cells in this thesis. The project aimed to produce a 3D-printed prototype using a CAD-model designed with the help of principles from Ulrich and Eppinger. This prototype was to be tested where temperature measurements could give a comparison between the cooling effects from the new prototype and the existing solution.

Due to the limited time for the project of 20 weeks, a complete and well-functioning product could not be designed. The main focus had to be on designing a prototype that could demonstrate an example of the cooling effects of this particular design with the chosen PV cells. This could later be used as a template for further research and development on the subject.

1.3 Delimitations

The delimitations for the project was initially to consider PV cells as a possible source of energy when directly powering a cooling system. In order to fit the timeline of this project further delimitations for the case study were made. As the cooling system was not the main focus of this project it was chosen that fans should state as the power needing cooling system. Since fans are well known at Axis it was decided that for this concept the PV cells would be tested together with a fan. It should be noted that fans do not necessarily need to be the application for the PV cells as they can be combined with any type of system that require electricity. The type of fan used is a small 12 V DC fan (Sanyodenki, 2019). The prototype is to be adapted to the Dubai climate and sun movement. It was, as previously mentioned, decided that the PV cell system should run a cooling system directly, without energy storage. This increase the level of importance of the angling of the PV cells. The camera within the scope of the case study is the P3225-LVE camera.

The PV modules used for the prototype had to be off the shelf items since it was impossible to design PV modules and receive them within the time frame. It has not been possible to be at the site, Dubai, of the case study to perform tests which is why simplifications have had to be made. Testing at the site would give more accurate results than testing in a laboratory and more parameters in need of consideration would probably be found.

2 Methodology

This chapter shows and describes the methodology used in this project.

2.1 Planning

The project was planned with a GANTT chart. The GANTT chart for the planned and actual outcome is shown in Appendix A.

2.2 Approach

The project started with analyzing and understanding the global issue within the scope of this investigation. Hence, a literature study was conducted in order to find where the issue could be applicable. For the case study the project used Ulrich and Eppinger's guidelines (Ulrich & Eppinger, 2012) for Product Development and Design.

2.3 Literature Study

Extensive research was performed in order to know how the solution to the problem should be designed. The main issue presented by Axis regarding this area is the need for cooling when the camera is exposed to irradiation. Therefore, the project started with understanding cooling systems in order to see how and where energy harvesting was needed and possible. PV cells were the energy harvesting solution within the scope of the project, and a deeper understanding of how they work was required. The literature study has focused on three divisions;

PV cells

The PV cells were investigated in order to find their limitations and their possibilities. The goal was to understand the important parameters when designing for a PV cell system.

Global Trends

There were two main questions in need for answer in this part. Firstly, a greater understanding about the need for energy harvesting and power supply in the world. Secondly, to grasp the concept of why PV cells are a possible solution. This was done by researching PV cells and understanding the reason for their recent popularity.

Cooling Systems

The underlying problem for the case study is the need for cooling. To understand how the power supply could be designed, the power needing system was investigated. Different types of cooling systems were researched in order to understand which aspects that needed to be considered for this cause.

2.4 Method

This project followed Ullrich and Eppinger's Product Development and Design guidelines in order to reach the best possible prototype that would fulfill the desires of all parties. The guidelines were however, adapted in order to fit the scope and timeline of this project. The Concept Development process contains the steps shown in Figure 2.1 (Ulrich & Eppinger, 2012).

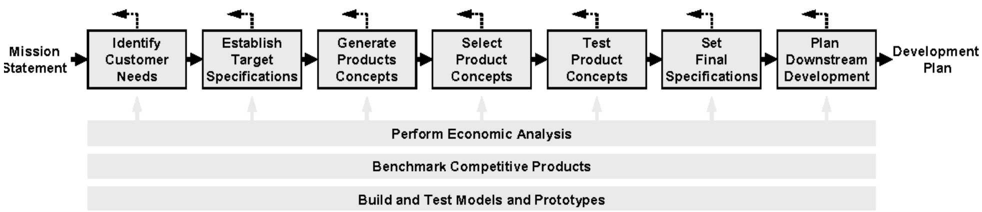


Figure 2.1 The concept development process.

The steps used for this project was the following:

- Identify Customer Needs
- Establish Target Specifications

- Generate Product Concepts
- Select Product Concept
- Test Product Concept

The identification of customer needs was conducted in five steps (Ulrich & Eppinger, 2012);

- Gather data from customers
- Analyze the data and translate it to needs
- Organize the needs hierarchically
- Determine the relative importance of the needs
- Reflect over the results and process

These steps were followed in order to get an overview and understand the needs of the customer.

The target specifications were established according to the steps in Ulrich and Eppinger's guideline (Ulrich & Eppinger, 2012):

- Prepare a list of specifications
- Benchmarking
- Establish ideal and acceptable target values
- Reflect over the results and process

The concept generation was performed by the team within the project. All the ideas were sketched individually and later presented to the group. Ideas were combined into new concepts and all the concepts were taken further to the next step.

This project used Concept Screening for the first part of the selection process and a combination of favorite product and external decision for the final selection. The concept screening is based on Pugh's concept screening matrix, which was prepared according to five of the steps from Ulrich and Eppinger's guidelines (Ulrich & Eppinger, 2012);

- Prepare the concept screening matrix
- Grade the concepts
- Rank the concepts
- Combine and improve the concepts
- Choose one or more concept

Choosing the favorite product can be done by an influential member of the project group. A customer or other external stakeholder can also choose the product considered to be the most preferable (Ulrich & Eppinger 2012, p. 199). For this project the favorite products were chosen after the concept scoring since both team members individually thought two of the concepts were most interesting. After, the engineers at Axis were to choose which of the products they thought were most advantageous.

A concept testing process is performed in order to validate the concepts included in the test. The test gives the possibility to understand what parts which have to be improved and what actually work (Ulrich & Eppinger 2012, p. 224).

Part 1 Literature Study

This chapter describes the background to the different aspects of this project, both on a global level and nano scale. In the conclusion of some chapters the identified parameters, which are in need of consideration when designing a PV system like the one in this project, are stated.

3 Global Trends

This chapter presents the global trends investigated as well as relevant parameters identified for this project.

Cities tend to grow higher, more dense and larger due to the trend of urbanization. A consequence of this is that large parts of the built areas will have a decrease in air flow, since the wind can take many different paths through the area and thus divides into less strong winds. As the wind speed decreases, the temperature rises. In contrast to more desert areas, the temperature within cities tend to remain high also during the night, due to the daily light absorption of walls, ground, concrete etc. (Ignatius, Wong & Jusuf, 2015, pp. 130-131).

In many parts of the world and in remote areas an electric power supply can be difficult. If the distance is far to the nearest larger power grid it can be both costly and unreliable to install cables to the area of interest. Cables can be damaged this often involve much effort and costs if placed underground. Since the technique for small scale electricity production is available it has become an alternative for remote areas with such needs. Even if a remote area would be connected to a larger distant grid it could result in risks if the grid would malfunction. It is often a need for back-up in such locations if the original power source is unreliable (Western Power, 2019).

Another important trend to consider for this project is that major progresses have been made regarding electronic devices over the past half century. Furthermore, electronic equipment is implemented in countless parts of the modern society. Smaller and more efficient components are constantly developed pushing the component design from micro scale to nano scale. As the computing technology advances and processing demands increases, so does thermal challenges making the power management and heat transfer critical (Moore & Shi, 2014).

An increase in temperature can negatively affect the function of different electronic devices. The thermal design and an effective heat transfer are important to meet the drive for smaller and faster CPU:s and microprocessors for instance. Smaller sizes of the integrated circuits combined with an accelerating number of transistors result in higher heat generation (Moore & Shi, 2014).

As the atmosphere of the Earth contains molecules, greenhouse gases, that absorb some of the energy from the solar radiation, parts of the absorbed radiation will be emitted back to space but also emitted to the Earth's surface. The heated surface will radiate and, due to the composition of the atmosphere, not all heat will leave the planet. This is a natural greenhouse effect that hinders some heat from escaping. The burning of fossil fuel contributes to an increase of greenhouse gases in the atmosphere and alters the natural atmospheric composition. The temperature on Earth will likely be affected as well as ecosystems of all kinds (NASA, 2018). The effects of global warming have a worldwide impact on people and triggers an involvement for alternative power sources, ways of living and consuming habits. Power production with low environmental effects have become a global trend where techniques for wind and solar power are rapidly developed and improved (Brennan, 2016). In an interview with NASA's Jet Propulsion Laboratory the Stanford university professor Mark Jacobson describes the reason of why to use wind and solar energy as "they are the only two forms of energy that theoretically can supply the entire world for all purposes, many times over" (Brennan, 2016).

In 1956 the Nobel prize was awarded for the transistor effect which was the result of the invention of the p-n junction. When the first silicon PV cell was produced it had an efficiency of 4 % and in the 1960 the silicon PV cells started to be commercially available. At that time the efficiency had already been improved to reach about 14 % (Tress, 2014). Figure 3.1 visualizes the development of PV cell efficiencies for different types over time. The figure shows several different PV types, and the interesting point is that all the PV cell types in this chart have reached higher efficiencies over the years.

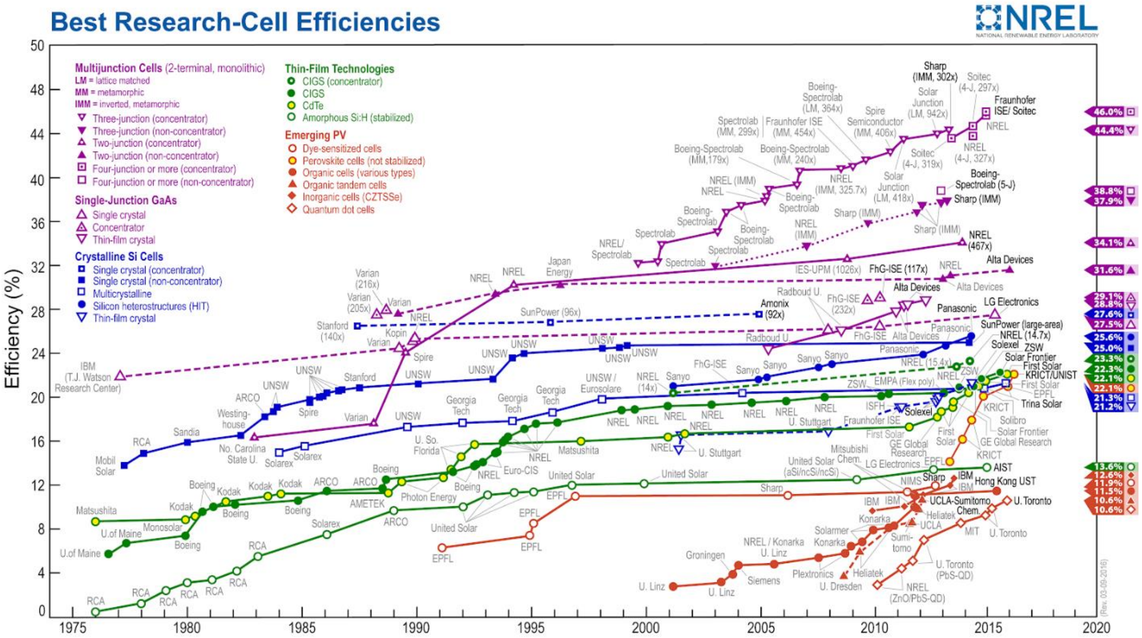


Figure 3.1 The chart visualizes the development of PV cell efficiency over time, for several different PV cell types displayed in the chart as lines of different colors and marks.

Swanson’s law describes the price development of photovoltaic cells over time. As the global volume of PV cell modules increases, the price drops, which can be seen in Figure 3.2. According to Swanson’s law the price of PV cell modules will drop 20 % per a double of the global volume (Fitzgerald Weaver, 2017).

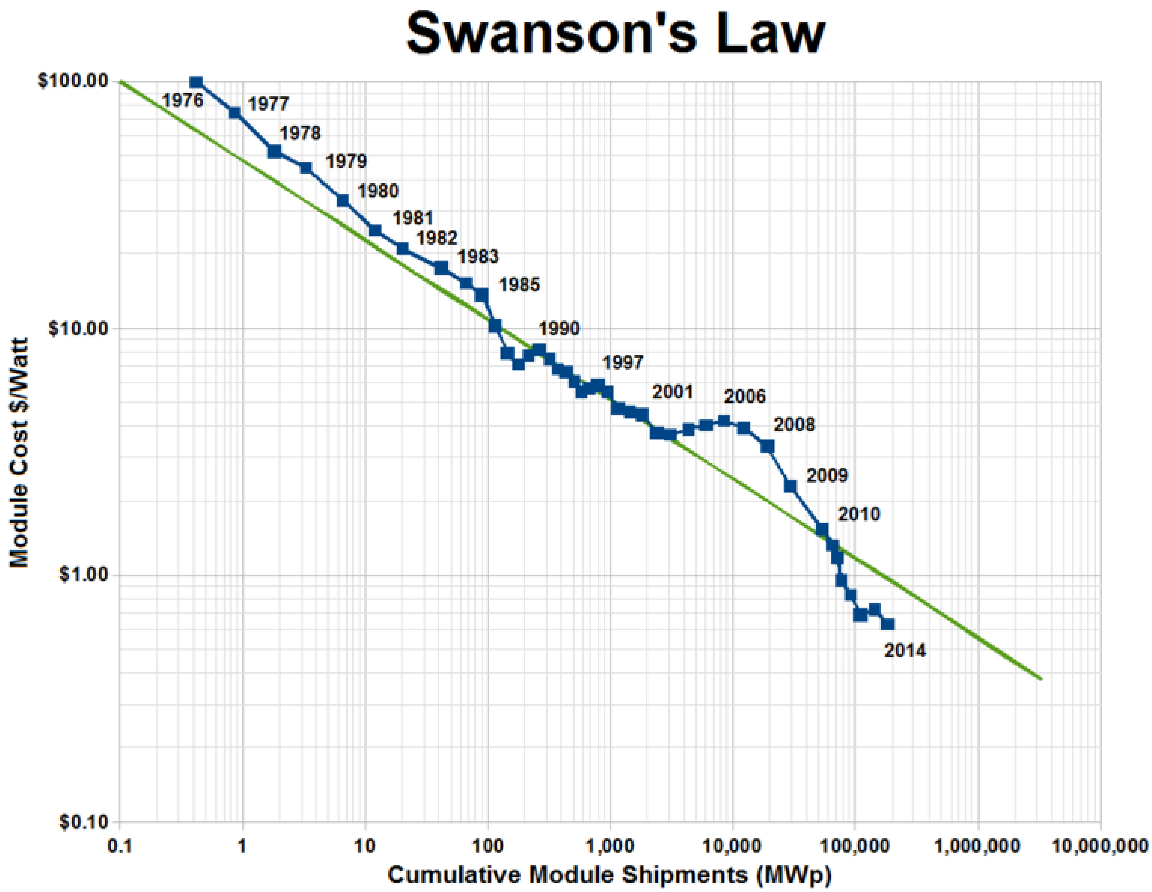


Figure 3.2 Shows the cost development of PV cells over produced module volume and time.

3.1 Photovoltaic Cells and Relevant Parameters

An overview of the function, usage and limitations of PV cells is presented below. The focus is small-scale applications for PV cells and how to generate electricity in an efficient way. In order to understand the different terms used in this chapter and further on, when discussing photovoltaics, three different terms will be used;
PV cell: The area where the electricity is generated.
PV module: Several PV cells connected on a plate which can have different sizes.
PV system: Several PV modules connected to each other

For more detailed information regarding how PV cells work, see Appendix B.

Figure 3.3 explains the different terms.

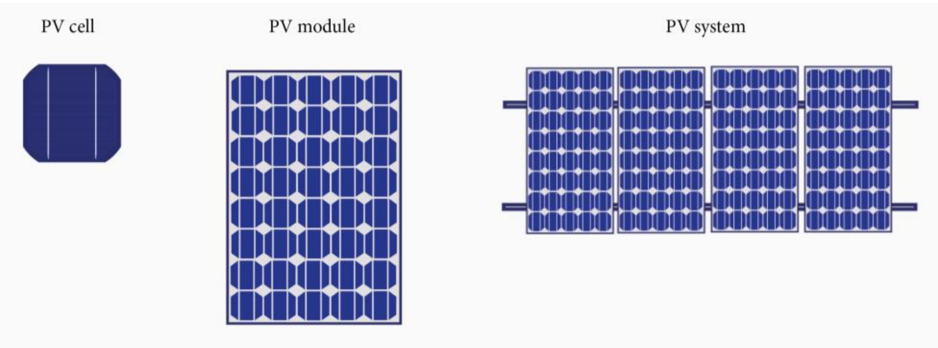


Figure 3.3 Typical looks of a PV cell, PV module and PV system.

When a PV module is exposed to irradiation one can measure a short circuit current and an open circuit voltage. The short circuit current is denoted I_{sc} and is measured directly over the module with no resistance, i.e. a short circuit. The open circuit voltage is denoted V_{oc} and is measured over the module with an infinite large resistance, i.e. an open circuit, see Figure 3.4 (Bowden, S. & Honsberg, C., 2019b&d). The power output from PV cells is dependent on the load. If the load has a too high current demand, the PV cell will not operate at its highest potential. If the drawn current is very low the PV cells are not used to its fullest potential (Petreus, Farcas & Ciocan, 2008; Chou, Li & Kim, n.d.). The point at which the load perfectly matches the characteristics of the PV cell can be found by tracking the maximum power point, see Figure 3.4. If for instance a light bulb is connected to the PV cell system and requires a voltage and a current corresponding to Vmax and Imax, then this particular light bulb will utilize as much energy as possible from the PV cells. The maximum power point is however affected by the intensity of the irradiation. To keep the input voltage to the load steady even if the PV cell output varies it is therefore beneficial to use a converter between the PV cell system and the load. With a converter the optimal voltage for the PV cell can be set and switched up to match the optimal input voltage of the load, despite variation in radiation intensity (Olsson, 2018).

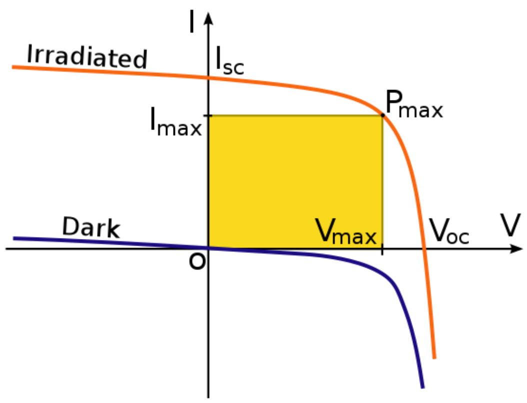


Figure 3.4 I-V curve for maximum power point tracking.

The shorter distance the radiation from the sun's surface has to travel through the atmosphere, the more radiation reaches the Earth's surface, see Figure 3.5. Therefore, in theory, the highest irradiation is when the sun is at its highest position in the sky (Wenham, Green, Watt & Corkish 2007, p. 6).

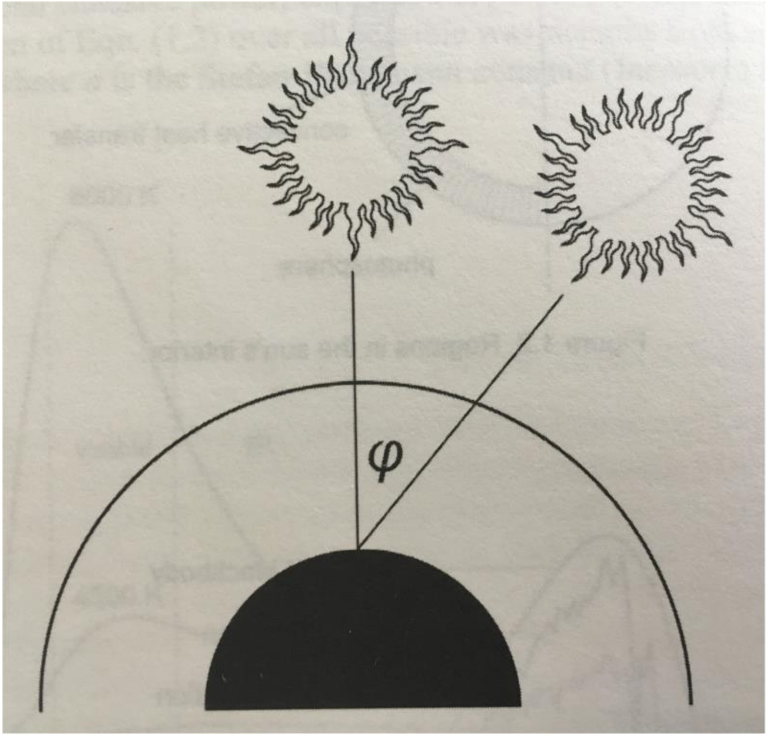


Figure 3.5 The sun at its highest, with the shortest distance for light to travel through the atmosphere. When the sun with the angle of φ from the highest, the distance for light to travel through the atmosphere is longer.

Parts of the high energy light with shorter wavelengths are reflected or absorbed by the atmosphere before reaching the Earth's surface, leaving the rest of the light to either be reflected or absorbed and emitted as heat (Wenham, Green, Watt & Corkish 2007, p. 9). The energy that reaches the Earth's surface can be used for energy production using for instance photovoltaic cells. Depending on the composition of the atmosphere the irradiation can vary. A clear sky with no air pollution or clouds is beneficial for the efficiency of PV cells (Wenham, Green, Watt & Corkish 2007, pp. 6-9).

When identifying the specifications for a produced PV cell, the uptake of radiation is estimated. For this estimation standard values are used where the module temperature is 25°C, with an irradiance of 1000 W/m^2 and an air mass of 1.5 (AM1.5). The air mass is a measure of the distance that the sunlight travels through the Earth's atmosphere (D. W. N., 2014).

To maximize the power produced by PV cells the tilt of the PV cells needs to be optimized. Depending on the geographic location the optimal tilt can vary (Siraki & Pillay, 2012). The power output is maximized when the PV cell surface is perpendicular to the incident light, meaning that a determination of the solar height is necessary for the calculations of the PV cell tilt (Morad, Al-Sayyab & Abdulwahid, 2018). The solar height, or the sun elevation angle (SE), is the angular height of the sun measured from the horizontal plane, see Figure 3.6. This angle will vary depending on time and geographic location (Bowden & Honsberg, 2019a) and can be calculated as presented in Appendix C, or by using simulation programs (Andrewmarsh, 2018).

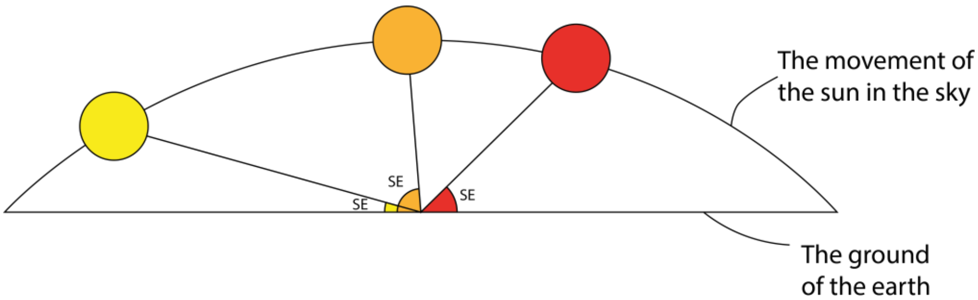


Figure 3.6 The movement of the sun and the sun elevation angle, SE.

When the elevation angle is determined, for instance as an average angle during a period of time, the tilt of the PV cell system can be calculated. The surface of the PV cell system should be perpendicular to the incoming light, which is obtained by subtracting the elevation angle from 90°. When discussing solar irradiation and tilt there are several terms which are good to understand measurements and solar data. The three most common ones are Global Horizontal Irradiation (GHI), Direct Normal Irradiation (DNI) and Diffuse Horizontal Irradiance (DHI). GHI is the total irradiation reaching a horizontal surface. DNI the irradiation reaching a surface perpendicular to the source of the irradiation, in this case the sun and the SE, see Figure 3.7. DHI is the irradiation not originating directly from the sun reaching a horizontal surface, see Figure 3.7 (Vashishtha, 2012). The three terms correspond to each other through the following formula (Vashishtha, 2012):

$$GHI = DNI * \sin(SE) + DHI$$

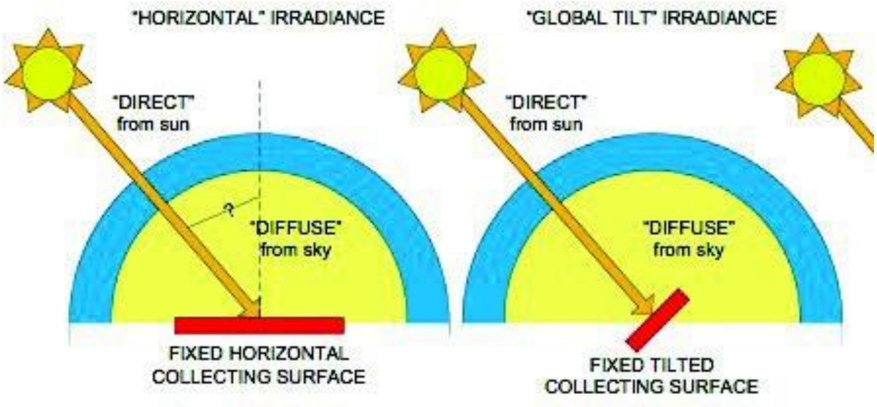


Figure 3.7 Explains the difference between DHI & DNI.

The supplier specifications of PV cells are commonly based on measurements and values at optimal conditions with a cell temperature of 25°C and an irradiance of 1000 W/m^2 (D. W. N., 2014). A lower irradiance consequently decreases the power output of the PV cell. The power output is further correlated to the area and efficiency of the PV module according to the formula (Singh & Ravindra, 2012, p. 38):

$$P_{out} = \eta \cdot P_{in} \cdot A$$

Where,

P_{out}: Power output [W]

P_{in}: Intensity of incoming irradiation [W/m^2]

η: PV cell efficiency [%]

A: PV cell area [m^2]

Additionally, the power output is also affected by a rise in temperature. As earlier stated, the excess energy higher than the energy of the band gap will be lost as heat. These heat losses consequently heat the PV cells. When the temperature of the PV cells increases, the band gap potential decreases, resulting in a lower efficiency (Singh & Ravindra, 2012, p.41).
The temperature dependence varies depending on the material of the cells. This is due to the light absorbance properties of different semiconducting materials. Heat losses will be smaller if the material can absorb a greater part of the solar spectrum, utilizing a larger part of the incoming solar energy to generate a current (Zeitouny, Lalau, Katz, Dollet & Vossier,

2017; Bowden & Honsberg, 2019e). To estimate the drop in efficiency for a specific type of PV cell, a temperature coefficient can be calculated. The temperature coefficient of the PV cells on the market is between -0.2 %/°C - -0.6 %/°C (PV Temperature Coefficient of Power, n. d.).

Since PV cells need electromagnetic radiation to generate power, they will not function properly if they are not illuminated. PV cell systems will consequently be affected when shaded, which is most likely to happen in different ways for most PV cell systems in an outdoor environment. Depending on how the PV cell modules are connected, the system will behave in a certain way when shaded (Bowden & Honsberg, 2019c)

When only considering one single module the power output is dependent on the illuminated area of the module. If for instance half the module is shaded, the I-V curve moves down to half the current output (Bowden & Honsberg, 2019c).

3.2 Conclusions of the Chapter

PV cells is a good energy source which does not contribute as much as fossil fuel to the global warming. The degree of efficiency of PV cells is increasing and will probably continue to do so in the future. This, at the same time as the price is dropping. PV cells will hopefully be a more affordable environmentally friendly energy source in the future. The size of electronic components is decreasing at the same time as more components are installed in electronic devices, causing increasing heat problems. Cooling systems might be a necessity in order for them to function properly. In areas where power grids are unpredictable or non-existent, independent power sources might be needed. The temperatures in cities are higher compared to the area around it. This issue will increase as more people move into and live in cities.

There are different types of PV cells which can be used for small-scale applications, which ones that should be used is dependent on more parameters than the material used in the PV cells. It is also important that the appropriate connections in the electrical circuits are used in order to utilize as much power as possible from the PV module. PV cells are dependent on the amount of irradiation reaching the cell. The irradiation is theoretically the highest when the sun is at its highest position in the sky, i.e. the sun elevation angle is the highest. The irradiation is also higher if the sky is clear compared to if there is pollution or clouds in the sky. The PV cell is also most efficient if it is placed perpendicular to the irradiation. The efficiency decreases if the PV cells are placed in areas with hot ambient temperatures. In those cases, it is important to consider the temperature coefficient of the PV cell. Shading also affects the power output, when designing products with PV cells one need to identify and understand the effects of shading. So, the parameters identified in this part which are needed further on in the project is stated below;

- Degree of efficiency
- Irradiation
- Sun elevation angle
- Air pollution and clouds
- Angle of the PV module
- Ambient temperature
- Temperature coefficient
- Shading
- Area

4 Cooling Systems

Cooling systems can be either passive or active. Active cooling refers to external power being added to remove the heat, for instance by using an electrical pump to move hot water. Passive cooling refers to when heat is removed by natural heat transfer, such as convection, conduction or radiation (Josefsson, 2018).

4.1 Passive Cooling

Heated air movement by convection happens as soon as there is a temperature difference between a heated body and the surrounding medium. When for instance the surrounding is of a lower temperature than a heat source, the air package close to the heat source will gain a lower density and move upwards, creating an airflow due to convection. This effect is what causes wind flow as the Earth's surface is heated by the solar radiation. Thermal conduction refers to the spread of heat due to the internal energy of molecules affecting close by molecules. If a material is heated the electrons will vibrate in different ways causing energy to be absorbed by nearby molecules and in that way spread through the material. Depending on the material composition the thermal conduction properties vary. Glass is for instance a poor heat conducting material in comparison to copper. Heat can also be transferred due to radiation. When a body has a temperature higher than 0 K it will always emit thermal radiation (Josefsson, 2018).

To efficiently drain heat from one point to another heat pipes can be used. The technique is based on a conducting material and a phase changing process and convection of a medium (Heat Pipe Resources, 2019).
A heat pipe is a vessel often made of copper, with a vacuum interior containing small granulates and a liquid, see Figure 4.1. When one side of the heat pipe is heated the liquid will evaporate and move towards the cold area on the other side of the pipe. Due to the vacuum the process is quickened. When the vapor reaches the cold side, it condenses to its liquid phase and due to the capillary forces by the small granulates inside the

vessel, the liquid is pushed back towards the warm area, see Figure 4.2. This process continues as long as there is a temperature difference between the two pipe ends and is an efficient way of quick passive heat transfer (Cofan USA, 2019).

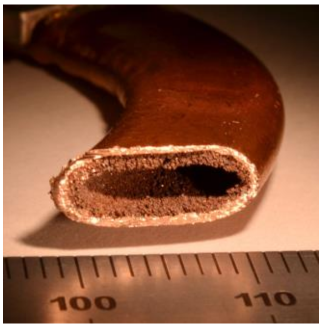


Figure 4.1 An intersection of a heat pipe.

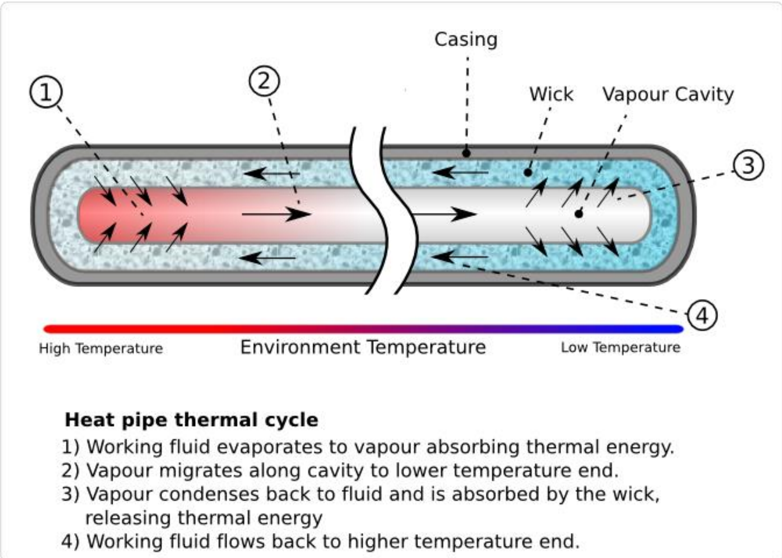


Figure 4.2 Shows how heat can be transported in a heat pipe.

Another way of emitting heat is by the use of heat sinks. Heat is emitted proportionally to the surface of the heat source. If the area of the heat source is increased, the heat can be removed faster, assuming there is a temperature difference between the heat source and the ambient temperature. The fin patterns in heat sinks efficiently increases the area and by convection the heated air nearby the fins can be removed (Heat Transfer Through Fins, n.d.).

4.2 Active Cooling

When natural convection is not enough to lower the temperature of a heat source, a common way to speed up the heat transfer is by the use of a fan, see Figure 4.3. The principle of a fan is to create an airflow using external power, to more quickly spread air packages of different temperatures than by natural convection. This type of heat transfer is called forced convection (Afework, Hanania, Stenhouse, Toor & Donev, 2018).

Figure 4.3 The type of fan used in this project.

Another way of actively transferring heat is by the use of a Peltier element, see Figure 4.4. Instead of transferring heated air surrounding the heat source, a Peltier element drains heat, as one side of the system can get colder than the ambient temperature. The technique is based on the bonding of two semiconducting materials. Similar to the physics of PV cells, the semiconducting materials in the Peltier element are p-type and n-type materials. When a voltage is added to the system, a temperature difference can be formed across the junction that is formed between the materials. When one side of the junction is heated, the other side will have a lower temperature, as long as an external voltage is applied to the system. An important aspect with this type of cooling is that the side with a higher temperature can get very warm, making it necessary to enable an efficient heat transfer (Liadov, 2018). It is also important to note that a Peltier element has a low efficiency. In contrast to fans this type of thermoelectric cooling has no moving parts and is therefore more silent (Liadov, 2018).

Figure 4.4 A Peltier Element.

4.3 Conclusions of the Chapter

Heat pipes are an efficient way of passively transporting heat from one point to another. Heat sinks are a good way of using natural convection for cooling of components. Fans are a good way of speeding up the natural convection. Peltier elements risk causing other heat problems due to its low degree of efficiency. Passive cooling might not always be enough to lower the temperature enough. Active cooling could be used as a complement to the passive cooling system. The passive cooling systems are effective in transporting the heat from one point to another. Thereafter the passive cooling sometimes needs assistance from active cooling in order to be able to continue transporting the heat.

Part 2 Case Study

This part presents the case study performed during the project. In the conclusion of some chapters the identified parameters, which are in need of consideration when designing a PV system like the one in this project, are stated.

5 Introduction

The case study was performed at Axis Communications in Lund, their cameras have on a few occasions failed when placed in warm regions. This could expose the cameras of the risk of ageing at a greater speed than normal. This risk is particularly high if the cameras electronic components reach temperatures over 80°C for long periods of time. It has been shown in previous studies, that a rise of irradiation from the sun cause temperatures to rise inside the cameras even though the ambient temperatures stays the same. The locations where this happens are normally hot areas with little wind and high sun irradiation. This case study therefore focuses on designing a PV integrated solar cap for the P32 in Dubai. The focus of the case study has been to investigate the design of the PV system if it is to be integrated or replace the existing solar caps.

5.1 Aims

The aim of this case study was to develop a working prototype where PV cells can power a cooling system, integrated with a solar cap for the Axis P3225-LVE camera. This project aimed to investigate the possibility of PV cells to directly power the cooling system. For this, one need to understand the limitations and possibilities of PV panels itself, the sun's movement in the sky, as well as the power needing system powered by the PV cells. Today the cameras are utilizing all of the power available from the Power over Ethernet cables and are therefore in need of an external power source to run these cooling systems.

6 Empirical Setting

This part presents Axis as well as the setting of where the cameras are in need of a PV system.

6.1 Company Description

Axis Communications is an international company developing network surveillance cameras based in Lund. This section will enlighten the problems that exist within Axis Communications in regards of the overheating and cooling solutions. There are several types of cameras designed by Axis, this project will focus on the fixed dome cameras as there are overheating problems and, so far, no cooling solution.

6.2 Problem Decomposition

The case study will focus on the P3225-LVE, which is an outdoor vandal proof fixed dome camera, see Figure 6.1. The chassis of the camera is made from plastic and there could possibly in the future be a higher risk of the cameras overheating compared to if the chassis were to be made of for example aluminum. This is due to the fact that aluminum transports heat better than plastic (Engineering ToolBox, 2003) and the heat can therefore travel out from the heat generating components to the air easier. Figure 6.2 shows the main parts of which the camera contains. Figure 6.3 shows the field of view that the camera has. Since the camera inside the dome can be angled in any direction it is difficult to design a solar cap that never disturbs the image. The restriction is therefore set to be, if the camera is angled straight forward the camera has to see the horizon.

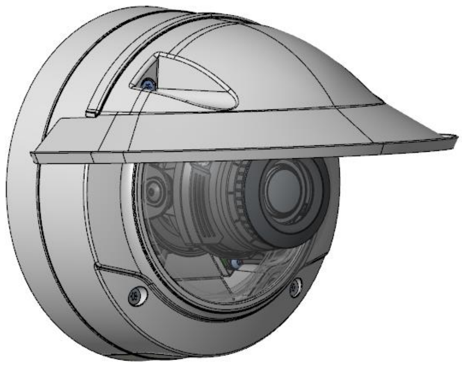


Figure 6.1 P3225-LVE

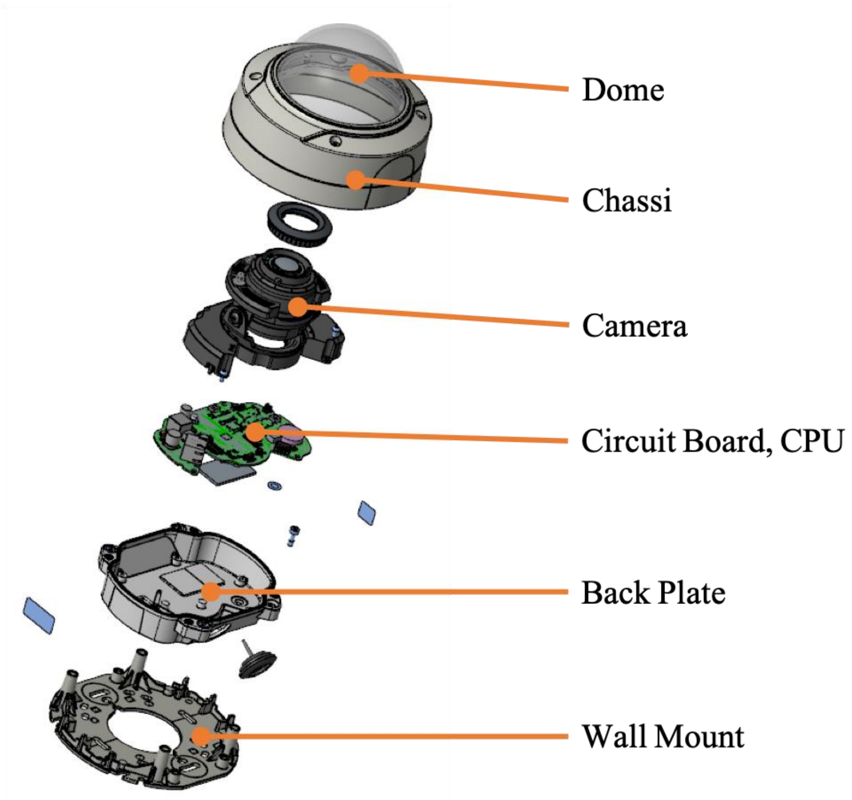


Figure 6.2 The main parts in the P32 camera.

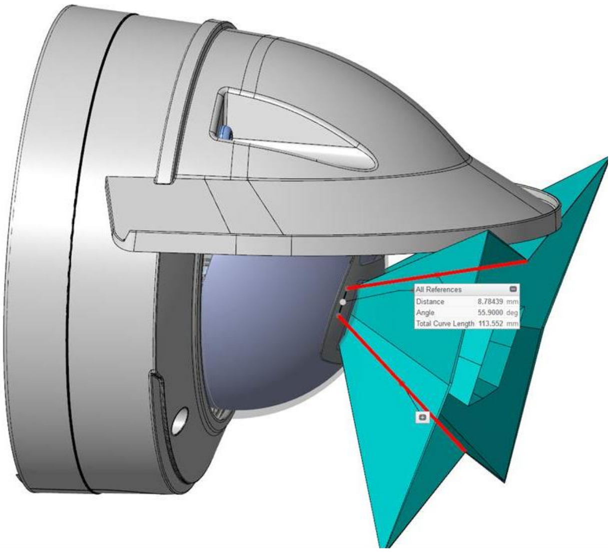


Figure 6.3 The field of view in the P32 camera.

Axis has the same type of progress as the rest of the world when it comes to electronic components. In order to be competitive on the market and to continuously improve their products the electronic components are becoming smaller and the number of components have increased. This causes more heat to be generated and might cause issues in the future which they want to avoid.

As components grow smaller the demand for products which can withstand higher ambient temperatures will possibly increase. Tests have shown that the temperature generally increases if the irradiation and/or ambient temperature increases (Axis Communications 2, 2015). The specification of the camera states a temperature range between -40℃ to 50℃ (Axis Communications 1, 2018). Axis wants to be able to keep those specifications in the future and does therefore need to investigate how the temperature increase should be minimized even though the components grow smaller and are exposed to irradiation. The built-in temperature sensors used in this investigation are placed on the PCB card, the heater and image card, shown in Figure 6.4.

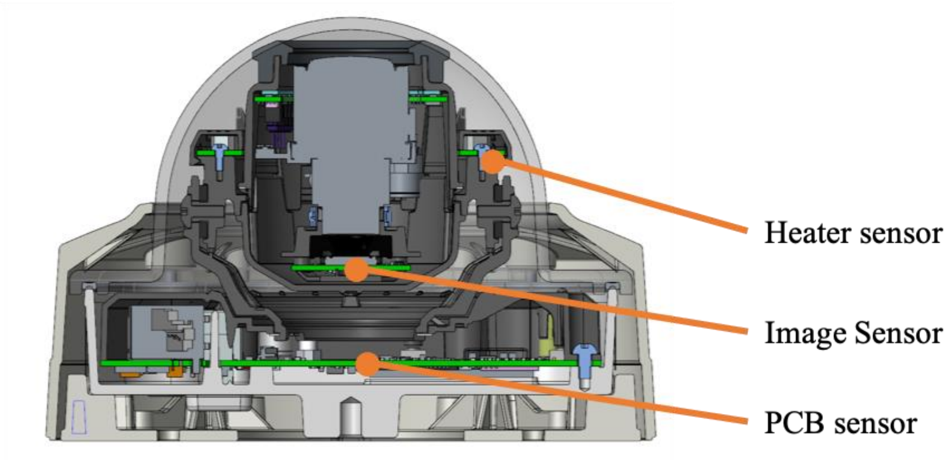


Figure 6.4 The built-in sensors in the P32 camera.

The solar cap solution existing today limits the light from the sun reflecting in to the optical lenses. It should also protect the dome from raindrops running throughout the surface and ease water run-off. All this at the same time as it should not disturb the image in any way. Several designs have been tested for a cap solution and it has been noted that insects sometime built nests in the spaces and slots, depending on the insect, this might also contribute to a poorer image quality. The existing solar cap is shown in Figure 6.5 from different angles. A cap can sometimes cause a so called “thermos effect” which increases the temperature of the camera due to air standing still and being heated between the chassis and the cap. However, it is still substantially better than having no cap at all.

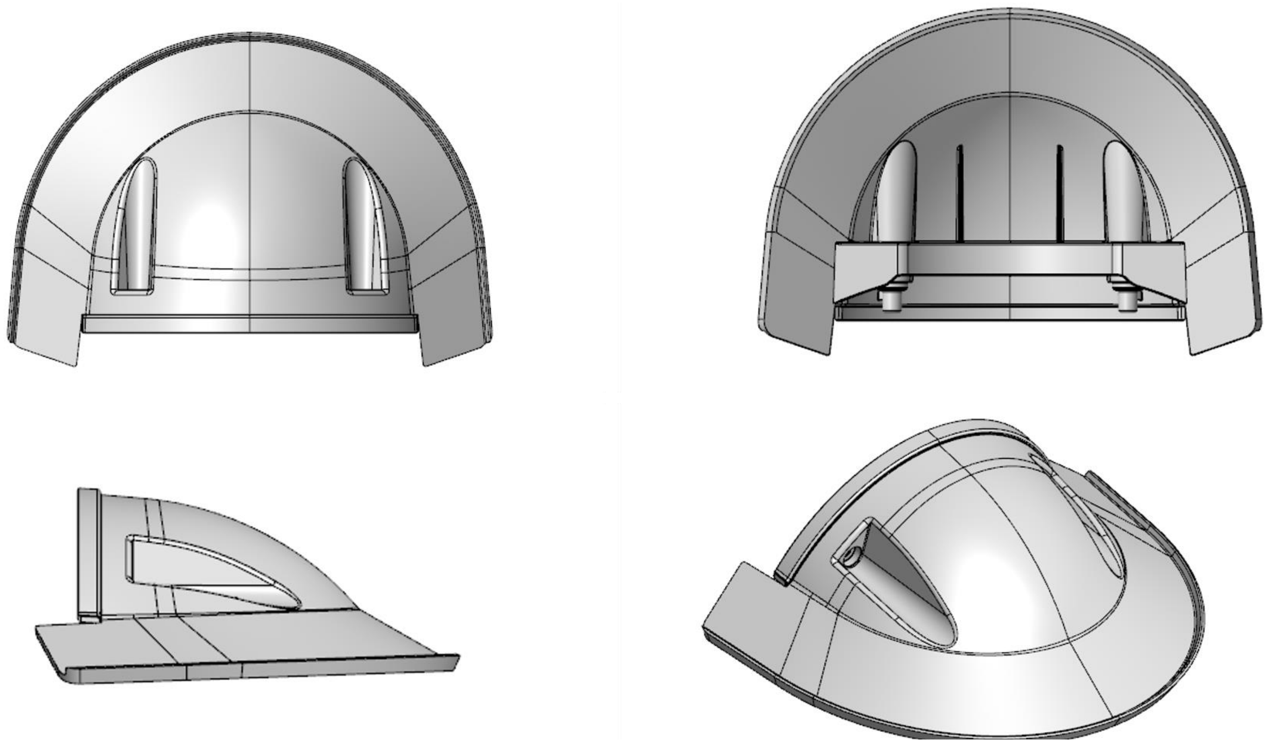


Figure 6.5 The existing solar cap from different views.

Today Axis uses Power over Ethernet (PoE) as the source of powering the cameras. The PoE is for almost all the cameras fully utilized and no power can be used from the Ethernet cable to power any external power needing system. At Axis today fans are used as active coolers in some of the products. There has also been one product which had a Peltier element combined with a fan. This solution has been removed from the product line since the Peltier elements have a very low degree of efficiency.

6.3 DC/DC Converters

In order to find how to design the circuits, electrical engineers at Axis were consulted. It was decided that the preferable way to connect the PV modules to the fan was to connect each module to a DC/DC converter and then connect each one to the fan. The DC/DC converter is connected to the modules to switch up the voltage output to match the voltage demand of the fan. Since the PV modules have to be connected in parallel there needs to be one DC/DC converter connected to each module in order for the system to not be dependent on the module producing the least amount of power. Since the fan connected to the system requires 12 V it is of interest to generate a high voltage, which is easiest achieved by using an area of the PV cell modules as large as possible, where the internal cells are connected in series.

6.4 Dubai

Dubai was the chosen location for several reasons. Partly since Axis has a test center located in Dubai and data could therefore be gathered. The local market is also aware that some equipment might not function as it should due to irradiation and the customers do sometimes require extra test certificates that proves the product's functionality when exposed to the outside climate (Hörnqvist, 2018). In Dubai the sun is shining a lot throughout the year. The sunshine hours are at an average of 9,82 hours per day and in the whole United Arab Emirates the sunny days throughout the year is over 330 (Radhi, 2010). The solar radiation varies throughout the day (Solargis, 2018). The radiation from the sun at noon comes from the south, which is typical for the northern hemisphere (Naraghi, 2009). It is tested by Axis that the cameras suffer the most from overheating during the sunniest hours when exposed to direct sunlight in combination with high ambient temperatures (Axis Communications 2, 2015).

6.4.1 **Weather Data**

In order to find what angles optimal for a PV solution in this case data had to be gathered and analyzed. Data containing solar angles, temperature and irradiance was obtained from Solargis (Solargis, 2018). This data was verified by comparing the elevation angle for a given time with the data presented in the Literature Study. The analysis is found in Appendix D. It included solar angles, temperature and irradiance at every hour between the year of 1999 to March 2018. The data of 2018 was not included in this study since the whole year cannot yet be analyzed. As the cameras overheat when exposed to both high temperatures and irradiation (Axis Communications 2, 2015) the goal was to find when the temperature and irradiance coincide and from there find the elevation angle of the sun. Three analyses were made; temperature, irradiation and temperature simultaneously as irradiation. It was discussed with two LTH professors experienced in the subject on how to perform these analyses in order to make sure the correct assumptions and calculations were used (Davidsson, 2018; Borgström, 2018). The weather data is used in order to find how the PV modules in the prototype should be angled.

All the data with a sun elevation angle (SE) of 10° was excluded in this analysis. This is due to the fact that it is impossible to generate power during the night with solar power. As the area where the PV cells are to be installed is in an urban environment it was also assumed that buildings will block the sun at low elevation angles.

The data included the global horizontal irradiation (GHI) and Diffuse Horizontal Irradiation this results in a false impression of the actual irradiation as it is measured on a horizontal surface. The GHI and DHI was therefore re-calculated into Direct Normal Irradiation (DNI) using the formula (Vashishtha, 2012):

$$\frac{GHI - DHI}{sin(SE)} = DNI$$

The thresholds were set after discussions and interviews with key people at Axis. Taking the heat damage on the components in to account with regards to temperature and irradiation.

The analysis showed that the maximum Sun Elevation angle (SE) in Dubai is around 85° and the maximum Direct Normal Irradiation (DNI) in Dubai is around 1000 W/m^2. As stated before, this project aims to find SE when the temperature and irradiation is at its highest. The results showed that the SE between 59-77° is when the temperatures and the irradiance are at the highest. All the results are shown in detail in Appendix D.

6.5 Conclusions of the Chapter

The inside temperature of the cameras is affected both by the level of irradiation and the ambient temperature. The “thermos effect” caused by the cap needs to be considered when designing a new cap. The reflections from the cap risking to disturb the image have to be considered, however they can be partly removed if the bottom of the cap is black. The existing cap will be partly used as a reference cap for the case study as it is the one which is to be replaced. The existing power source, PoE, cannot at all be utilized for cooling when designing the PV system. Using fans for the case study is beneficial since they are well known to Axis. It is important to use the DC/DC converters for this type of solutions if the power output is to be maximized for this type of solution. In theory the irradiation should increase as the SE increases. Looking at the actual weather data from reality it is shown that this is not always the case. This could be due to different weather phenomena, such as air pollution, which is why it is better to trust the actual measured data rather than the theoretical calculations. The results found could be used when deciding the angle of a PV module. The degree of efficiency is as stated previously, at 25 ℃. The PV modules in this project will be placed in Dubai where they will reach a much higher temperature. This means that the temperature coefficient will have an impact of the actual degree of efficiency when in use. The parameters presented below are the most vital parameters which have been taken further in the project and were considered in the case study.

- Irradiation
- Ambient temperatures
- Electrical circuits
- Temperature coefficient
- Degree of efficiency
- Cardinal Direction

7 Benchmarking

In order to find what the competition on the market is, a benchmarking can be performed (Ulrich & Eppinger, 2012). This benchmarking was performed in order to understand how the PV cell systems could be designed, an investigation into existing products was made. The benchmarking was divided into three different parts; cooling fans for computers, electronic devices powered by PV cells and PV cells.

7.1 Cooling fans for computers

This brand was investigated since Axis have worked with them before when cooling solutions have been necessary. Coolermaster produces and designs cooling systems mostly for computers, see Figure 7.1. They use solutions with heat sinks, heat pipes, liquid or in combination in order to cool computers. These components are then cooled by a fan. This is a way of firstly passive cooling and then use active cooling to remove the heat from the passive coolers.

Figure 7.1 Cooling fan for computers.

7.2 Electronic Devices Powered by PV Cells

There are patents of charging phones going back to 1999 where the idea was patented to have PV module on the backplate of a mobile phone (Zurlo & Schulcz, 1999). On the market today, there are several types of phone chargers which charges the battery of the phone by using PV panels (Bidder 2016), see Figure 7.2. Some of these are more portable than others, some can be taken in a small bag to support-charge the phone and some are larger which can be brought to the camping trip if no other power-supply can be found.

Figure 7.2 PV cell phone charger.

There are other products on the market which have PV panels as a possible charging solution. The PV module is sometimes seen as an additional way of charging as it is not reliable enough to be the only power source of for example cameras.

The camera shown in Figure 7.3 has a built-in PV module on its top plate. The PV cell charges a battery which the powers the camera. According to Sunivision, a 2 two-hour charging time can power the camera for 24 hours (Sunivision, 2018).

Figure 7.3 Sunivision solar cell camera.

There are other cameras on the market branded as cameras which can be placed in remote locations where no power or network connections are available (Reolink, 2018).

A part of the investigation was the see if there was a smart solution for the connection between the fan and the PV panel. In order to investigate our concept deeper, the fan powered by a PV module was bought for testing, see Figure 7.4. The PV module directly powered a fan, without storing energy. Meaning that the fan would only run when the PV module was illuminated. When testing this product, it was discovered that the function was highly limited by the tilt of the PV module as well as by shading. The fan did not run if even a small part of the module was shaded or if the module was poorly illuminated.

Figure 7.4 PV cell powered fan.

Solar panels are also applicable of car roofs, see Figure 7.5, for this type of application a flexible PV panel is needed. The flexibility of this application is relatively low but needed in order for the PV panel to fit the design of the vehicle. The risk of shading is relatively low since there is not much on the car which makes it shade itself. The radius of the bent PV panel is also so little which makes the efficiency loss insignificant (Borgström, 2018).

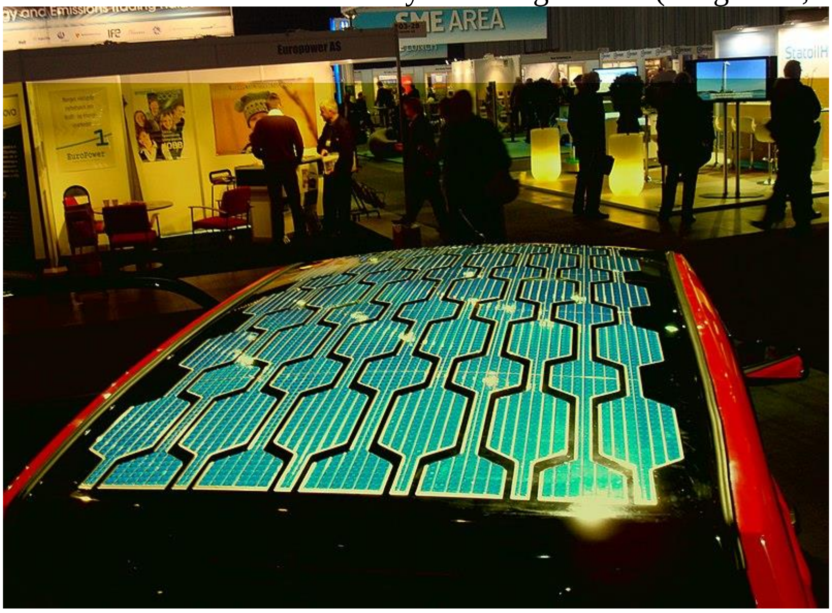


Figure 7.5 Flexible PV cells on a car roof.

7.3 PV Cells

There are several types of PV cells which can be used for this type of product. The cheapest and most common type of PV cell is the single junction silicon PV cells. There are, as stated before, more efficient PV cells which also sometimes have the possibility of being flexible. It was thoroughly researched if flexible PV cells and modules were possible and preferable for this type of application. The researched types of PV cells for this project are stated in the chapter below together with the positive and negative aspects.

Alta Devices claims to produce the world's most efficient thin-film PV cells. Their PV cells are single-junction Gallium Arsenide (GaAs) PV cells with an efficiency of 29.1 %. Thanks to the structure of the material the PV cells are flexible and can be bent in more than in direction (Alta Devices, 2019). However, they have a large demand and were not possible to receive during the timeline of this project.

The PV cells produced by Midsummer are Copper Indium Gallium Selenide (CIGS) PV cells. They were investigated as a part of this project due to its flexibility. However, they are only curvable in one direction with a diameter of 1 meter (Löfquist, 2018).

7.4 Conclusions of the chapter

There are many products on the market today using PV cells for power. Most of them charge a battery which is slightly different to the product to be designed in this project. This project aims, as before stated, on direct power supply. The difference between the two is mainly visible when understanding that for the case of charging a battery, the PV cells are to generate as much power as possible. Compared to when no battery is used the PV cells are to generate enough power when needed.

It seems to be very lucrative placing PV panels on cameras since solar power is very popular however, after some calculations, it can be concluded that the Sunivision camera has a power need of under 2 W. The P3225-LVE has a power consumption of 7.3 W. Aiming to power an Axis camera with only PV cells placed in a similar way on the camera would today not be possible. However, as the efficiency of the PV cells increase it might be a possibility in the future.

The conclusions drawn after the investigation of the fan powered by a PV module was that the panel can power the fan when sunlight hits the PV panel. However, it is sensitive and the angle of which the sunrays hit the panel need to be almost exactly 90° to the surface of the module. If not, the fan will not be powered at all. The solution is also sensitive to shading and if a small part of the panel is shaded (approximately ⅛) the fan will not be powered at all even though the sunrays are in an advantageous angle. The connection between the PV panel and the fan is simple with cables directly connected to the fan.

Flexible PV cells were investigated during this project. However, it was decided by the team members that flexible PV cells would not be applicable for this product. The curve radius for this product would be less than 200 mm, the only PV cell known to the project with this possibility of being curved is the GaAs PV cells from Alta Devices. Worth noting is that the flexible PV cells are not always flexible when in use, it commonly means that they can be bent over some type of curved surface.

8 Pre-Testing

The tests conducted in this part of the project aimed to investigate if the PV cells chosen for the case study could generate enough energy to power an active cooling system. It also aimed to investigate how the energy production is affected by different types of module connections as well as different types of module shading. The PV panels used in this project is IXYS solar panels with an efficiency of 22 %.

8.1 PV modules self-heating

A test was conducted in order to find how much the PV panels were heated when exposed to irradiation. The test could only be performed under a lamp, but it still allowed for an understanding of how much and if the PV module was heated over the ambient temperature. The ambient temperature was 25°C and the irradiation was set to 850 W.

Table 8.1 Temperature increase of the PV module over time.

Time [min]	Module temperature [°C]
0	25.2
5	44.7
10	48.2
20	48.9
30	50.6
900	53.0

8.2 PV Module Powering Fan

An experiment was made to see if one PV module can run a small fan that requires a voltage of 12 V and a current of 0.09 A. The PV modules used in the experiments generated an open circuit voltage of 6 V and a short circuit current of 0.2 A per module under optimal conditions. The efficiency of the PV cells was 22 % according to the supplier (IXYS, 2019). One PV module was connected to a DC/DC converter that switched up the output voltage from the V_{oc} of 6 V to 12 V. The PV module and the converter were then connected to the fan. At direct illumination the fan created an airflow. This confirmed that in order to power one fan at least one PV module needed to be fully illuminated.

8.3 Shading Test

In order to understand how the PV modules are affected by shading a test was conducted, see appendix E. The test showed that a parallel connection is vital in order to ensure the power output from the PV modules. The test could also show the importance of having several PV modules to ensure that irradiation can be obtained from different angles.

8.4 Conclusions of the Chapter

Due to the fact that this project aims to have PV modules with different angles in different cardinal directions, one or more PV modules will be shaded when one or more PV modules are exposed to irradiation. To design a PV system robust enough to also withstand other types of shading such as for example dust, parallel connections ensure that a partial shading of the system will not cause the whole system to fail. The tests show the importance of having the PV modules connected in parallel for this type of solution. It was shown that the PV cell generates a lot of heat when in use this can be used later on in the project to make qualified assumptions when calculating the degree of efficiency with consideration to the temperature coefficient. The most stressing point which resulted in the decision of not designing for curved PV modules was the risk of shading. Shading, especially when the PV panels are curved in such way that some part on the module cannot receive any irradiation from the sun. Shading of a part of a PV module can, as stated before, cause major efficiency losses. This can be devastating for a product which only relies on power from the sun via PV cells. This was also the case for the PV powered fan solution mentioned in the benchmarking. In order to avoid this, it was decided that the design should preferably have several flat PV modules, tilted in efficient ways.

The PV panels themselves will not and should not be limited to one specific type of panel. The parameters identified when designing a PV system for direct powering is for this chapter:

- Temperature of the PV cell
- Shading
- Cardinal Direction
- Connections

9 Concept Generation

The design process followed the steps described by Ulrich and Eppinger's concept development steps. However, it was slightly altered in order to fit both the type and timeline for this project.

9.1 Identify Customer Needs

To find what needed to be considered when developing this product interviews and email conversations with relevant parties were conducted. Axis do not sell their products to the end-user, they sell via external distribution centers who then sell it to the end-user. It was therefore decided that the sales team and quality assurance team would represent the end user. To understand how the overheating problem affects the internal components of the camera, data was also gathered from the engineers at the Fixed Dome department at Axis. As PV cells are not included in any product at Axis today it was also of importance to understand the limitations with PV cells in combination with the need from Axis and their end-user.

Gather Data from Customers

The data was gathered through e-mail conversations, Skype calls, meetings and investigations of claims. The interviewees were engineers at R&D, Sales and the Testing team within Axis. The interviewees area of expertise is presented in Appendix F. From the interviews customers statements were found, these are presented in Appendix G.

The customer statements were interpreted into customer needs by following the guidelines from Ulrich and Eppinger. The guidelines are (Ulrich & Eppinger, 2012);

- Express what, not how
- Express the need as specific as the data
- Use positive wording, not negative

- Express the need as a feature of the product
- Avoid have to and will

Some of the needs were derivations from the background study or from interviews with people outside Axis. The needs can be organized hierarchically into primary and secondary needs, sometimes tertiary needs are needed (Ulrich & Eppinger, 2012). The needs were organized hierarchically by the team in this Master Thesis. The organized customer needs can be found in Appendix H.

9.1.1 **Determine Relative Importance of the Needs**

Relative importance of the needs should be done in order to structure the project and to be sure the correct trade-offs between specifications can be made (Ulrich & Eppinger 2012, p.131). The customer can often be a good resource when determining the importance of the needs. Together with Axis as the customer the relative importance of the needs was determined, this is shown in Appendix H.

9.1.2 **Reflection of the Result and process**

The needs were gathered in the best way possible considering the timeline of the project. However, the needs could be more thorough if more end-users were interviewed and if observations of cameras in heated areas could have been done.

9.2 Establish Target Specifications

The list of specifications was prepared the following points from Ulrich and Eppinger was considered (Ulrich & Eppinger, 2012);

- The needs have to be complete
- The needs have quantifiable variables
- The needs have to be practical
- Some needs can be subjective

A need-specification matrix can be used in order to see the relationship between the needs and specifications (Ulrich & Eppinger, 2012). The list of specifications was prepared, and a need-specification matrix was made. This is shown in Appendix I.

The Ulrich and Eppinger guidelines were partially followed when the ideal and acceptable target values were set, this project included the target values in the specifications. The guideline states the following five ways to express the target values (Ulrich & Eppinger, 2012):

- Minimum X
- Maximum X
- Between X & Y
- Exactly X
- Discrete values

The product specifications were ranked from 1-5 in order to determine the importance of the specifications, in the table below is the definition of the rank numbers.

1. Essential
2. Needed
3. Desirable
4. Good to have
5. Not needed

The specification together with its rank is shown in table 10.2 below.

Table 9.1 List of Specifications

Rank	Spec. Number	Specification
5	3	The product has the same IP class as the P32
1	4	The product is always angled more than 0° from the horizontal plane
3	5	The products edges are less than 50°
3	6	The edge of the product has no seams
5	8	The product has the same IK class as the P32
2	9	The product can reach twice the efficiency need when clean
3	10	It takes 1 minute to clean the product
5	11	The product sends out a signal when power output is less than 50 %
3	13	The gaps of the product are not 3-10 mm
1	15	Each PV module generates at least 1 W
1	16	The product reflects 0 W/m^2 in to the camera

1	18	The PV cells have a 15% degree of efficiency at a temperature of 80°C
1	19	The product appears in 0% of the image
5	20	The total cost is low
3	21	The product is quickly installed
4	22	The product has one wire to the cooling system
4	23	The product weighs max 1 kg
3	24	The product is properly installed
4	26	The thermos effect is no more than 10%
2	27	The gap between the chassis and the product is smaller than 1 mm or larger than 100 mm
1	28	The product has at least one PV Cell
2	29	The product can generate the efficiency need when 50% of the PV cells are shaded
2	31	The product can reach twice the efficiency need when T= 25°C and the irradiation is 1000 W/m^2
5	32	The product generates 9 W
5	35	The product can charge a battery
3	36	The PV modules can be angled between 1°-90°
2	37	The product is aesthetically appealing to the users
2	38	The product has a max; width of 200 mm from camera center, height of 300 mm, depth of 300 mm
5	39	The product is discrete
4	42	The product replaces the functions of the solar cap

9.2.1 **Reflection of the Result and process**

The needs from the different stakeholders were identified and the previously mentioned “Parameters Identified” for this type of project was interpreted in the list of specifications. Some of the specifications are referring to the same outcome but this was sometimes hard to understand early on in the project.

9.3 Generate Product Concepts

9.3.1 **Clarify the need**

Considering the previous steps of the project it was established that the most vital part of the new solution was the shape. Therefore, the main focus was to find the optimal shape of the solar solution as well as the number of cells needed. It was stressed by Axis to find a solution which combined the PV cells with the existing solar cap. However, it was decided to firstly focus on the PV cells and integrate it in a later stage.

9.3.2 **Search externally**

During the Concept Generation, it was important not only to focus on the specifications which had been established. Different stakeholders had different opinions regarding what was most important for the new solution. This external search is previously mentioned in the Benchmarking chapter.

9.3.3 **Explore Systematically**

It was difficult to find experts within this specific region to discuss this issue with since there are not many products which have the goal to directly power a system. The scope therefore becomes very different as the goal is not to produce as much power during the day as possible. The experts consulted outside Axis were either experts within PV cells or within PV power design. It is also preferable if the shape aligns with the design of the existing products within Axis. However, the existing design for the P32 cameras which is generally of spherical or rounded shape was considered to be difficult to achieve due to the limitations of the PV modules. However, it was important to consider all of these interests and focus on both sides of the spectra and solutions which contained some trade-offs from the different stakeholders.

9.3.4 **Concept Generation**

Several concepts were generated, and all the sketched concepts are presented in appendix J.

9.3.5 **Reflections and Results of the process**

Many concepts were generated, this gave many possibilities for the design. Some concepts generated were contradictive to the specifications, but this was still welcomed since it is important to keep an open mind and not reject ideas this early on in the project.

9.4 Select Product Concept

The selection of the product concept was performed according to Ulrich and Eppinger's guidelines through concept screening (Ulrich & Eppinger, 2012).

9.4.1 **Concept Screening**

In order to find which concepts to continue with in the project a concept screening was conducted. It was concluded that five of the concepts should be continued within this project, concept H, E, I, P and X. Concept E and I was combined. Concept X was introduced after the concept screening was performed due to the fact that there was a perceived need for a solution which was as simple as possible. To get a deeper understanding about how the concepts look like compared to the camera and to get an approximate size of the cap, CAD models were made of the concepts. The angels were decided based on the knowledge that the solar height at the critical irradiations and temperatures was between 59°-77°. To maximize the power output the PV modules should be placed perpendicular to the incoming light. Resulting in an optimal angle of the PV modules between 13°-31°. The concept screening matrix is shown in Appendix K.

Concept H

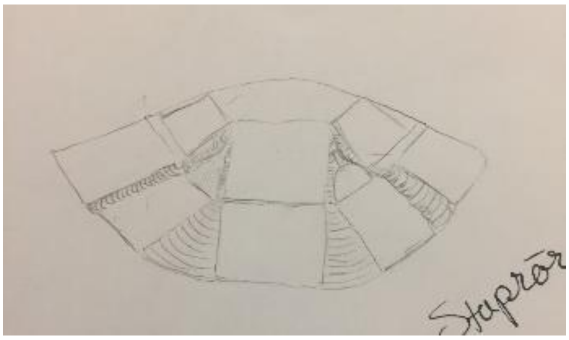
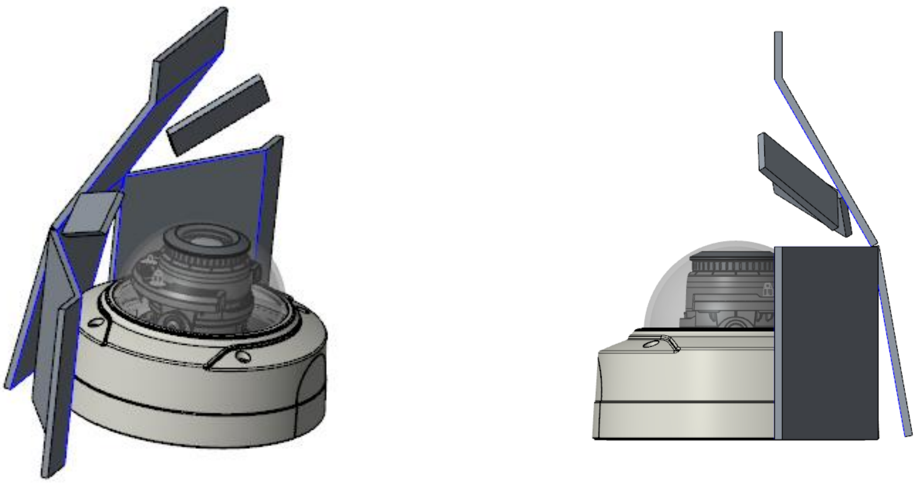


Figure 9.1 Early sketch of concept H.

Concept H contains eight differently tilted PV modules, seen in Figure 9.1. The areas between the cells are formed to ease water/dust runoff. The PV modules are to be placed so that the cap can be placed in any cardinal direction and still harvest enough energy to run a cooling system. The angles set for the PV modules are 10° on the top and edge, 30° on the side panels and 0° on the edges. The number of PV modules was changed to nine, this due to the thought of the different placement might be more beneficial, see Figure 9.2. The size of this prototype is;

- Width = 323 mm
- Depth = 210 mm
- Height = 71 mm



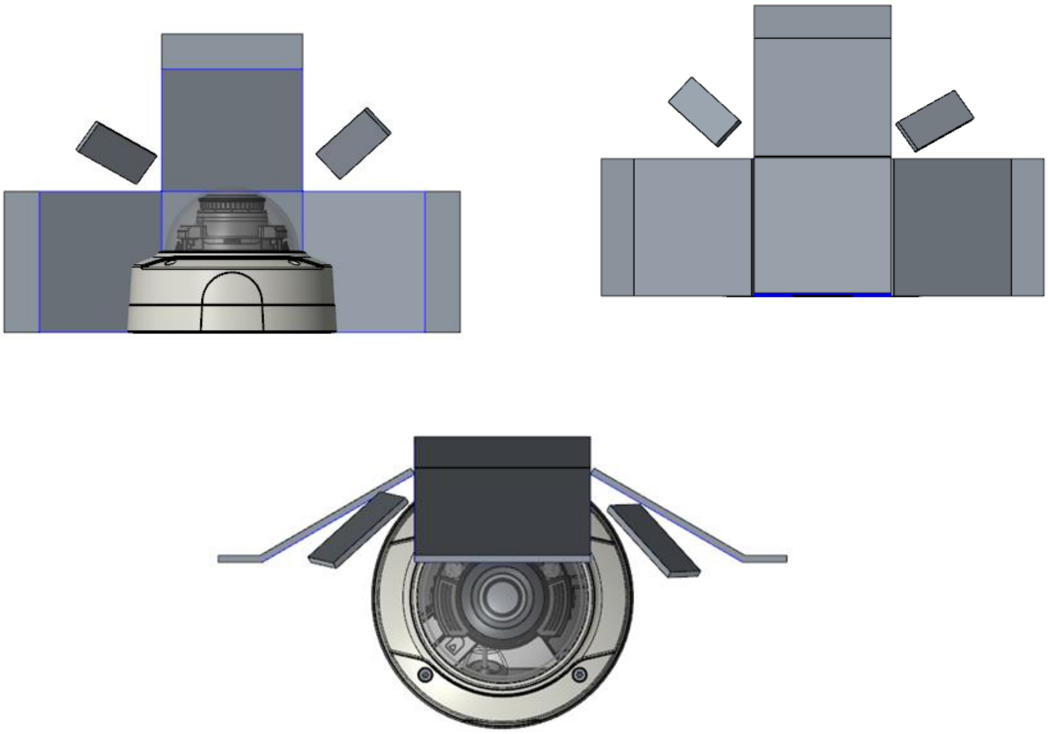


Figure 9.2 CAD models of concept H from different angles; ISO, side, bottom, top and front view.

Concept E

Concept E contains four PV cell modules connected to each other. The three modules on the sides are tilted and the top module is slightly tilted to the wall, see Figure 9.3.

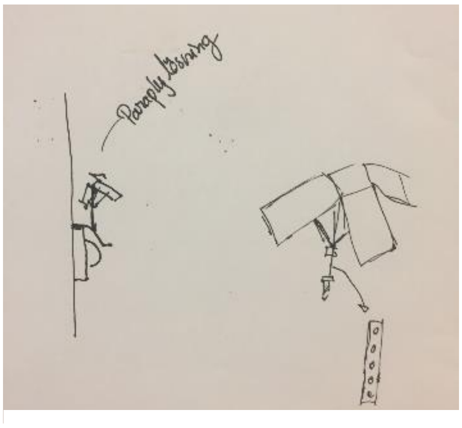


Figure 9.3 Early sketch of Concept I.

Concept I

Concept I contain three PV modules, see Figure 9.4. The modules are placed on the sides and are equally tilted towards the sun at different time periods. The area between the modules are formed to ease runoff, with shapes of the edges similar to the existing solar cap.

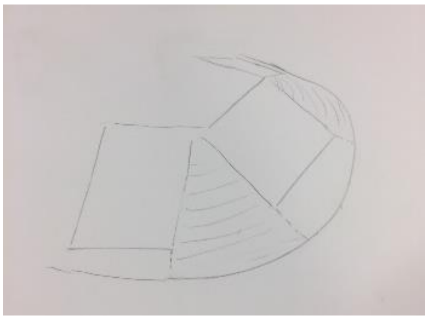
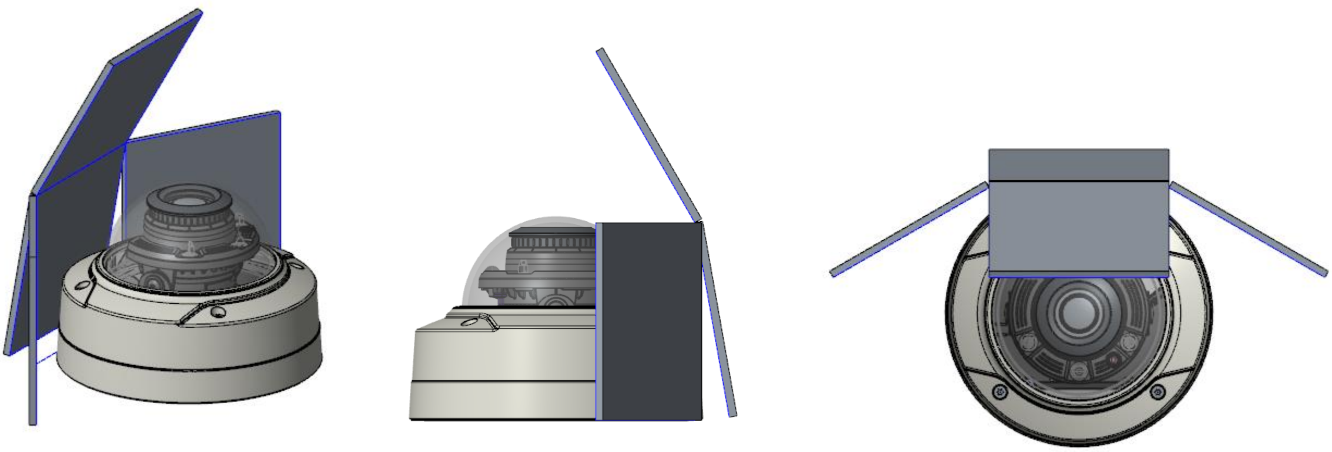


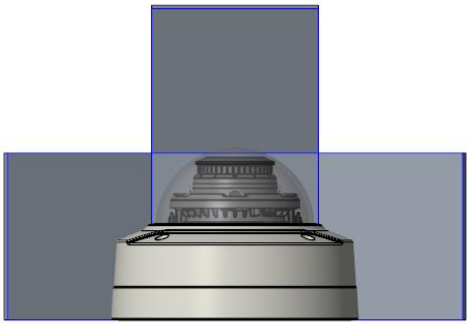
Figure 9.4 Early sketch of concept I.

Concept E and I combined

Concept E and I are relatively similar, the combination includes the top plate of concept I to be placed on concept E, see Figure 9.5. Both of these concepts allow for the camera to be installed with the cap in any cardinal direction and still being able to harvest energy. The angels of the side panels are set to 30° and the top plate is set to 10°.
The size of this prototype is;

- Width = 277 mm
- Depth = 188 mm
- Height = 71 mm





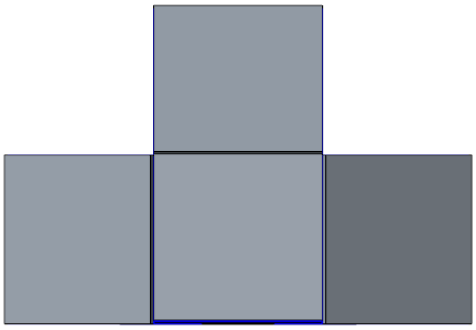


Figure 9.5 CAD models of concept EI from different angles; ISO, side, front, bottom and top view.

Concept P

Concept P has five rectangular solar modules above the dome, see Figure 9.6 and Figure 9.7. The rectangular areas are tilted downwards and towards the center. The plates are set to 0°, 15° and 30° from the front and 30° when on the sides.
The size of this prototype is;

- Width = 237 mm
- Depth = 124 mm
- Height = 49 mm

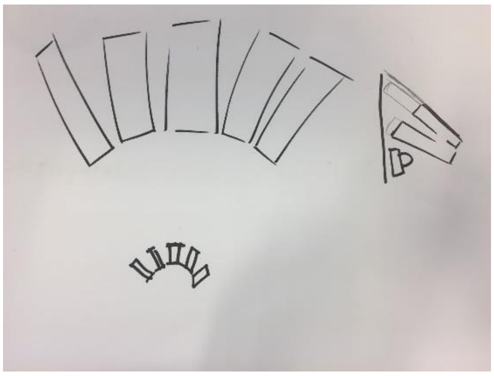


Figure 9.6 Early sketch of concept P.

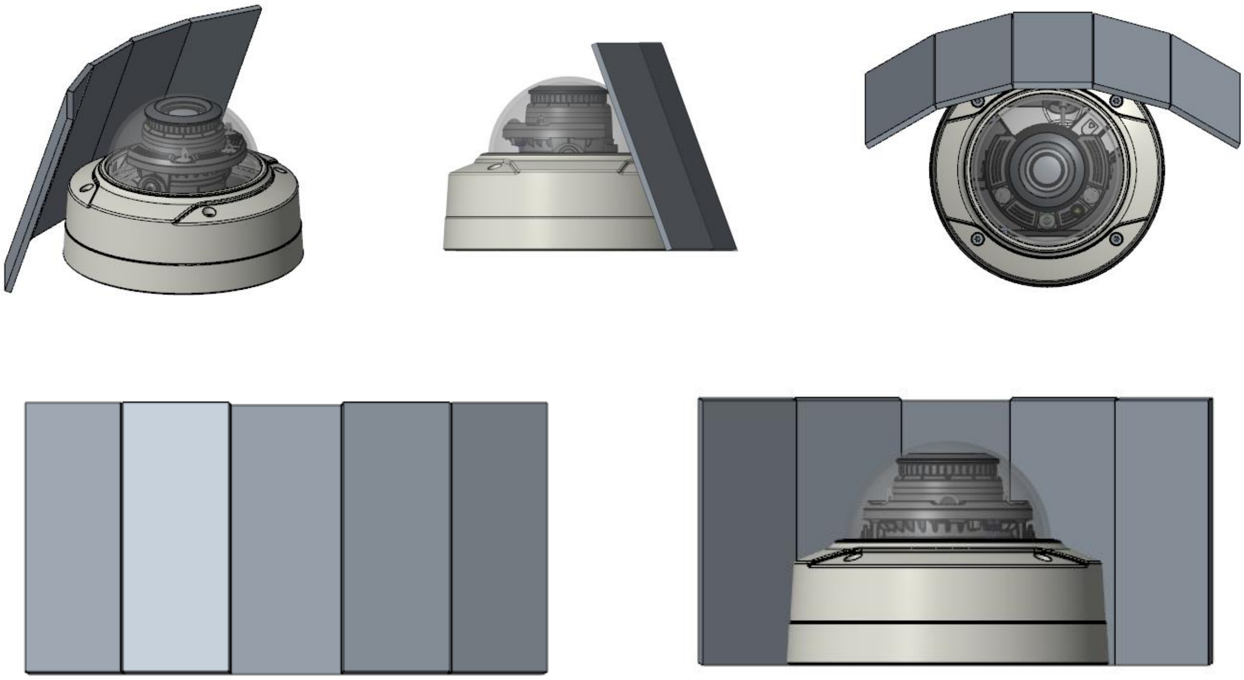


Figure 9.7 CAD models of concept P from different angles; ISO, side, front, top and bottom view.

Concept X

Concept X has one solar panel which is mounted on the existing cap, see Figure 9.8 and Figure 9.9. The panel is to be angled in the correct direction by the installation staff. The angle is set to 25°.
The size of this prototype is;

- Width = 70 mm
- Depth = 182 mm
- Height = 98 mm

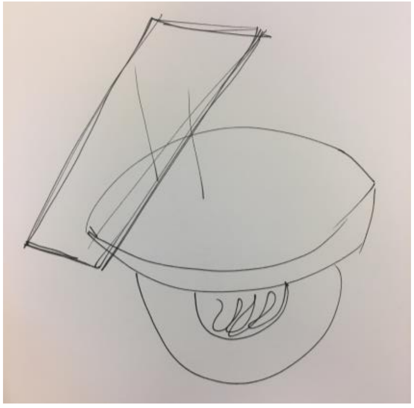
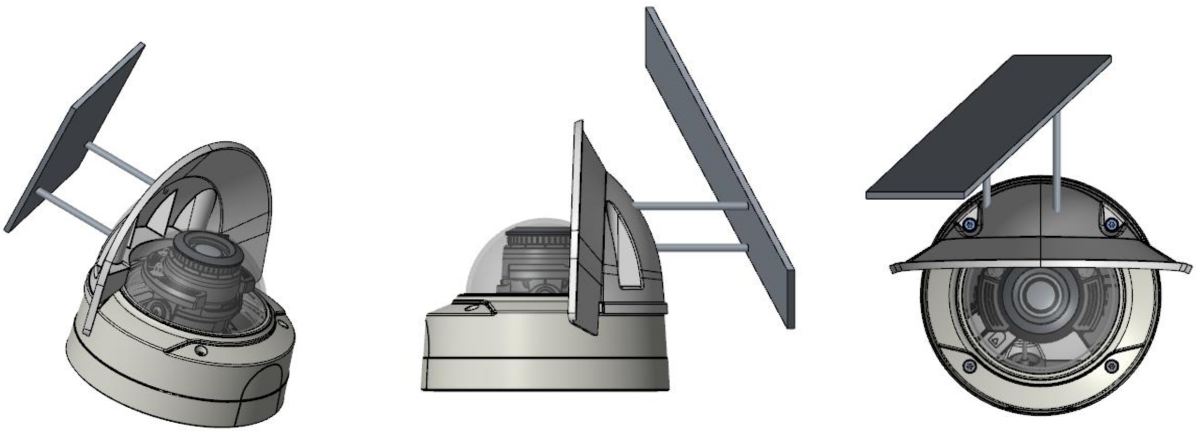
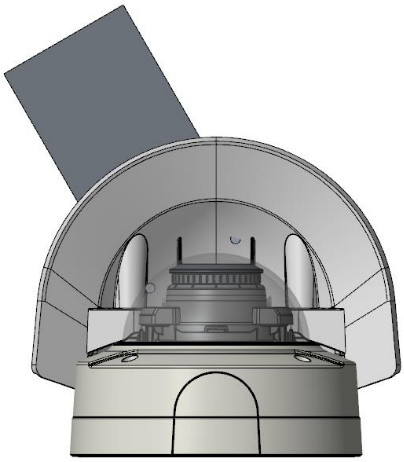


Figure 9.8 Early sketch of concept X.





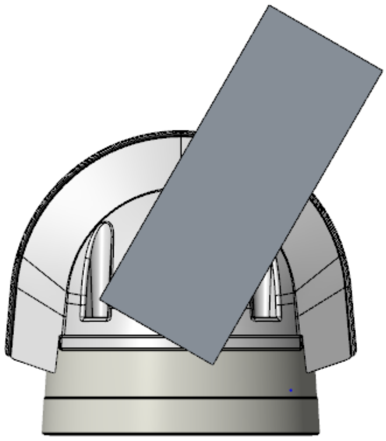


Figure 9.9 CAD models of concept X from different angles; ISO, side, front, bottom and top view.

9.4.2 **Favorite Concept & Concept Scoring Matrix**

The concepts EI, P, H and X were scored with the help of a scoring matrix. The matrix is shown in Table 9.2. The specifications used were similar to the screening matrix but more detailed. Each specification was weighted to assure that the most important needs were not undermined. The specifications in Table 9.2 are numbered from 1-7, which represents the following specifications;

1: Generates an equal amount of energy from each side as from the front.
2: Prevents water droplets to form in front of the camera.
3: Protects the camera from direct irradiation.
4: Minimizes reflection of light into the camera.
5: Generates at least 1 W when illuminated.
6: The product is small.
7: Contains a small number of solar modules.
8: Possibility to integrate with the existing cap.

The reference concept was defined as the existing cap however on some specifications concept EI was defined as reference, which can be seen as bold numbers in the table. This was since the existing cap does not contain any PV cells.

Table 9.2 Concept scoring matrix, where *Ref.* refers to the reference concept, *p* refers to points and *wp* to weighted points.

		Concept									
		Ref.		**EI**		**H**		**P**		**X**	
Specification	*Weighting factor*	p	wp	p	wp	p	wp	p	wp	p	wp
1	0.2	1	0.2	**3**	0.6	3	0.6	1	0.2	1	0.2
2	0.1	**3**	0.3	3	0.3	3	0.3	2	0.2	3	0.3
3	0.1	**3**	0.3	3	0.3	3	0.3	2	0.2	3	0.3
4	0.1	**3**	0.3	2	0.2	1	0.1	3	0.3	3	0.3
5	0.2	1	0.2	**3**	0.6	3	0.6	3	0.6	2	0.4
6	0.1	**3**	0.3	2	0.2	1	0.1	1	0.1	4	0.4
7	0.1	1	0.1	**3**	0.3	1	0.1	2	0.2	4	0.4
8	0.1	3	0.3	2	0.2	1	0.1	2	0.2	1	0.1
Total points		2		2.7		2.2		2		2.4	

The specifications were weighted based on opinions both from the team members and from Axis staff. It was also based on how well the concepts would work in reality. For example, it was considered important that all sides of the product could generate as much energy, to assure an energy production regardless of the mounting direction. Additionally, it was important that the product could generate 1 W when illuminated. If these two specifications could not be met, the product would not function, hence the high priority.

As mentioned earlier, the reference concept was defined as the existing cap and for some specifications concept EI was defined as reference. However, the project decided that this result in combination with the feeling of which concept that might succeed the most. The concepts scoring the highest as well as being the favorite concept was concept EI.

Concept H was not continued since it was thought to be relatively similar to concept EI and could, if necessary, at a later stage be combined with EI. Concept H is more or less concept EI but with some PV modules added, if the project were to discover that the power generated from the PV cells would not be enough. Concept P was considered being too big compared to the amount of power it could generate. Furthermore, concept P risked to not protect the camera dome and at the same time to block the field of view.

It was decided that the two favorite concepts would be taken further. These were concept X and EI. The reason for moving forth with X was that it was the simplest solution and not many alterations to the existing cap would be needed. EI was chosen since it was considered to be the best solution in regard to the PV modules possibility generate power, no matter where it was placed or what time of the day it was in combination with its relatively small size.

9.4.3 **Reflection of the Results and Process**

It is not always optimal for team members to choose the favorite concept since the choice might not be as objective as necessary. But since the scoring matrix gave a similar result there is still enough background data to allow for this choice.

9.5 First Prototypes

Two mockup prototypes were built in order to understand the shape and size of the solutions. The two prototypes were discussed and evaluated with Axis. The prototypes are made in cardboard.

9.5.1 **Prototype EI**

This prototype has four plates where PV modules are to be placed. The plates are shown in Figure 9.10 below. The PV modules each generate 1 W when irradiation is 1000 W/m^2 and the temperature is 25°C. The angles of the PV modules are set to 60° on the side plates and 80° on the top plate. The lower angles on the side plates were set since the top plate has a very high angle and can there for contribute to the power generation when the sun is at high angles. The prototype is shown from different angles in Figure 9.11.

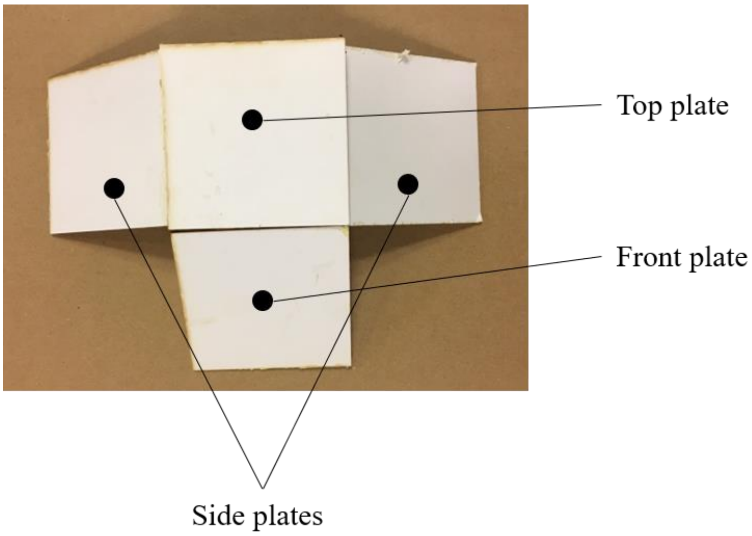


Figure 9.10 Showing the plates of prototype EI.

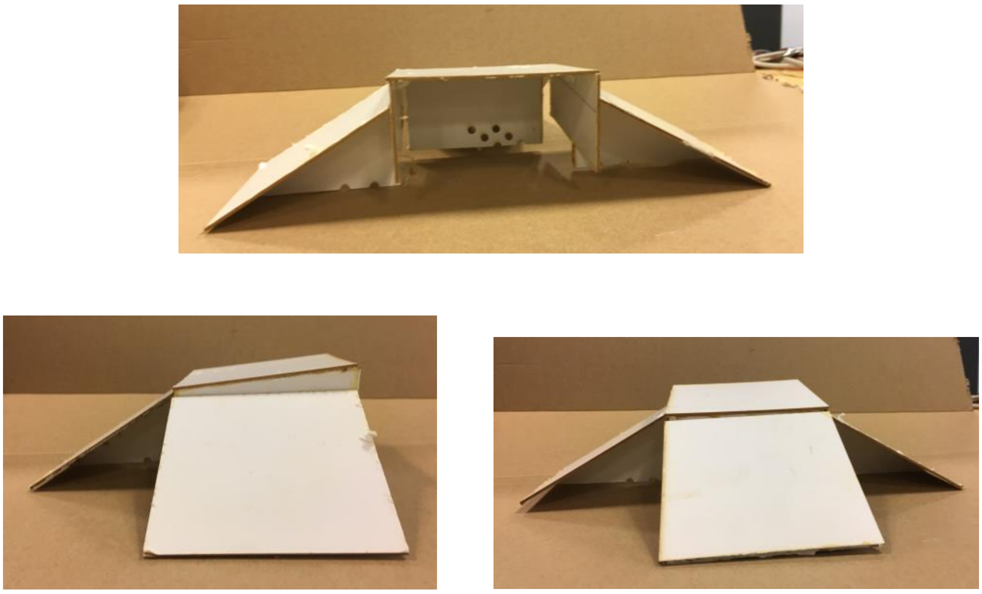


Figure 9.11 Prototype EI seen from back, side and front.

Concept X

On the plate is where the PV modules are to be mounted. The size is dependent on the PV cells which for this application is decided to have a power output of 2 W. The legs can be mounted on any type of cap. The plate (see Figure 9.12) and “legs” (see Figure 9.13) can also be adjusted in order to fit the suns movement regardless of time of year. For this project the angle is 70° form the horizontal plane.

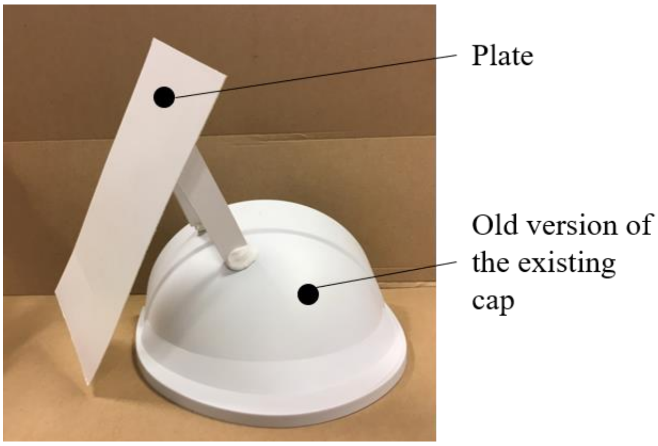


Figure 9.12 Plate and cap for concept X.

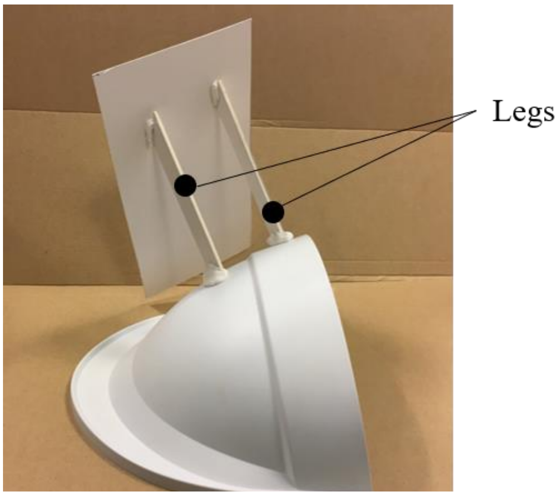


Figure 9.13 Legs of concept X.

9.5.2 **Reflections and Results of the process**

After discussions with experts, concept X was thought to risk being affected by external forces in a large extent, such as wind and vandalism. Concept EI was believed to be the most promising concept since it had a shape that had the possibility to fulfill the requirements of a solar cap and was therefore taken forward into the second prototype design. Only choosing one concept to continue with to testing is often not desirable but considering the time frame it was decided that designing more than one concept would be too time consuming.

9.6 Second Prototype Design

In order to test concept EI, the cap holding the PV system and fans was designed in CAD and 3D printed, see Figure 9.15 and Figure 9.16. The fans were placed to move the surrounding air beneath the cap. Important to note is that this cooling system is not optimized. It has a few improvements from the mock-up model; the side PV modules are tilted in the same way as the top plate in order to avoid shading from the wall and unnecessary gaps. The triangular holes were included in a cap that surrounded the PV modules. Since no concept generation was performed for how the prototype should be mounted on the wall in was decided that an existing backplate for the P32 should be used for the mounting of the prototype, see Figure 9.14.

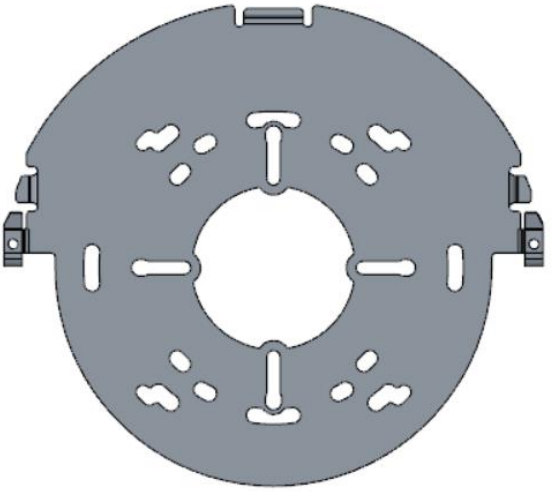


Figure 9.14 Existing backplate for mounting the P32 camera.

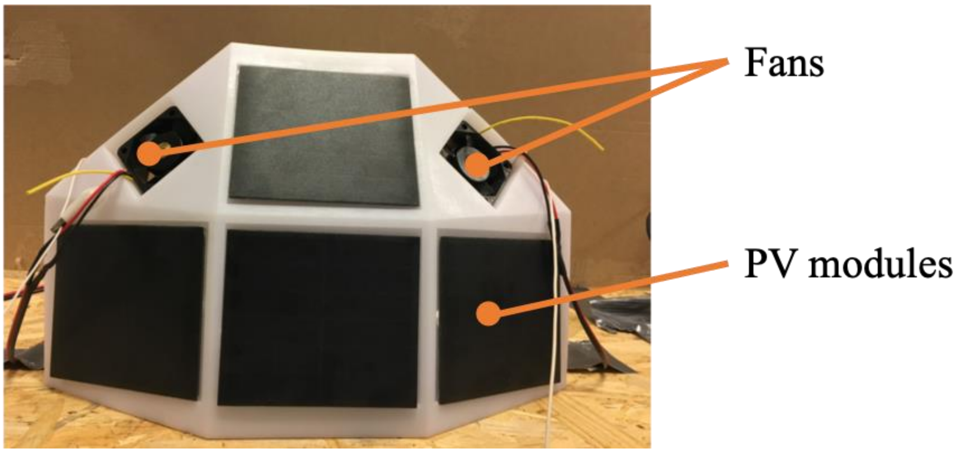


Figure 9.15 Top view of prototype 1.

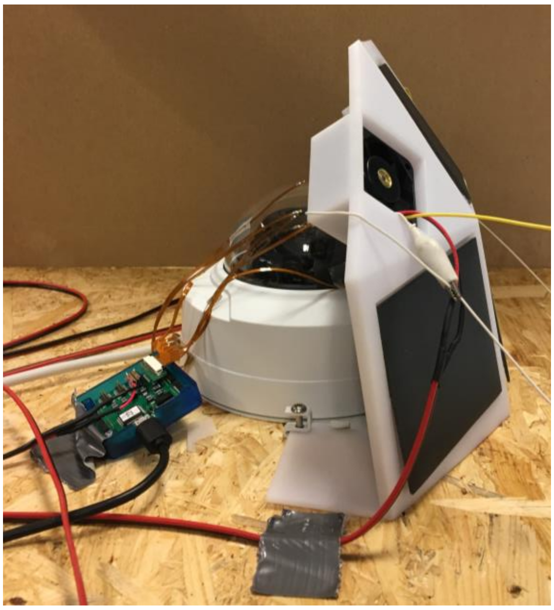


Figure 9.16 Side view of prototype 1.

It was decided that the fans should be placed in the triangular sections of the prototype. This is however something which is not an optimized cooling system. Since, the actual cooling system is not a part of the scope of the project.

9.6.1 **Reflection and Result of the Process**

The cap of where the PV modules and fans were to be places was successfully designed. However, after placing the fans in their placeholders it was quickly discovered that there were no room for the wires connected to it. This would have to be re-designed later on.

9.7 Test Product Concept

It was tested in the research part of the case study that the PV modules could power a fan. This experiment conducted for the case study aimed to examine the cooling effect provided by the original solar cap in comparison to the prototype.

9.7.1 **Method**

In this chapter the effects of direct illumination on the prototype compared to the original solar cap covered P32 are examined by experiments carried out in the solar simulation laboratory at LTH. The solar simulation lamp used to simulate the solar irradiation has seven 2.5 kW lamps placed with reflecting sides by each lamp (Solar Laboratory, n. d.), see Figure 9.17.

Figure 9.17 Solar simulation lamp in LTH solar laboratory.

When the lamp has stabilized the irradiation was measured to 900 W/m^2 on the test setup and the lamp was simulated to have a solar angle of 60°. The program PyTools provided by Axis was used to log the temperature development over time for nine sensors located at different points on the two cameras respectively. The sensors were placed according to the following description, see also Figure 9.18 – Figure 9.20:

- Sensor 1: Placed on the metal back-plate close to the CPU.
- Sensor 2: Placed on the inside of the dome, directly on the metal optic holder
- Sensor 3: Placed on the inside of the dome in the air, 5 mm from sensor 2.
- Sensor 4: Placed on the outside of the dome, directly on the plastic of the dome.
- Sensor 5: Placed on the outside of the dome, 10 mm over the dome and directly over sensor 4.
- Sensor 6: Placed under the solar cap and the prototype, directly over the dome.
- Sensor 7: Placed on the solar cap and the prototype, on the side facing the dome.
- Sensor 8: Placed on the solar cap and the prototype, on the side facing the lamp.
- Sensor 9: Measuring the ambient temperature.

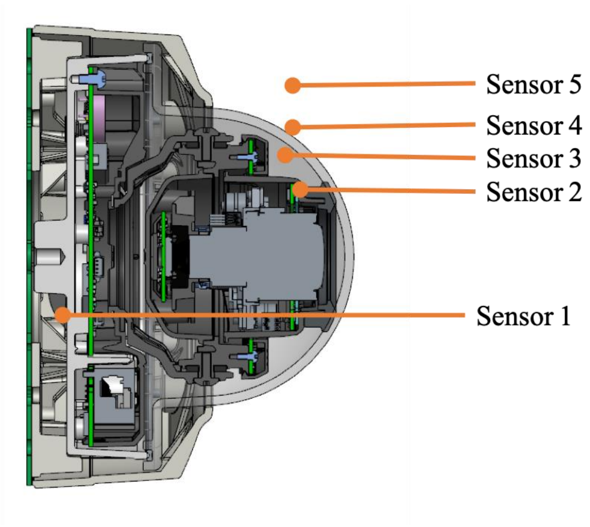


Figure 9.18 Sensor 1-5 shown in top section view.

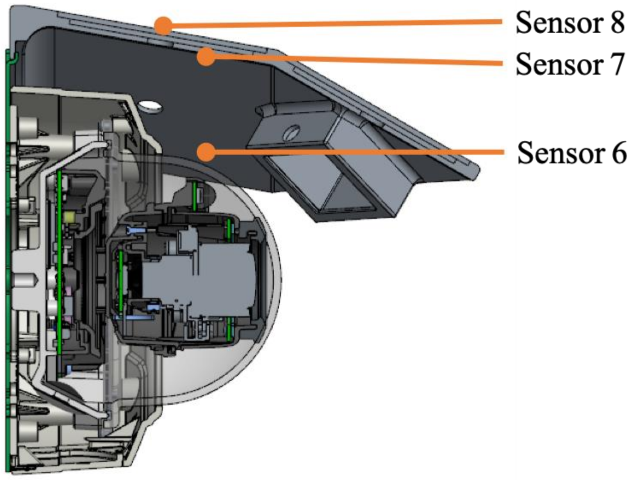


Figure 9.19 Sensor 6-8 show in side section view of the prototype.

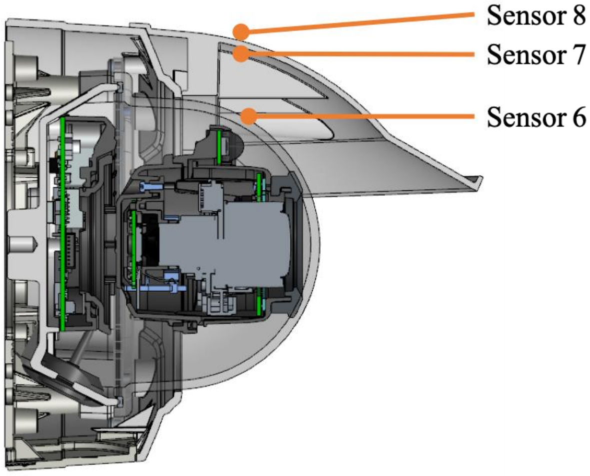


Figure 9.20 Sensor 6-8 show in side section view of the existing cap.

Each PV module on the prototype was supposed to be connected to a DC/DC converter, but due to the lack of enough converters, the modules were connected to another load instead of the two fans. The PV modules were connected in parallel to generate a total V_{oc} corresponding to the V_{oc} of one single module, to efficiently match the feed voltage of the load. The fans were powered by an AC/DC adapter with 12 V, connected to the wall socket. As the output voltage from the adapter was 12 V it corresponded well to the output of one illuminated PV module connected to a converter, which was shown in the earlier experiment to be enough to power one fan under direct illumination.

A cardboard was placed between the two cameras to prevent the airflow from the prototype fans to interfere with the temperature measurements for the camera with the original solar cap. Figure 9.21 below describes the experimental setup of the P3225-LVE with the existing solar cap and the prototype.

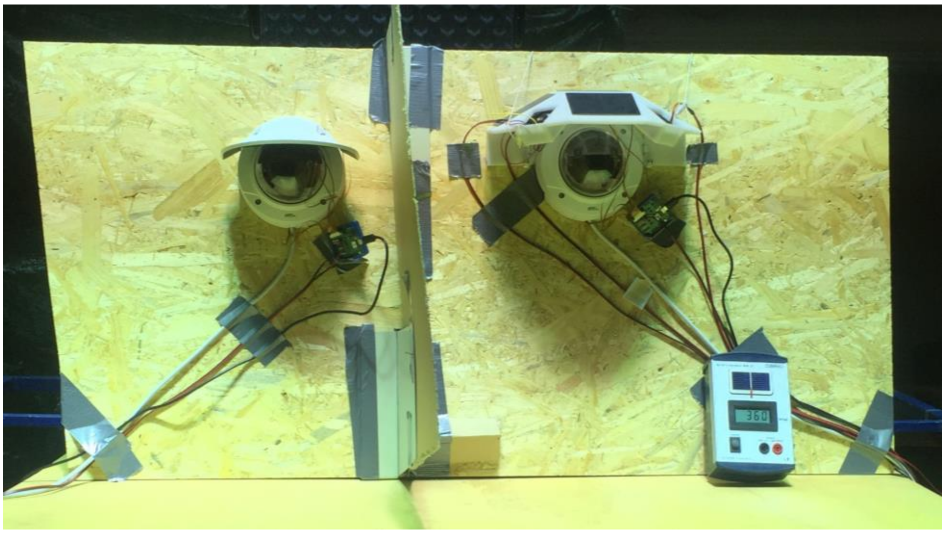


Figure 9.21 Set up of the test. Existing camera to the left and prototype to the right.

The experiment was divided into three parts. The methods of the three tests are described below. The test for the camera with the existing solar cap was conducted the same way for all the tests. The test was however still necessary to see if any drastic deviations in the ambient temperature occurred.

9.7.1.1 Test 1

The aim of Test 1 was to investigate if the cooling system attached to the prototype can generate a cooling effect for the camera in comparison to the cooling effect of the original solar cap. This test was carried out simultaneously as the PV modules on the prototype provided a current to a load matching the voltage output of the system. The solar simulation lamp was started and when stabilized the fans were started and the PV cells begun to power the connected load. The measurements were collected and logged for three hours.

9.7.1.2 Test 2

The aim of Test 2 was to compare the "thermos effect" between the two cameras when the PV modules power the load, but the fans on the prototype are switched off. The same methodology was applied for this test as for test 1, but the fans were disconnected.

9.7.1.3 Test 3

The aim of test 3 was to investigate the heating effect when the PV modules are not connected to a load and when the fans are disconnected. A comparison was made between the temperature development over time for the two cameras.

9.7.2 **Test Analysis**

The temperature sensors were manually placed on the camera with the original solar cap and the camera with the prototype. This resulted in deviations in the sensor locations, that should have been placed on the exact same respective locations for an accurate and precise comparison.
Sensor 8 malfunctioned during the two last parts of this experiment 2. Due to this, the temperature result from test 1 was used for the other tests as well. Since the three tests were identical for the camera with the original solar cap, this was not a critical error for the overall results. Comparing the other sensor temperatures, the temperature difference in % between the tests was negligible. The temperature differences between the prototype and the existing solar cap are shown in Table 9.3 below. The test reports are shown in Appendix L.

Table 9.3 The temperature difference due to unloaded PV modules, for sensor 1-8, denoted S1-S8, ambient temperature as *A*, heater sensor as *HS* and image sensor denoted *IS*.

	pcb	HS	IS	S1	S2	S3	S4	S5	S6	S7	S8	A
ΔT [%]	0	1	1	0	1	2	4	4	5	1	0	5

Table 9.4 Temperature difference due to the fans, for sensor 1-8, denoted S1-S8, ambient temperature as *A*, heater sensor as *HS* and image sensor denoted *IS*.

	pcb	HS	IS	S1	S2	S3	S4	S5	S6	S7	S8	A
ΔT [%]	-14	-15	-14	-15	-16	-20	-23	-6	-22	-12	-2	3

Table 9.5 Temperature difference between the different settings of the prototype compared to the existing cap, for sensor 1-8, denoted S1-S8, ambient temperature as *A*, heater sensor as *HS* and image sensor denoted *IS*.

	pcb	**HS**	**IS**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**A**
Test1												
ΔT [%]	-23	-17	-20	-23	-18	-26	-33	-20	-33	-23	-3	1
Test2												
ΔT [%]	-10	-2	-7	-10	-2	-8	-13	-15	-14	-13	-2	-1
Test3												
ΔT [%]	-10	0	-7	-10	-1	-6	-10	-11	-10	-12	-2	3

The temperature difference between the tests in Table 9.5 is between the existing solar cap and the different scenarios for the prototype. So, test 1 ΔT(%) shows the total cooling effect from the prototype. Test 2 ΔT shows the cooling effect for just replacing the cap. Test 3 ΔT(%) shows the cooling effect for just replacing the cap and the potential heat generated by the PV cells when not connected to a load. From test 1 and 2 the cooling effect from the fans can be extracted which is shown in Table 9.4. Table 9.3 show the potential heat generated due to the PV modules not connected to a load. The temperature difference is so small that no conclusions can be drawn except that the generated heat does not affect the temperature of the whole system and can be assumed negligible in this case.

The sensors of which are of a highest importance for the electronics are the ones built in the camera i.e. the where the electronics are heated the most and which is inside the camera. These sensors are:

- PCB
- Heater
- Image
- Sensor 1
- Sensor 2
- Sensor 3

The sensors of most importance to the thermos effect is:

- Sensor 6
- Sensor 7

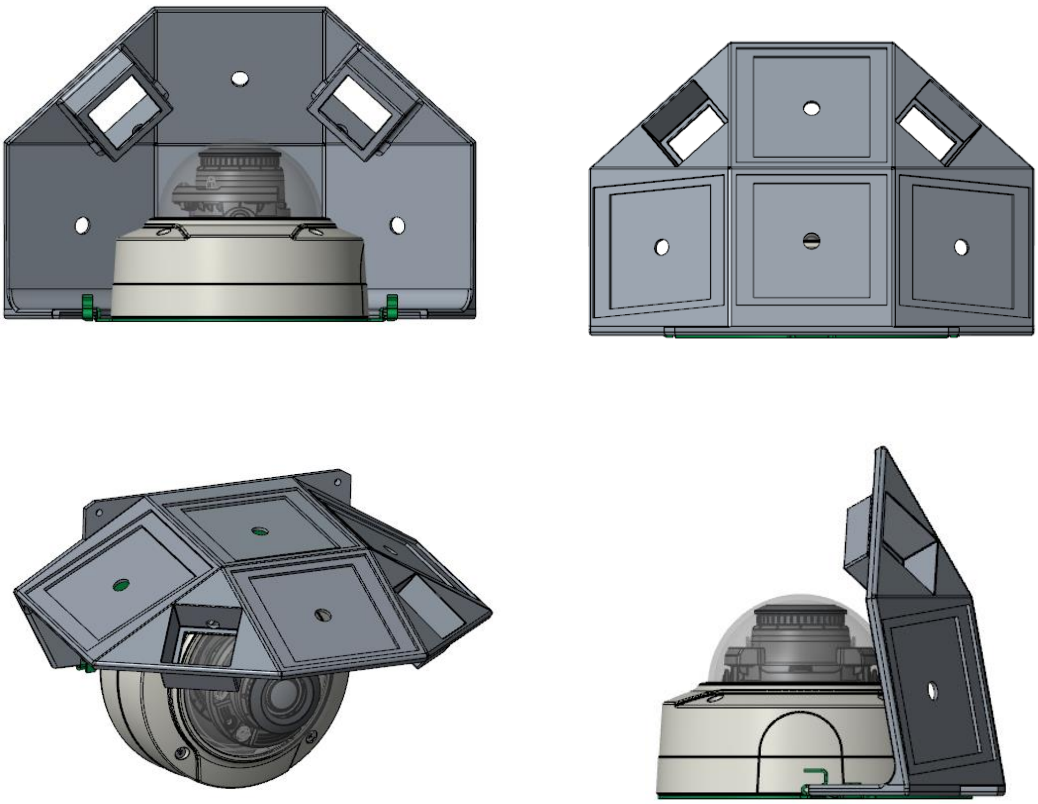
The temperature of the PCB decreases thanks to the cooling system and the replacement of the cap was -23 %, seen in Table 9.5. The decrease caused by just replacing the cap is -10 % and the cooling effect from the fan was -14 %. The heater temperature with the existing solar cap decreased with the new solution where -15 % was due to the cooling system. The image sensor decreased with 20 %. Sensor 1-3 showed similar reductions in temperature. Sensor 6 and 7 which were placed above the dome and underneath the cap also showed a decrease in temperature. S6 decreased with 33 % and S7 with 23 %. The replacement of the cap stands for around -13 % on both sensors.

9.7.3 **Reflections and results from the process**

The test shows that the prototype is working in the way the project aimed for it to work. The prototype is larger than the original solar cap resulting in that the camera is more protected from direct irradiation and thusly has a greater chance of protecting the camera against gaining temperature. The prototype does not encapsulate the camera as much as the solar cap does, which partly explains the temperature difference. The material of the solar cap differs from the prototype, which also could be a reason for higher temperatures for the camera with the existing solar cap. It was discovered that a lot of temperature decreases can be made by just replacing the cap. The cooling system does decrease the temperature but can be optimized further in order to be as efficient as possible. What can be concluded from this is that the PV modules produces enough power for the fans to cool the camera. The cooling system is not a part of the scope, it is however positive to see that the fans could cool effectively.

9.8 Final Concept

During the set of tests performed, it could be concluded that the prototype needed further alterations in order to work as a stable prototype. There were two main functions which needed alterations, the placement of the fans and the wall mounting. In prototype 1 the placeholders for the fans broke, this was altered to the second prototype in order to avoid the problem. This also allowed for the prototype to be slightly decreased in size. The wall mounting in the first prototype was not able to withstand the weight of itself. This was improved by changing the mounting design which can be seen in Figure 9.22. A small change was also made, holes in the placeholder of the fans were also added in order to allow for the wires connecting the fans to the PV system to be drawn under the cap. The angling of the PV modules was considered to be well chosen from the first prototype and were not changed.



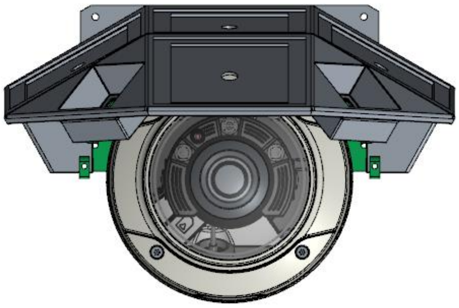
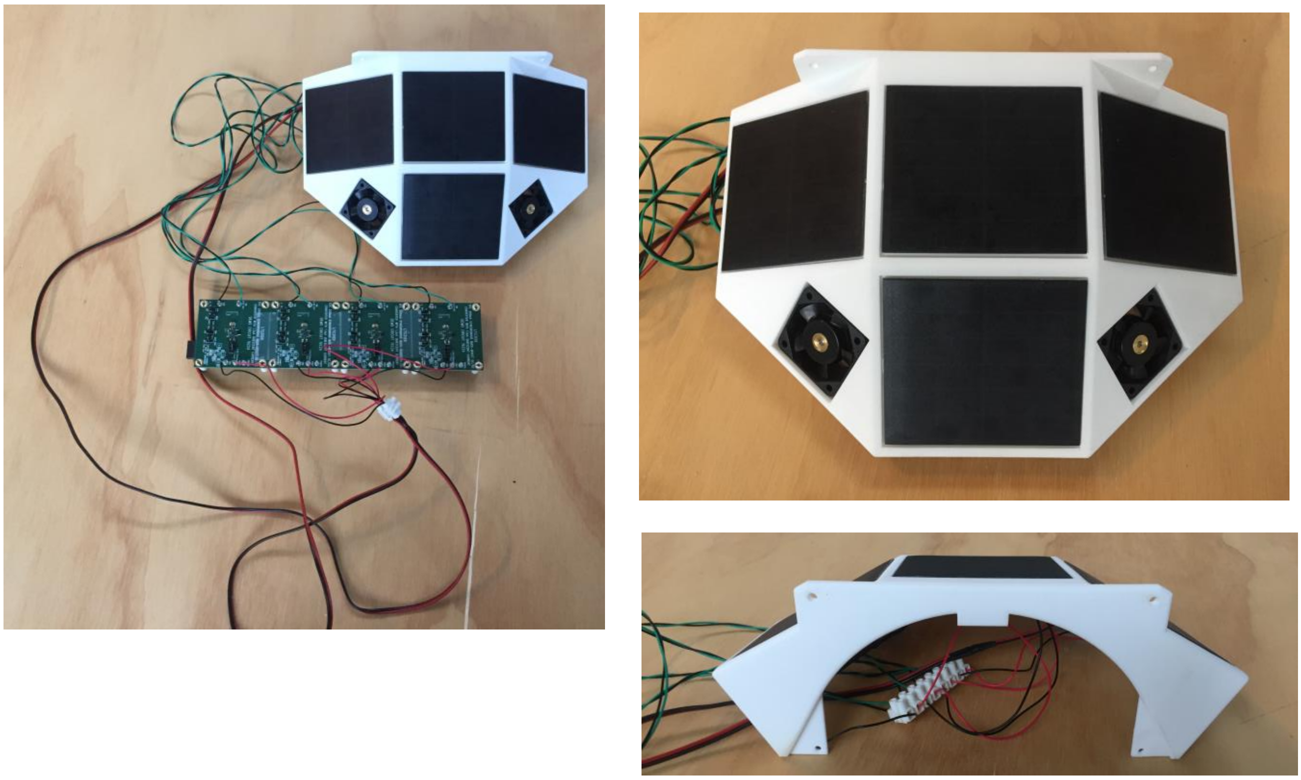


Figure 9.22 Prototype 2 shown from different angles, bottom, top, ISO, side and front view.

The improved cap was 3D printed. The PV system, fans and DC/DC converters were connected and installed in the cap. Figure 9.23 shows the final prototype.



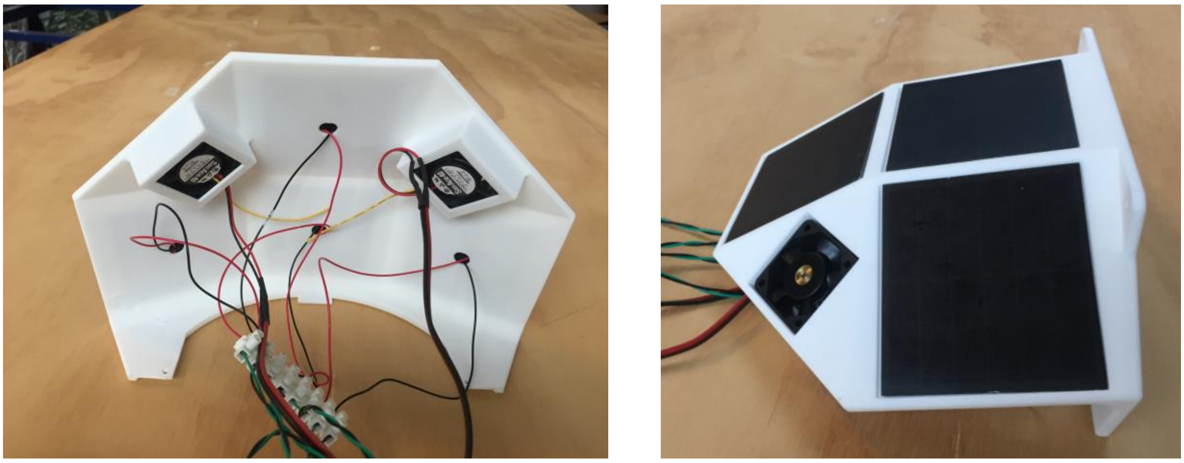


Figure 9.23 Final prototype from different angles; full system viewed from above, top, back, bottom and side.

9.8.1 Cost analysis

The total cost of a product would be substantially higher than the existing cap. Even if the prices would be reduced when produced in larger scale, there will still be a substantial price rise. It will only be defensible to use the product if it were to increase the functionality and life time of the camera substantially.

9.8.2 Worst Case Scenario Calculations

From the weather data analysis, it can be shown that the worst-case scenario is when the temperature is 44°C, the DNI is 700 W/m^2 and the elevation angle is 77°. Calculations according to Appendix M shows that the power output from the prototype at worst-case scenario conditions is 2.42 W.

9.8.3 Testing of Final Concept

Since the DC/DC converters were not available at the time of the first prototype test it was of importance to test the complete solution. This test was performed to show that the PV system could power the fans. The prototype was set up with the same angle towards the lamp as the test presented in chapter 9.7 and the lamp used was the same. The test got the successful result of showing that the fans could be powered by the PV system.

9.8.4 **Field of view**

The field of view was tested by taking photos with the camera when placed in a horizontal angle. This was done for the existing solution, prototype 1 and 2. The results are presented in Figure 9.24 – Figure 9.26.

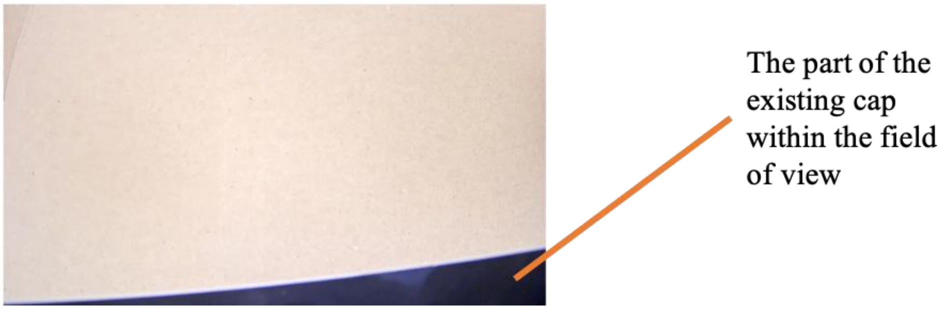


Figure 9.24 Field of view of the existing solar cap.

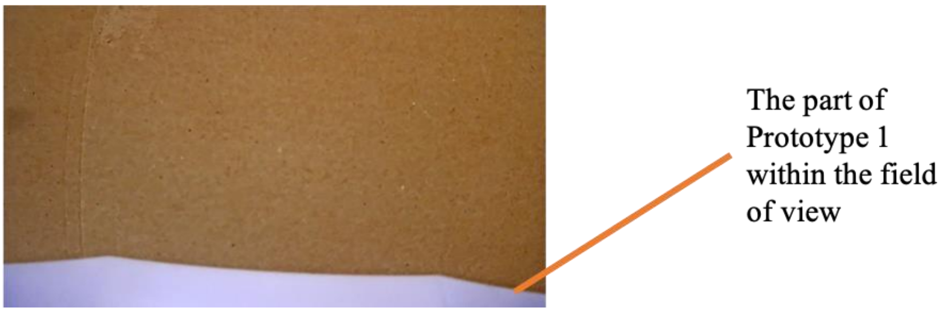


Figure 9.25 Field of view of the first prototype.

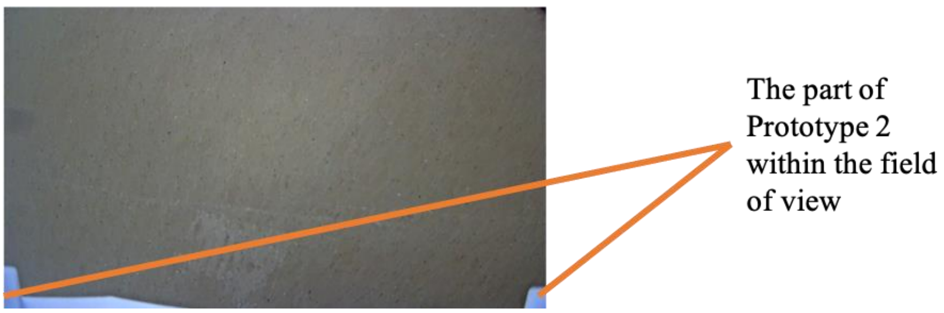


Figure 9.26 Field of view of the second prototype.

Prototype one took up a larger area of the image than the existing cap. This was improved and prototype two took up a smaller area than the existing cap. The placeholders of the fan were showing in the second prototype, in future designs this should be avoided and can be done by moving the placeholders further back and further to the sides of the cap.

9.8.5 **Reflections and results from the process**

The final concept worked well and when calculation the worst-case scenario it was shown that the PV system could generate enough power for the fans to be maximally utilized. To evaluate the prototype further, tests in Dubai for a longer period of time would have to be performed. Since this is not possible no more lab evaluations would give useful results for further development and design alterations needed.

9.9 Results of the Chapter

In order to find if the prototype fulfilled the specifications an analysis was made, see Table 9.6. The specifications which are stroke through are the ones considered as unfulfilled. As the main focus have been to find optimal angles in order to produce enough power the trade-offs have always been in the advantage of that. This does not mean that they cannot be fulfilled in the future, it means that more considerations have to be taken of this in further developments. The delimitations were during the course of the project increasing due to the deeper understanding of the project. The width of the project was narrowed down continuously in order to fit the time frame.

The specifications which were met are stated here together with how they were met. Specification 4, the angling of the product was more than 0° was fulfilled. Since the previous analyzes showed that the optimal angle was between 13°-31° from the horizontal plane, no trade-offs were needed here. This resulted in that water run-off is possible which was a main design specification for the existing cap. The prototype had 4 PV modules so specification 28 is fulfilled. Specification 15 was considered fulfilled. This is, as previously stated more a question of choice in PV modules chosen. Shading of the PV modules in specification 29 ranked as a 2, with the knowledge obtained it can be concluded that this should have been ranked a

1 since it is vital for the functionality of the product. The specification was fulfilled. The prototype is according to the team members considered aesthetically appealing, specification 37, this is however a subjective specification and end users would need to be consulted to fully conclude this. The prototype does look like a cap protecting the camera which is good since that is what the project wants the shape to communicate to its observers. The size of the product is within the specifications, specification 38. The thermos effect in specification 26 should have been stated as a comparison between the existing cap and the new solution since existing cap was the reference throughout the project. The thermos effect was lowered with more than 10% and the specification can be considered fulfilled. Specification 42 is also considered a success since the main function of the solar cap protecting the camera from irradiation was fulfilled. Functions such as water runoff are not full optimized in the prototype but is possible with minor design alterations. The cost of the product, specification 20, was fulfilled. The product can, as stated before, generate power of any type of power needing system. The system can charge a battery, specification 35, but is not optimized for it, it is optimized to generate power for the cooling system when the camera needs cooling. The prototype is within the size and is does not draw extra attention so specification 39 can be considered fulfilled.

The specifications which were not met and need further investigation are stated here. The reflections caused by the prototype, specification 16, was not measured and more tests will have to be conducted before this specification can be considered fulfilled. Specification 5 was set in order to reduce water running down in front of the camera. The design of the edges of the product were not considered due to the timeframe and will need further design before being fulfilled. The seams, specification 6, were non-existent which was desirable. Regarding cleaning and maintenance, specification 10, no conclusions can be drawn since not dust or dirt analyses were made, and it can therefore not be known how much effort or time it takes to clean the product. Installation of the solution was tested by the team members when setting up the prototype for testing. The product was quickly installed and specification 21 can be considered fulfilled. No specific concept generation was made for the installation of the product, specification 24 was not fulfilled after the first prototype but this was improved for the second prototype. Specification 36 was set in order to keep an open mind and referred to having an adjustable solution which

could be adjusted depending on the time of the year. This was decided to be too complex and unnecessary and the specification was not met.
The weight of the product will depend of the weight of material used in the final product, this is not known today and specification 23 cannot be considered fulfilled. The IP and IK class in specification 3 and 8 were not fulfilled. They have to be further developed since they depend on other design parameters than investigated in this project. Specification 11 is a relevant parameter, due to the timeframe of the project there was not enough time to develop such a solution.

The specifications which were not met but were considered good enough are stated here. Specification 19 was not fulfilled as shown in the field of view test. The amount of cap visible to the camera was however just a bit more than the visible part of the existing cap. The specification is considered to strict and the result is therefore considered acceptable.
The prototype cannot generate double the power need when clean, as needed in specification 9. For this case it would need to be 4 W (1 W per fan). The specification was an aim of investigating how dirt and sand affected the PV modules. The time was not enough to analyze this and will need further investigation. Specification 32 was not fulfilled and can be considered a wrongfully stated specification as it refers to the possibility of powering the camera as well as the cooling system. It should be changed to generating enough power to power the cooling system and would thereby be fulfilled. It was important in the beginning to aim to generate enough power as possible but trade-offs regarding the area and thereby the size of the product had to be made. Specification 18 was considered not full filled. This is only partly true, considering that during the course of the project it was understood that those specifications are concerning the PV cells and not the actual design of the PV system. The PV modules used, did however fulfill these specifications.

The specifications which were not met but were considered to be too strict are stated here. Specification 27 is set too strict and was an aim of limiting the risk of insects living and nesting in the products. Specification 13, on the same theme was fulfilled. Specification 31 is also considered too strict. There are 4 PV modules which can each generate 1.08 W, they are however angled in such a way that they can never generate a total of 4 W, which is double the power need. The wires from the PV system can be no less than 8 if the PV modules are connected in parallel. The parallel connection was considered more important than the number of wires and specification 22 was not fulfilled.

Table 9.2 List of specifications.

Rank	Spec. Number	Specification
1	4	The product is always angled more than 0° from the horizontal plane
1	15	Each PV module generates at least 1 W
1	16	~~The product reflects 0 W/m^2 in to the camera~~
1	18	~~The PV cells have a 15 % degree of efficiency at a temperature of 80°C~~
1	19	~~The product appears in 0% of the image~~
1	28	The product has at least one PV Cell
2	9	~~The product can reach twice the efficiency need when clean.~~
2	27	~~The gap between chassis and product is smaller than 1 mm or larger than 100 mm~~
2	29	The product can generate the efficiency need when 50% of the PV cells are shaded
2	31	~~The product can reach twice the efficiency need when T= 25°C and the irradiation is 1000 W/m^2~~
2	37	The product is aesthetically appealing to the users
2	38	The product has a max; width of 200 mm from camera center, height of 300 mm, depth of 300 mm
3	5	~~The products edges are less than 50°~~
3	6	The edge of the product has no seams
3	10	~~It takes 1 minute to clean the product~~
3	13	The gaps of the product are not 3-10 mm
3	21	The product is quickly installed
3	24	The product is properly installed
3	36	~~The PV modules can be angled between 1°-90°~~
4	22	~~The product has one wire to the cooling system~~
4	23	~~The product weighs max 1 kg~~
4	26	The thermos effect is no more than 10 %
4	42	The product replaces the functions of the solar cap

5	3	~~The product has the same IP class as the P32~~
5	8	~~The product has the same IK class as the P32~~
5	11	~~The product sends out a signal when power output is less than 50 %~~
5	20	The total cost is low
5	32	~~The product generates 9 W~~
5	35	The product can charge a battery
5	39	The product is discrete

Looking back, one of the most important specifications have not been properly stated for the case study; the PV system can power two fans. This was since the project wanted to keep an open mind of what the PV system could power. But it is clear that this should have been more properly stated in the specifications to start with. The project has had to investigate both the parameters in need of consideration as well as setting specification which made the project rather complex.

9.10 Conclusion of the Chapter

The product did not reach all the specifications stated in the beginning of the project. This is partly due to the fact that some tradeoffs were not correctly made at the start and some specifications were later during the project understood as being specifications of the solar cells rather than the product itself. It was understood during the project that it is unnecessary to specify the PV cells type to be used. Since it is not the PV cell type that determines if it can be used or not, it is rather the efficiency at high temperatures that determines this. The prototype did fulfill 15 of the specifications, where some of the specifications unfulfilled now can be fulfilled when the product is further developed. It also turned out that the prototype worked well in the tests conducted managing to power 2 fans which could cool the camera more than expected.

10 Results of the Project

This chapter explains the results of the project.

This project has shown that there is a great possibility in using PV modules to directly power a cooling system. As the global warming comes higher up on the agenda of the global issues of today, this type of solution could be used to cool without emitting carbon dioxide. The need for this will increase for outdoor electronic equipment as the components grow smaller and thusly generates more heat. In cities where the temperatures are generally higher due to a higher light absorption and lower wind flows this type of solution can also be advantageous. This type of solution is also independent of the power grids which allows for them to be fully functionable if the power from the grid is down, however it can only work at certain hours of the day. The improvement in the efficiency of PV cells together with the decreasing costs will allow for more price competitive solutions of this kind.

There are several parameters identified during this project. These have been categorized into three different sub-groups; free parameter, semi free parameter and set parameters. A free parameter means that it can be chosen by the designer after taking the semi free and set parameters into account. The semi free parameters are mainly the specifications of the PV cells. The set parameters are the conditions of which the PV systems is set to be in. The parameters presented below are the ones which have been taken under consideration during the case study, there are however probably several more parameters but considering the time frame all of these could not have been identified by this project.

The free parameters which have been identified are; area, shading, connections, angle of PV modules and electrical circuits used to optimize the power output. The area is often of importance when designing since it is often limited. It is however up to the designer to choose how big the area needs to be after taking the semi free and set parameters under

consideration. Shading of the PV modules is important when designing in order to make sure that the design does not shade itself. If the design at any point shades itself, it has to be made aware of and trade-offs regarding the design versus the power output have to be made. If there are more than one PV module in the design the connections between those have decided.
The connections between the modules affects the output voltage and current. Often a high voltage is desired which is achieved by connecting the PV modules in series. This makes the system more sensitive to shading which is why a parallel connection is sometimes a better option. The parallel connection gives a high current, when this is undesirable a DC/DC converter can be connected to each of the PV module which can optimize the voltage and give a desirable power output.

The semi-free parameters are represented by factors regarding the PV cells. The choice of PV cells in the project are considered semi-free as there are several different types of PV cells on the market, but there is a desire to use a type that is efficient and relatively cheap at the same time. The semi-free parameters regarding PV cells which have been identified are; the efficiency and the temperature dependence of the PV cells. The efficiency of the PV cells is important to consider as this decides the PV module area and the power output. It is also important to consider the temperature dependence of the PV cells, as the efficiency often drops when the cell temperature increases. When the PV cells are exposed to radiation and heat the cell surface will be heated which decreases the efficiency and thus the power output. The temperature coefficient describes how the efficiency is affected by changes in temperature for a specific type of PV cell, which is why it has to be considered.

The set parameters identified by the project are; irradiation, air pollution & clouds, ambient temperature and sun elevation angle. The irradiation at the specific location affects the power output of any PV module, low irradiation results in low power output. The air pollution and clouds affect the irradiation that can reach the PV module and thus the power output. The ambient temperature will result in the PV module having the same temperature before being exposed to the sun. A high ambient temperature causes the PV modules to heat and lowers the degree of efficiency. The sun elevation angle affects how the PV modules need to be angled in order to optimize the power output. The cardinal direction of where a product is placed affects the expected power output, if a PV module is facing north in the northern hemisphere the power output will be lower than if it was facing south.

The identified parameters have been considered during the design of the prototype. The prototype was designed to fit a P32 camera. It was desired to protect the camera from direct sunlight as well as prevent warm surrounding air to heat the camera. In order to protect the camera from direct sunlight, the prototype resulted in a shape similar to the original solar cap. To prevent warm surrounding air to heat the camera, two fans were used to actively cool the bottom of the prototype and thus the camera below the prototype. This prevented air from standing still that would heat the camera. The fans were powered by four PV modules placed on the top of the prototype. The PV cells chosen for the project are mono-crystalline silicon cells with an efficiency of 22 % at standard testing conditions. A high efficiency could result in a small area of the prototype, which was one of the main requirements of the project. The placement of the PV cells was decided to assure power output regardless of the cardinal direction of the product mounting. The four PV modules were of equal sizes facing three different directions enabling a power output as soon as one of the sides were sufficiently illuminated. The angle of the PV cells and thus the shape of the prototype was decided based on the analyzed weather data from the site in Dubai. As the most critical temperatures were reached when the solar height was between 59°-77°, the three side plates were tilted by 30° from the horizontal to optimize the light absorption throughout the day. And the top plate was tilted 10° from the horizontal. The reason why the top plate was tilted 10° was because when the solar height is 77° and higher, all modules will still be illuminated, and the 10° tilted module would receive the highest amount of irradiation. It would be reasonable to place the prototype facing the south in the Dubai case, since that is when the sun is at its highest position in the sky. Simultaneously the design was also optimized for allowing the specifications of the solar cap to be considered. The optimal cardinal direction of the prototype in Dubai is when it is facing the south, since it will be most exposed to the irradiation and thus will generate more power. It is also beneficial to have the top plate tilted by only 10° from the horizontal to utilize as much energy as possible at times when the solar height is above 77°.

The prototype was as earlier mentioned designed to include two fans. These fans were selected so that the power input from the PV cells matched the power demand of the fans. From the product concept testing a comparison between the prototype and the original solar cap was demonstrated. The test resulted in two important factors regarding the temperature differences between the two cases. It could be seen that a cooling effect was acquired by substituting the original solar cap with the prototype. Additionally, cooling effects from the fans were also shown, as the heat transfer through convection increased.

The use of the two fans successfully lowered the temperature of the camera and the surrounding air. However, the cooling system in this project is not optimized and a more efficient cooling system could be designed. It could be valuable to make use of passive cooling systems such as heat pipes and heat sinks, to more efficiently transfer the heat from the camera. This in combination with an active cooling system, such as for example fans would probably result in even lower temperatures. It was however not possible to design a cooling system within the time frame of the project. The project resulted in a proof of concept, where it was shown that the prototype with the chosen PV cells could power two fans to actively cool the P32 camera, assuming that the prototype is used in Dubai. This result can later be used as an example for further research on the subject. The results of the project were based on and justified by analyzed measured weather data, the tests performed in the lab and by research. It would however be necessary to conduct more live site testing for more accurate results.

11 Conclusions of the Project

This chapter presents the conclusions which can be drawn from the project.

This project has successfully designed a prototype where PV modules, DC/DC converters and fans are placed in an optimized way to cool the P32 camera in Dubai. The project has successfully shown the possibilities and future need of this kind of solution. It can be concluded that this PV system directly powering a cooling system can be successfully used. The results from the testing of the developed prototype shows that the PV system generated enough power. The system powered by the PV system does not necessarily have to be a cooling system, but the power need does have to coincide with when irradiation from the sun is available. On a larger scale these kind of PV systems optimized regarding the parameters identified during the project can be useful where and whenever there is a need for cooling. The identified parameters in need of consideration are;

- Free parameters
  - Area
  - Shading
  - Connections
  - Angle of the PV module
  - Electrical circuits

- Semi free parameters
  - Temperature coefficient
  - Degree of efficiency
  - Temperature of the PV cell

- Set parameters
  - Irradiation
  - Air pollution and clouds
  - Ambient temperature
  - Sun elevation angle
  - Cardinal direction

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B.1 https://commons.wikimedia.org/wiki/File:Silicon_solar_cell.gif

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B.9
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Appendix A Work distribution and time plan

This appendix presents the planned activities and their time frame. It also presents the actual outcome activities and their time frame as well as the work distribution.

A.1 Work Distribution

Both the students have participated in all activities. However, Louise has focused more on the theoretical aspect of the project and Kajsa has focused more on the practical part and design process.

11.1 Project Plan and Outcome

The planned Gantt chart is presented in Figure A.1. The actual outcome is presented in Figure A.2. The main difference is that the writing of the report took longer than expected. In the planned time plan, writing the report was included. This was not always possible since iterations had to be done and some conclusions until the end of the project when the testing was finished.

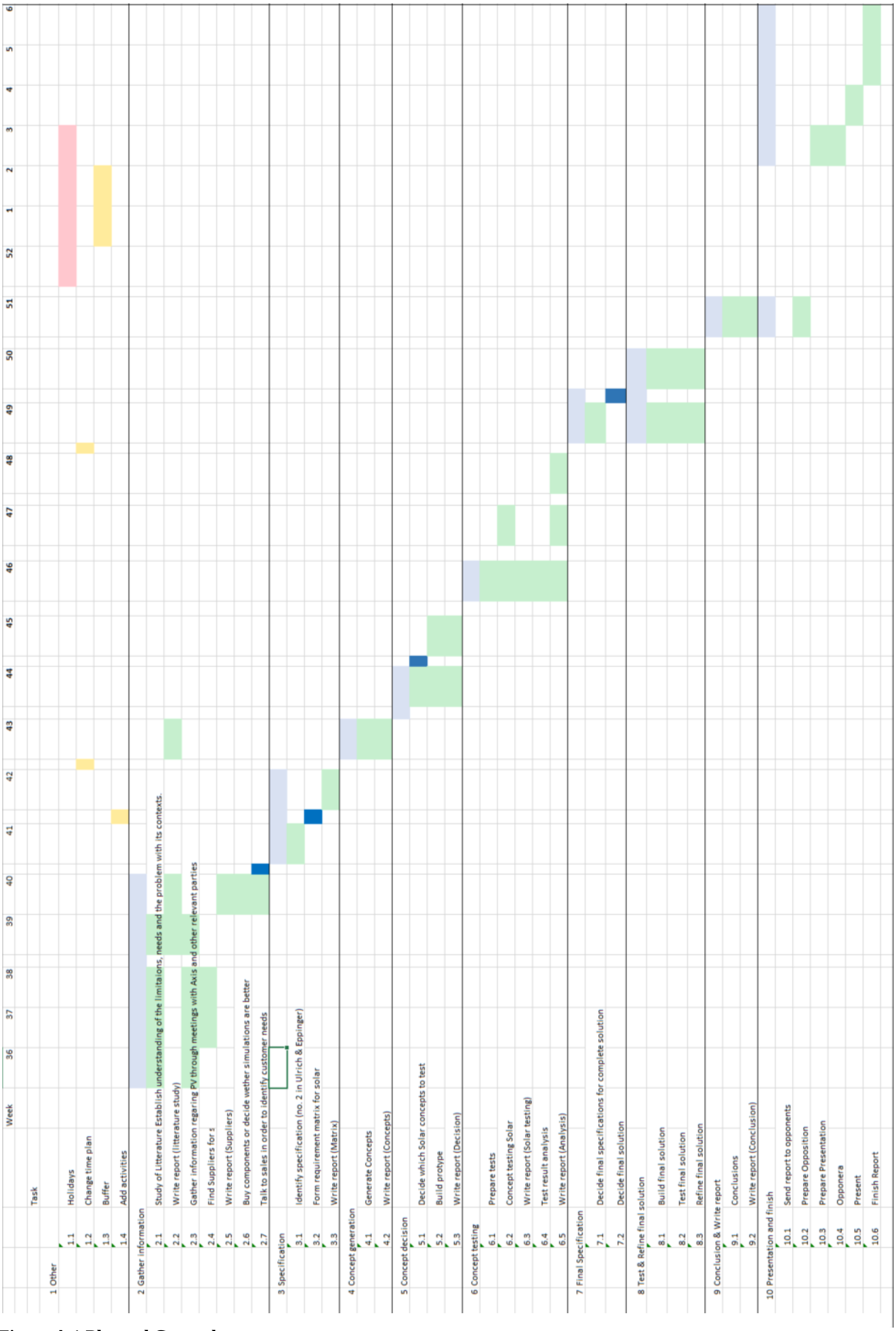


Figure A.1 Planned Gantt chart.

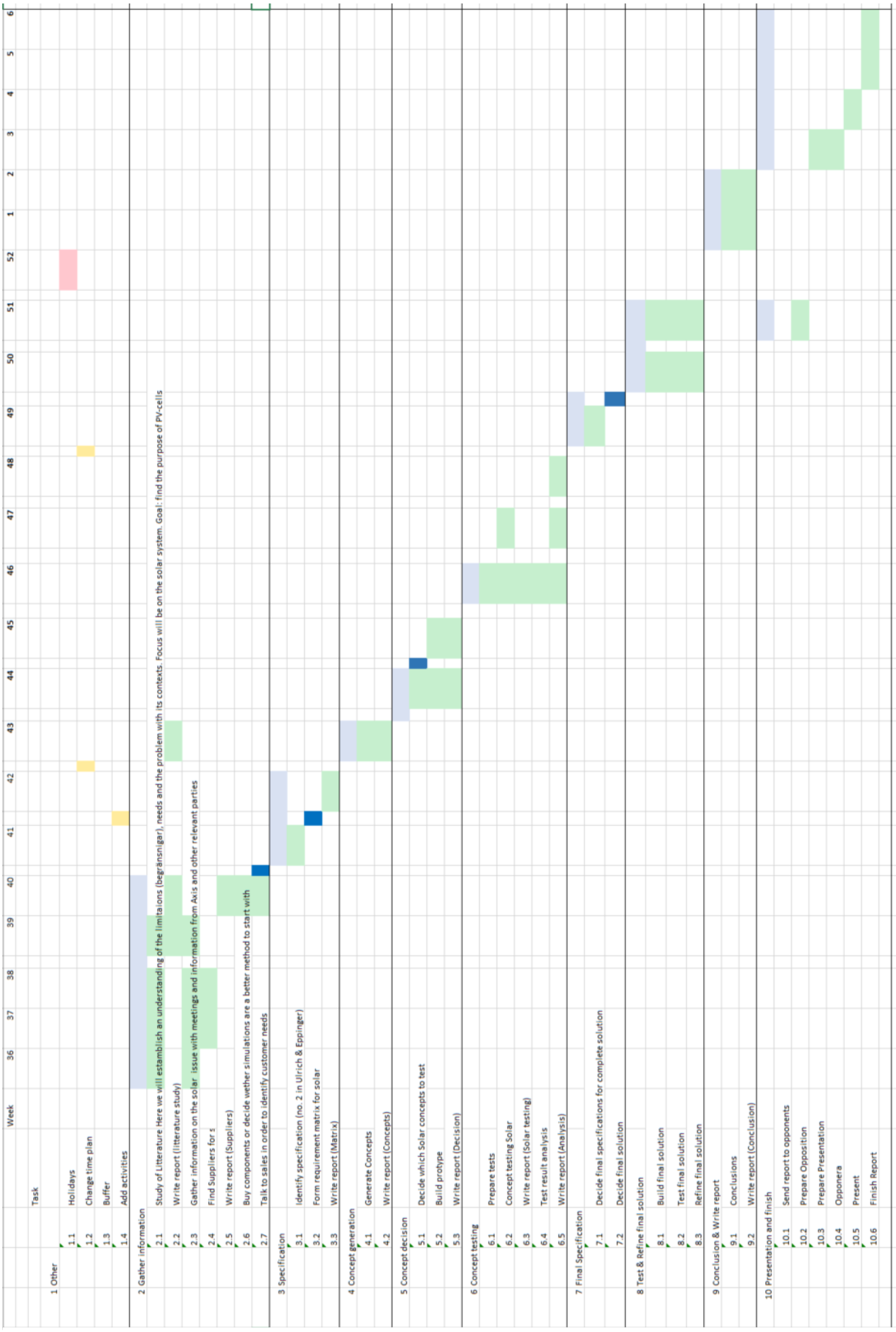


Figure A.2 Actual outcome Gantt chart.

Appendix B The physics of PV cells

This Appendix presents how PV cells work.

Photovoltaic (PV) cells are used for generating electricity from the photon energy in the incoming solar radiation. Photovoltaic cells consist of semiconducting materials where the most common material today is Silicon (Soga, 2006). The function of PV cells depends on the semiconducting material, which enables a current to flow when the PV cells are illuminated. There are different semiconductors that can be used that give the PV cells different light absorbing qualities (Sproul, n. d.).

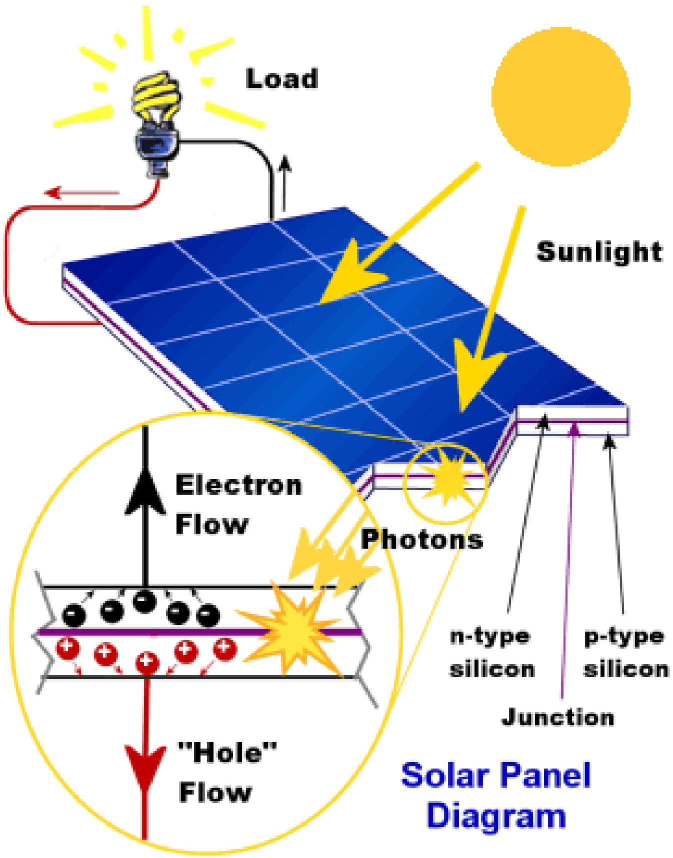


Figure B.1 A descriptive image of the different parts of a PV cell.

All types of PV cells have the same basic function (Common Types of Solar Cells, n. d.), in order to understand these functions, the properties of a silicon-based semiconductor are described below.

Silicon atoms can form a crystalline structure through bonding, where two electrons are shared at each bond. The crystal structure has no net electric charge since all electrons are occupied and the material acts as a good electric insulator. If enough energy is added by for instance light, the bonds between the atoms can be disrupted enabling an electron to freely move between atoms (Sproul, n. d.).

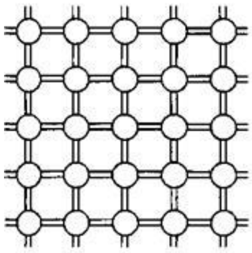


Figure B.2 Silicon crystalline structure.

To increase the electrical conductivity of silicon different dopants are used. Typically, phosphorus is used, which has one more valence electron than silicon. This leaves one electron to move freely through the crystal. Since there are unbonded electrons in the crystal this type of doping is called n-type silicon (Sproul, n. d.).

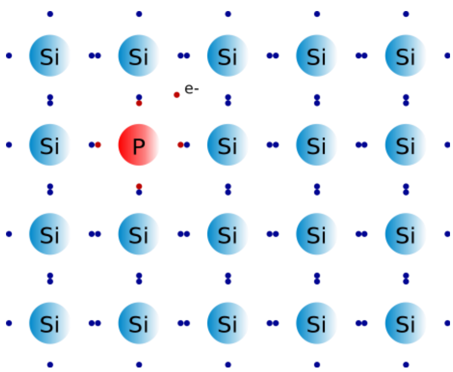


Figure B.3 N-doped silicon crystal.

Boron is also used as a dopant in silicon crystals. Boron has one less valence electron than silicon. When doping the silicon with boron, only three bonds can be formed with silicon atoms. This leaves one silicon atom unable to bond, creating an absence of an electron in its valence band - a hole. Similar to the free movement of the loosely attached electrons in the n-type silicon, the free holes can move through the crystal. This type of doping is called p-type silicon since positive charged holes are able to move (Sproul, n. d.).

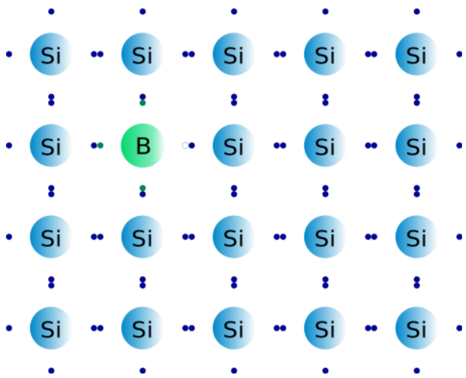


Figure B.4 P-doped silicon.

When the p-type and n-type silicon are brought together the free electrons in the n-type region are attracted to the holes in the p-type region and vice versa. Electrons from the n-type region wander across the junction to join holes on the other side. This results in a static negative charge near the junction in the p-type region. The same happens for the free holes in the p-type region, resulting in a built-in electric field, see Figure B.5.

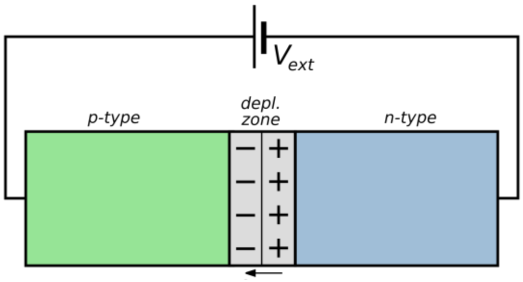


Figure B.5 Depletion zone between the two doped parts.

When enough energy is added, by for instance light, electrons will be separated from the atoms and move towards the n-type region. This results in a potential difference across the junction, see Figure B.5. When connecting a load to the two sides of the system, electrons and holes can flow through the wire and recombine, creating a current between the two doped regions. This process can go on as long as enough energy is added to excite electrons (The Solar Spark, 2013).

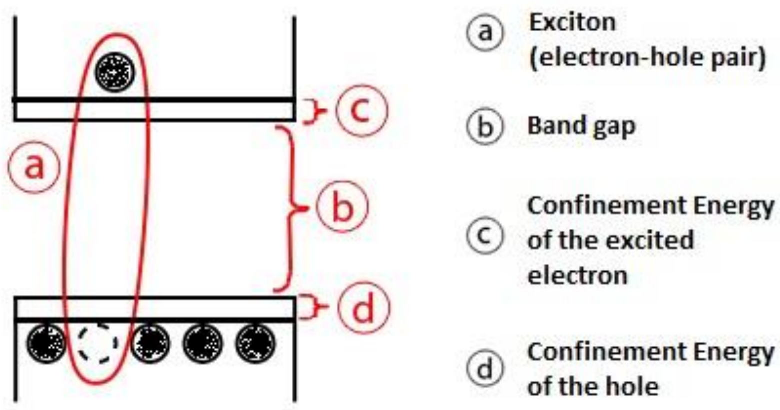


Figure B.6 Electron excites, leaving a hole behind.

The energy added is the energy of the photons in the incoming light. In order to create a current, the electron need to obtain enough energy from the photon to move from the valence band to the conduction band, see Figure B.6 and Figure B.7. This energy is specified as the band gap energy, which the photon energy need to correspond to.

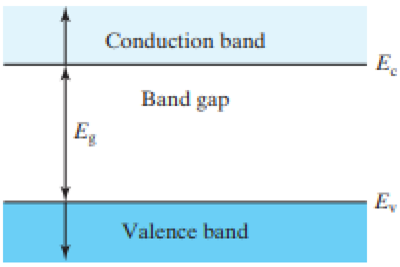


Figure B.7 Valence band, band gap potential and conduction band.

In order to excite electrons located in the valence band in a silicon atom, the energy of the incoming photons need to correspond to at least the band gap energy. This energy can excite an electron, enabling it to travel to the conduction band. The excess energy is lost as heat, since only a precise amount of energy is needed to excite the electron (Electrons and Holes in Semiconductors 2009, p. 23). Figure B.9a demonstrates the part of the solar spectrum that a silicon PV cell can utilize. Radiation with wavelengths outside the red marked area will not contribute to the electricity generation (Electrons and Holes in Semiconductors 2009, p. 9).

Other semiconducting materials have a different specific band gap energy, meaning that depending on the composition of the irradiation different materials are more efficient than others (Electrons and Holes in Semiconductors, 2009, p. 9).

Different Types of PV cells

Depending on what type of PV cell that is used the applications can vary. There are many different semiconducting materials and combinations of them that can be used for a photovoltaic effect. The most common types can be described by different groups and sub-groups. Silicon mineral is one of the most abundant elements on Earth and useful for its semiconducting properties, making it a common material for PV cell production (Goetzberg, Hebling & Schock, 2003, p. 4). Silicon based PV cells are often recognized as two variants, crystalline and non-crystalline. Crystalline silicon is often known as either *mono-crystalline* or *poly-crystalline*, and non-crystalline silicon is also called *amorphous* silicon, see Figure B.8. (Common Types of Solar Cells, n. d.) The other most common types are thin-film PV cells where Cadmium-Telluride and Copper-Indium-Gallium-Selenide are the most common ones on the market today (Common Types of Solar Cells, n. d.).

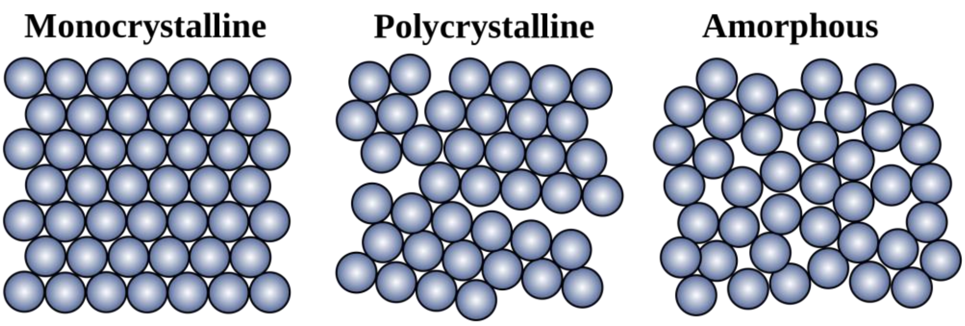


Figure B.8 Different types of silicon structure.

Single- and Multi-Junction

As described earlier, the choice of semiconductor in the PV cell will determine how much energy in the incoming light that can be used to generate electricity. For silicon a specific part of the solar spectrum can be utilized to generate electricity, see Figure B.9a. Single junction silicon PV cells are as described earlier based on that one junction is formed to enable a current to flow. When combining other semiconducting materials, other parts of the solar spectrum can be utilized, since the band gap energy is different for those materials (Electrons and Holes in Semiconductors, 2009, p. 9). Figure B.9b describes the absorption properties of a combination of three different materials.

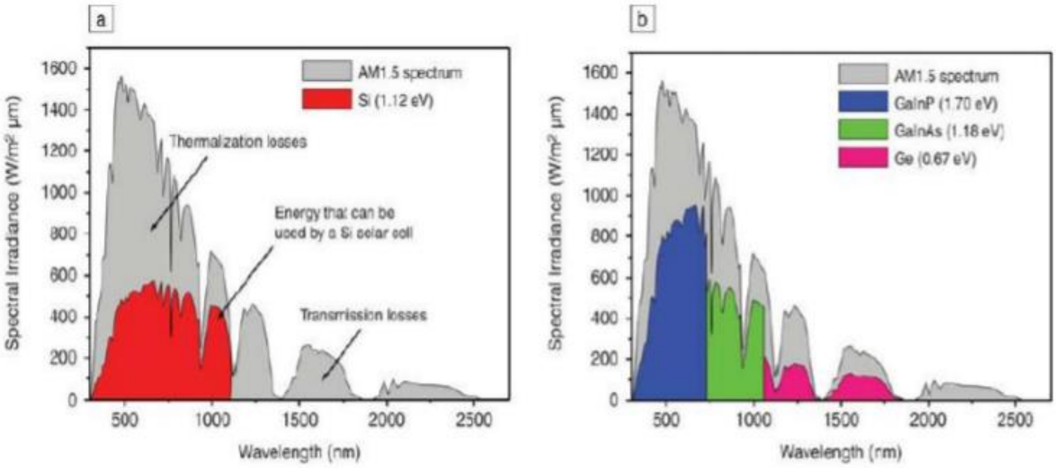


Figure B.9a & b Utilized parts of the solar spectrum for different semiconducting materials.

Appendix C Calculation of Sun elevation angle

Description of parameters

α: The elevation angle is the angular height of the sun measured from the horizontal plane. At sunrise the elevation is 0° and when the sun is directly above the horizontal plane the elevation is 90°.
δ: Declination angle of the sun is the angle between the equator of the Earth and a line drawn from the Earth's center to the sun's center.
ϕ: Latitude at a specific location.
LT: Local time at a specific location.
LST: The local solar time is defined as the time when the sun has its highest position in the sky during the day.
LSTM: The local standard time meridian is calculated for a specific location's deviation from the meridian of Greenwich.
EoT: Is an empirical equation that compensates for the elliptical shape of the Earth's orbit and the axial tilt of the Earth.
HRA: The hour angle is the conversion of the local solar time into the degrees that the Earth rotates during the day.

Elevation angle at solar noon:
$\alpha = 90° + \varphi - \delta$

Where,
α: Elevation angle [degrees]
δ: Declination angle [degrees]
ϕ: Latitude [degrees]
Note that when the equation gives a value that is greater than 90°, the result should be subtracted from 180°. Such a value means that the radiation from the sun at noon comes from the south, which is typical for the northern hemisphere (Naraghi, 2009).

Declination angle, δ:

$$\delta = -23{,}45° \cdot cos(\frac{360}{365} \cdot (d + 10))$$

Where,
d: day of the year with the 1st of January as d=1.

Elevation angle at other times of the day:

$$\alpha = sin^{-1}(\sin(\delta)\sin(\varphi) + \cos(\delta)\,cos(\varphi)\cos(HRA))$$

Hour angle, HRA:

$$HRA = 15°(LST - 12)$$

Where,
LST: Local solar time [hours]

Local solar time, LST:

$$LST = LT + \frac{TC}{60}$$

Where,
LT: Local time [hours]
TC: Time correction factor [minutes]

Time correction factor, TC:

$$TC = 4(Longitude - LSTM) + EoT$$

Where,
LSTM: Local standard time meridian
EoT: Equation of time

Local standard time meridian, LSTM:

$$LSTM = 15° \cdot \Delta T_{UTC}$$

Where,
ΔT_{UTC}: time zone
Note that ΔT_{UTC} is equal to the time zone of a specific location. For instance, Sydney, Australia is UTC +10, which gives the value of

LSTM=150°.

Equation of time, EoT:

$$EoT = 9{,}87\sin(2B) - 7{,}53\cos(B) - 1{,}5\sin(B)$$

Where,

$$B = \frac{360}{365} \cdot d \cdot (-81)$$

Appendix D – Irradiation Data & Results

The results are presented with the relevant values under the result headlines below.

The column points indicate on how many occasions the thresholds have been reached. The values are an average of the values in the investigated interval. The average values when SE > 10° are shown in Table D.1.

Table D.1 Average SE, temperature and DNI.

	SE	*TEMP*	*DNI*
SE > 10	42	32	487

D.1 Temperature analysis

In order to find when it is important to cool the camera different temperature thresholds was decided. The data was filtered over these thresholds which were the ambient temperatures of 43.9°C, 38.9°C, 34.9°C and 29.9°C. The average elevation angle was then calculated.

D.1.1 Results

As shown in Table D.2 below one can see that SE and DNI rises with the temperature. When the ambient temperature reaches over 44°C, the sun has an average height of 68°. Worth noting is that the angle is still not close to the highest SE angle of 85°.

Table D.2 Average SE & DNI and number of ocations where this occurred.

T	*SE*	*DNI*	*Points*
T ≥ 30	48	489	43854

T ≥ 35	54	498	27960
T ≥ 39	62	508	11548
T ≥ 44	68	446	243

D.2 Irradiation analysis

The thresholds for the irradiation were set to 600 W/m^2, 700 W/m^2, 800 W/m^2 and 900 W/m^2. The results are shown in Table D.3.

Table D.3 Average SE & temperature and number of occasions where this occurred.

DNI	*SE*	*TEMP*	*Points*
DNI > 600	51	32	24876
DNI > 700	52	31	13046
DNI > 800	52	29	4273
DNI > 900	52	26	667

D.3 Temperature and Irradiation Analysis

In order to find where the high temperature coincide with high irradiation and how that affects the solar angle this data was analyzed.

D.3.1 Results

DNI > 600	*SE*	*Points*
T ≥ 30	59	14348
T ≥ 35	64	9049
T ≥ 39	69	3538
T ≥ 44	77	23

DNI > 700	*SE*	*Points*
T ≥ 30	61	6713
T ≥ 35	66	3880
T ≥ 39	71	1270
T ≥ 44	77	7

DNI > 800	*SE*	*Points*
T ≥ 30	63	1573
T ≥ 35	69	757
T ≥ 39	76	160
T ≥ 44	-	0

DNI > 900	*SE*	*Points*
T ≥ 30	66	111
T ≥ 35	73	23
T ≥ 39	-	0
T ≥ 44	-	0

Appendix E Shading Test

This Appendix presents the approach of the shading test.

E.1 Method

In this chapter the effects of different types of connections and shading are examined by experiments carried out in the solar simulation laboratory at LTH. The laboratory results in this section are conducted using mono-crystalline silicon PV cell modules with a maximum power production of 0.5 W- 1.08 W per module. The light source used to simulate the solar irradiation is a halogen lamp. The distance from the lamp of which the test setup was placed resulted in an incidence irradiance of 900 W/m^2 on the PV cell surface.

Figure E.1 Solar simulation lamp.

The light source in the experiments does not correspond to the same spectral composition as the sun. Hence the measurements are only used for a principal understanding of the behavior of illuminated PV cells and different parameters affecting the power production. It is therefore important to note that the values conducted from the experiments only represents a power output from this specific lamp and these values can only be presented relatively to each other (Davidsson, 2018).

The first part of the experiments included a visualization of the effects on power output at different types of connections. The results describe the differences in power output when using one single module, two modules in series and two modules in parallel.

The different shading types of the modules are visualized in Figure E.2 – Figure E.7. Effects of shading has been examined for two modules connected in series and two modules connected in parallel.

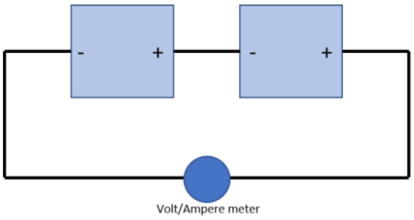


Figure E.2 Two unshaded modules in series.

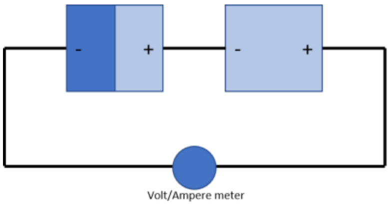


Figure E.3 Two modules in series, one module half shaded

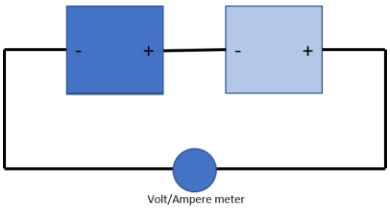


Figure E.4 Two modules in series, one module fully shaded.

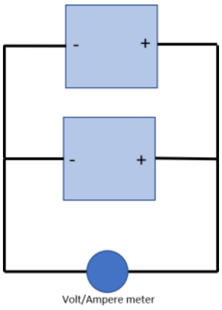


Figure E.5 Two unshaded modules in parallel.

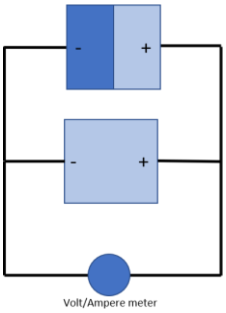


Figure E.6 Two modules in parallel, one module half shaded.

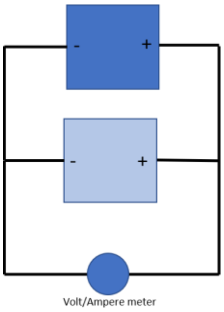


Figure E.7 Two modules in parallel, one module fully shaded.

E.2 Results

When one single module is illuminated it results in an I_{sc} of about 50 mA and a V_{oc} of 6 V, see Figure E.8. When adding a module with series connection, the I_{sc} is unaffected but the V_{oc} is doubled. If the modules are connected in parallel the V_{oc} is the same, but the I_{sc} is doubled, see Figure E.9 and Figure E.10. Which connection solution to choose (series or parallel connection) depends on the requirements of the selected load connected to the system. For example, if connecting a PV cell system to a power grid with a voltage of 230 V it is appropriate to use more series connections between PV cell modules to generate a high voltage.

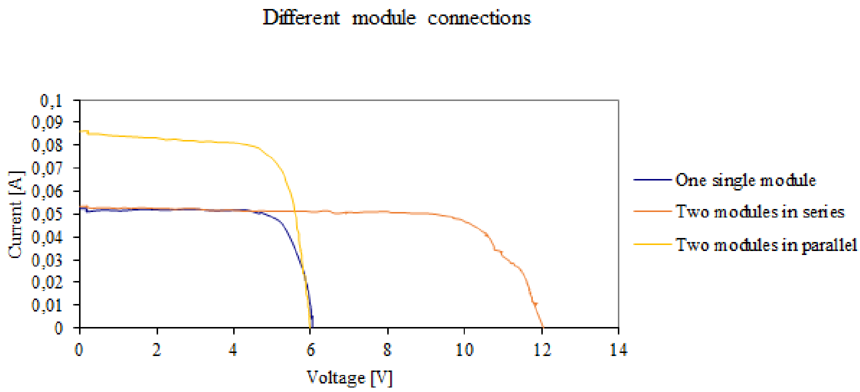


Figure E.8 Example PV cell set-up. Comparison between power output from one single module, two modules connected in series and two modules connected in parallel under direct irradiation and varying resistance.

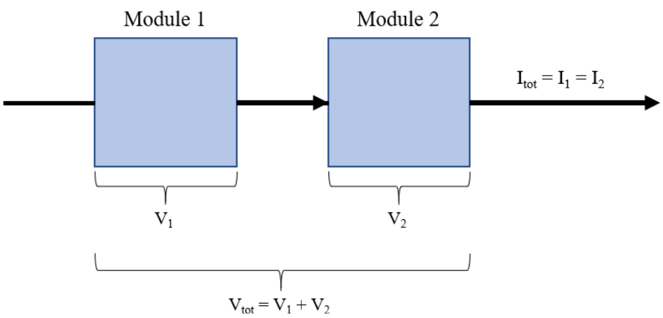


Figure E.9 Two modules connected in series.

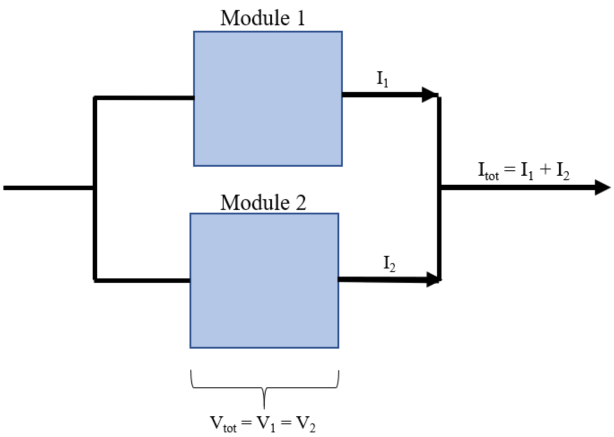


Figure E.10 Two modules connected in parallel.

Figure E.11 demonstrates the difference in power output at different types of shading for a case with two modules connected in series. When the system is not shaded the example, set-up generates a short circuit current of 45 mA and an open circuit voltage of 12 V. When ¼ of the system is shaded for the case with series connection, the I_{sc} is decreased to half of the original value. When one of the modules is completely shaded the output is decreased to nearly zero. The shaded module will limit the whole system due to the series connection.

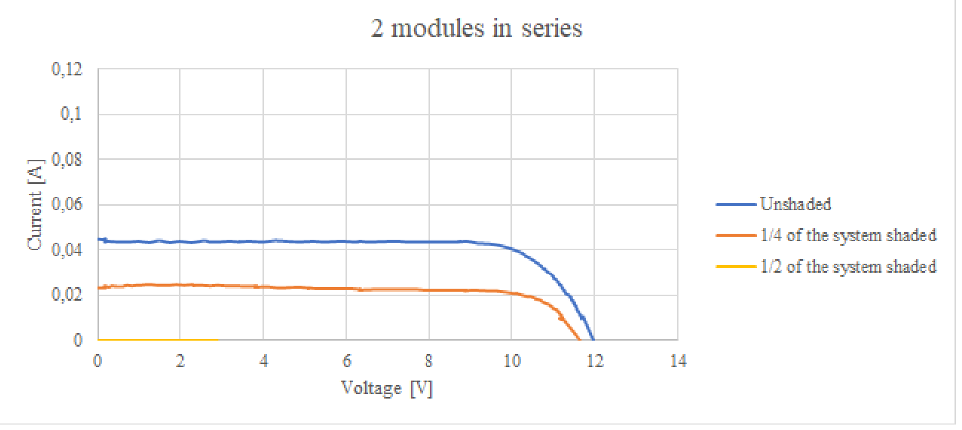


Figure E.11 The difference in power output at different types of shading for two modules connected in series.

The effects of shading will be different when two modules are connected in parallel, as indicated in Figure E.12. The system generates a short circuit current of about 0.1 mA when unshaded and an open circuit voltage of 6 V.

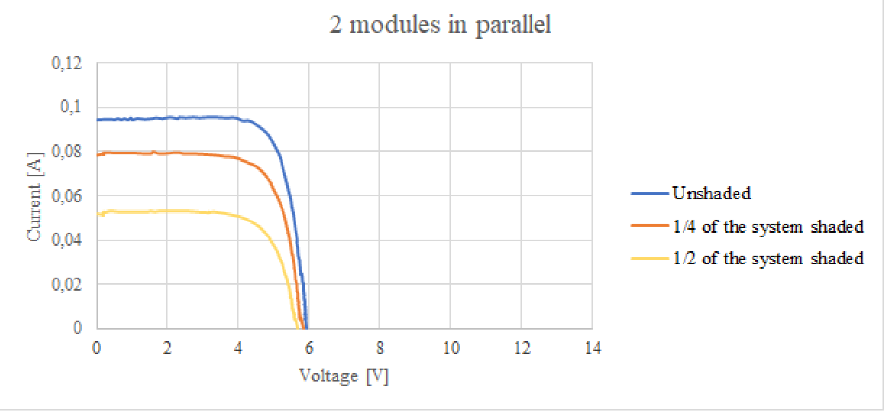


Figure E.12 The difference in power output at different types of shading for two modules connected in parallel.

Compared to the system with series connected modules the voltage now corresponds to 6V, which is what a single module can generate, but the current is twice as high due to the parallel connection. When ¼ of the system is shaded only ¼ of the current output is affected and when ½ of the system is shaded the output is decreased to half of the original value. Consequently, two modules connected in parallel are more resistant to shading compared to a connection in series. However, as the modules are less sensitive to shading, a higher current output is obtained at the expense of a lower voltage output.

Appendix F Table of Interviewees

Appendix F shows a table of the people interviewed in this project.

Table F.1 Interviewees and their area of expertise.

Interviewee	**Function**
Interviewee 1	Mechanical Engineer, Fixed Dome, Axis
Interviewee 2	Engineer, PTZ, Axis
Interviewee 3	Product Introduction Manager, Product Introduction/Management, Axis
Interviewee 4	Engineer, Hardware Test, Axis
Interviewee 5	Engineer, Fixed Dome Electronics, Axis
Interviewee 6	Doctoral Student, Solid State Physics, Lund University
Interviewee 7	Professor, Solid State Physics, Lund University
Interviewee 8	Doctoral Student, Energy Systems, University of Gävle
Interviewee 9	Master Student, Lund University
Interviewee 10	Field Service Engineer, Axis
Interviewee 11	Field Service Engineer, Axis
Interviewee 12	Mechanical Engineer, EVP, Axis
Interviewee 13	Engineer, Fixed Dome Electronics, Axis

Interviewee 14	Engineer, Fixed Dome Electronics, Axis
Interviewee 15	Mechanical Engineer, Fixed Dome, Axis
Interviewee 16	Senior Lecturer, Energy & Building Design, Lund University
Interviewee 17	Product Specialist, Axis
Interviewee 18	Expert, Product Concept New Ideas, Axis
Interviewee 19	Sales Engineer, Axis
Interviewee 20	Sales Manager, Axis
Interviewee 21	Senior Sales Engineer, Axis
Interviewee 22	Engineering Manager, Fixed Dome, Axis

Appendix G Customer Statements

Appendix G shows the customer statements gathered for this project.

Table G.1 Customer statements.

Nr.	Area	**Kundutlåtande**
	Omgivning	
1		Användaren vill placera sin kamera utomhus
2		Där användaren placerar sin kamera är det ibland väldig varmt
3		När användaren får problem med sin kamera är det vid direkt solinstrålning
4		Produkten ska tåla regn
5		Den existerande kepsen ser till att det inte kan ansamlas något vatten
6		Ibland bildas istappar vilket inte är bra
7		Viktigt att damm och fågelbajs inte påverkar produkten
8		Insekter bygger gärna bon i skyddade hålrum, vilket varit problematiskt i tidigare produkter
	Användningsfas	
9		Användarna behöver veta mha sensorer eller liknande när produkten behöver rengöras
10		Det måste vara lätt att rengöra
11		Användarna rengör bara kameran när de ser att bilden blir dålig
12		Produkten ska inte vara så tung så att den lossnar eller blåser av
13		Termoseffekten har skapat stora problem tidigare

14		Kunder kommer inte vilja köpa massa dyra tillbehör
	Estetik	
15		Användaren ska vilja köpa produkten, den får inte vara ful
16		Den ska vara så liten som möjligt och inte vara större än den existerande kepsen
17		Produkten ska inte dra åt sig för mycket uppmärksamhet, vandaler ska inte se den
	Bildkrav	
19		Inga tillbehör får blockera bilden
20		Kameran måste se horisonten
21		Inga tillbehör får störa bilden
	El	
22		Lösningen måste ha solceller
23		Vid remotea intallationer måste solcellerna driva mer än bara kameran, det vill säga även nätverksuppkopplingen
24		Ibland är det varmt under en längre tid på dagen
25		Ibland är det varmt även när solen inte lyser så mycket
26		Man ska inte få elchocker av våra produkter
27		Tillräckligt med el ska kunna genereras för att driva en fläkt
28		Vi har kunder i både Dubai och USA som har överhettningsproblem
29		Vi har kunder i många kalla länder där kamerorna blir för kalla
30		Vi har kunder som förflyttar sig mycket och kan inte dra kablar till alla platser
31		Det kan vara bra att ha ett komplement till Ethernet.
32		Vandaler klipper ibland av kablarna
33		PoE räcker inte till för att driva extra utrustning
34		Man vill minimera strömåtgången från PoE
	Installation	

35		Vi vill inte ha för mycket sladdar som gör det jobbigt för kunden att installera
36		Kamerorna med överhettningsproblem sitter oftast på väggar
37		Installatörerna vill slippa krångel vid installationen
38		Det finns många produkter med överhettningsproblem
	Specifikt för P32	
39		Lösningen ska först och främst vara till P32
40		Borde klara samma IK-klass som P32
41		Borde klara samma IP-klass som P32
	Övriga behov	
43		Det får inte bli för dyrt
44		Kamerorna är för varma
45		Kamerorna sitter på olika väggar men det är när de utsätts för direkt solljus som de överhettas
46		Vinkel mellan punkten längst ut på kepsen och tangenten från domen ska vara maximalt 52 grader
47		Solljus är dåligt för kamerabilden
48		Om domen har vattendroppar på sig blir bilden dålig
49		Det värsta scenariot är när vatten rinner längs med domen

Appendix H Customer Needs, Hieratically Organized

Table H.1 Hieratically organized customer needs.

Nr	*Rang*	*Hierarkiskt rangordnade behov*
1	1	Produkten kan placeras utomhus
2	2	Produkten tål vatten
3	3	Produkten har samma IP-klass som P32
4	2	Produkten möjliggör vattenavrinning
5	3	Produkten försvårar droppbildning
6	2	Det är svårt att klippa/vandalisera produktenssladdar
7	3	Produkten har samma IK-klass som P32
8	2	Produkten klarar långa perioder utan rengöring
9	3	Produkten är lätt att rengöra
10	4	Produkten meddelar när rengöring är nödvändigt
11	3	Produkten är utformad så att dammansamlingar minimeras
12	3	Produktens hålrum är obeboeliga
13	3	Produkten är ovänlig mot fåglar
14	2	Produkten hjälper kameran att fungera även vid direkt solinstrålning
15	3	Reflektioner av ljus in i kameran minimeras så mycket som möjligt
16	1	Produkten fungerar vid höga temperaturer
17	1	Produkten är placerad så att den inte stör bilden
18	2	Produkten tillåter kameran att se horisonten
19	1	Produktionskostnaderna är låga
20	2	Produktkostnaden är låg
21	1	Produkten är enkel att installera
22	2	Produkten har få sladdar
23	2	Produkten trillar inte ned

24	2	Produkten kan placeras på en vägg
25	1	Produkten är säker att använda
26	1	Produkten värmer inte kameran ytterligare
27	2	Produkten utformas så att termoseffekten inte ökar
28	1	Produkten innehåller solceller
29	2	Produkten fungerar även då den är delvis skuggad
30	2	Produkten fungerar vid direkt solinstrålning
31	2	Produkten fungerar även vid låg solinstrålning
32	1	Produkten minskar risken för att belasta PoE ytterligare
33	2	Produkten behöver inga sladdar från en stationär strömkälla
34	1	Produkten driver extrautrustning
35	2	Produkten kan driva en fläkt
36	3	Produkten säkerställer kamerans funktion utan Ethernet
37	4	Produkten kan driva en kamera och även ha energi över till annat
38	2	Produkten är kompatibel med P32
39	3	Produkten är kompatibel med många kameror
40	1	Produkten fungerar på olika geografiska platser
41	1	Produkten är estetiskt tilltalande för användaren
42	2	Produkten är liten
43	2	Produkten är diskret

Appendix I Need-Specification Matrix

Table I.1 Need-Specification Matrix

		Produkten klara IP-klass X	skarvar) är alltid vinklad mer än 0 grader mot marken	Produkten har inga perifer kanter trubbigare än 50 grader	Produkten har 0 skarvar i periferikanten	Produkten har IK-klass X	Produkten klarar 2 gånger effektbehovet vid helt ren	produkten	Produkten sänder ut en signal när effektförlusten är större än 50%	Springor får ej vara mellan 3-10mm	Produkten generar minst 1 W per modul	kameran	Produkten ska vid 80C ha en verkningsgrad på minst 15%	kameranssynfält	Totala komponentkostnaderna är max 2000 Sek	installera	Produkten har max 1 sladd till det energikrävande sysytemet	Produkten väger max 1kg	Produkten är välmonterad	Användaden kan vidfelanvändning max få X Volts stöt??	Produkten värmer upp kameran 10 (???) C mindre än vid direkt solljus	Produkten har antingen inte mer än 0mm luft mellan sig och kamerachassit eller mer än 100 mm, dvs värmer inte upp kameran mer än kepsen gör idag	Produkten innehåller minst 1 solcell	Produkten kan generera minsta effektbehov vid 50% skuggning	Produkten klarar 2 gånger effektbehovet vid 1000 W/m2 solstrålning vid 25 C	Produkten genererar 9 W	Produkten genererar mer än 9 W	kontaktstandarder som axis (?) Vilka är detta?	Produkten laddar ett energilagringssytem (ex batteri) som kan generera 9W under minst 12 h	Solcellerna kan vinklas mellan 1 till (-)90 grader från marken	Produkten är estetiskt tilltalande för användaren	Får max sticka ut; bredd: 200 mm från kamerns centrum, höjd: 300mm, från vägg: 300mm	Produkten är diskret
1	Produkten kan placeras utomhus	x	x	x	x	x	x	x	x	x	x	x																					
2	Produkten tål vatten	x																															
3	Produkten har samma IP-klass som P32	x																															
4	Produkten möjligör vattenavrinning		x																														
5	Produkten försvårar droppsbildning			x	x																												
6	Det är svårt att klippa/vandalisera produktenssladdar																																
7	Produkten har samma IK-klass som P32					x																											
8	Produkten klarar långa perioder utan rengöring						x																										
9	Produkten är lätt att rengöra							x																									
10	Produkten meddelar när regöming är nödvändigt								x																								
11	Produkten är utformad så att dammansamlingar minimeras		x							x																							
12	Produktens hålrum är obeboeliga																																
13	Produkten är ovänlig mot fåglar		x																														
14	Produkten hjälper kameran att fungera även vid direkt solinstrålning										x																						
15	Reflektioner av ljus in i kameran minimeras så mycket som möjligt											x																					
16	Produkten fungerar vid höga temperaturer												x																				
17	Produkten är placerad så att den inte stör bilden													x																			
18	Produkten tillåter kameran att se horisonten													x																			
19	Produktionskostnaderna är låga														x																		
20	Produktkostnaden är låg														x																		
21	Produkten är enkel att installera															x	x	x															
22	Produkten har få sladdar																x																
23	Produkten trillar inte ned																	x															
24	Produkten kan placeras på en vägg																		x														
25	Produkten är säker att använda																			x													
26	Produkten värmer inte kameran ytterligare																				x	x											
27	Produkten utformas så att termoseffekten inte ökar																					x											
28	Produkten innehåller solceller																						x										
29	Produkten fungerar även då den är delvis skuggad																							x									
30	Produkten fungerar vid direkt solistrålning																																
31	Produkten fungerar även vid låg solinstrålning																								x								
32	Produkten minskar risken för att belasta PoE ytterligare										x																						
33	Produkten behöver inga sladdar från en stationär strömkälla										x																						
34	Produkten driver extrautrustning										x																						
35	Produkten kan driva en fläkt										x																						
36	Produkten säkerställer kamerans funktion utan Ethernet																									x			x				
37	Produkten kan driva en kamera och även ha energi över till annat																										x		x				
38	Produkten är kompatibel med P32																											x					
39	Produkten är kompatibel med många kameror																											x					
40	Produkten fungerar på olika geografiska platser																													x			
41	Produkten är estetiskt tilltalande för användaren																														x		
42	Produkten är liten																															x	
43	Produkten är diskret																																x

Appendix J All generated concepts

This appendix shows the concepts generated during the concept generation.

Concept A

Concept A contains one solar cell module placed over the dome, with an angle adjusted to the solar irradiation. See Figure J.1.

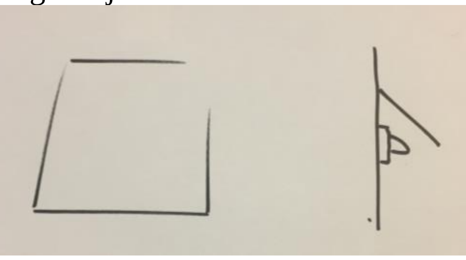


Figure J.1

Concept B

Concept B contains of one tilted solar cell module placed in front of the dome and has one tilted area towards the wall. The edges are bent to ease runoff. See Figure J.2.

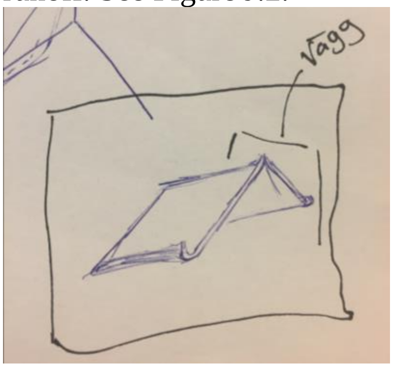


Figure J.2

Concept C

Concept C contains two solar cell modules tilted towards the solar irradiation during two time periods of the day. The edges are bent to ease runoff, see Figure J.3.

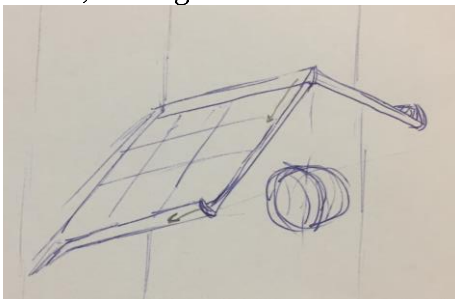


Figure J.3

Concept D

Concept D contains three solar cell modules, all tilted towards the sun at different positions. The product as whole is also tilted away from the wall, see Figure J.4.

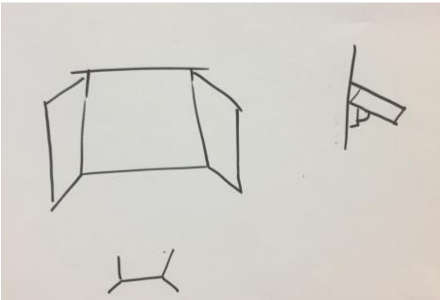


Figure J.4

Concept E

Concept E contains four solar cell modules connected to each other. The three modules on the sides are tilted and the top module is slightly tilted and almost perpendicular to the wall, see Figure J.5.

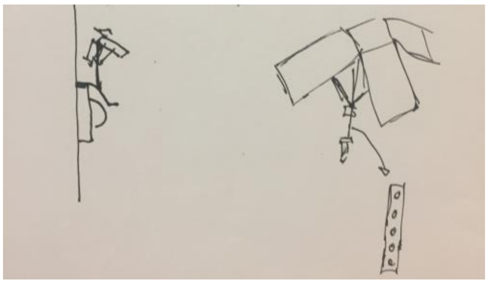


Figure J.5

Concept F

Concept F has a bendable solar module along the dome, with no space between the dome and the product, see Figure J.6.

Figure J.6

Concept G

Concept G contains bendable solar modules, which are tilted and shaped cylindrical over the dome, see Figure J.7.

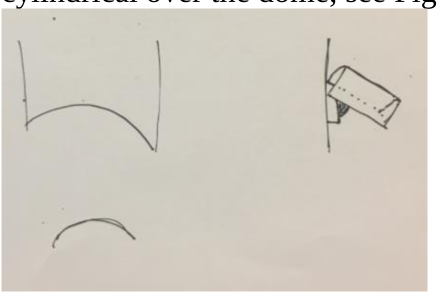


Figure J.7

Concept H

Concept H contains eight differently tilted solar modules. The areas between the cells are formed to ease water/dust runoff, see Figure J.8.

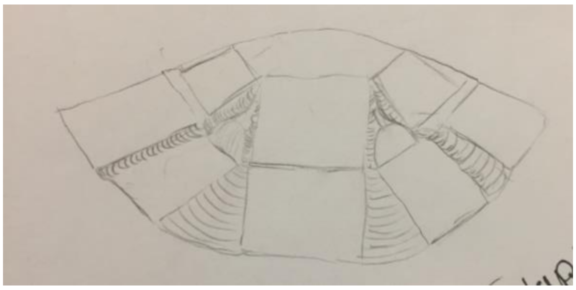


Figure J.8

Concept I

Concept I contain four solar modules. The top module is not tilted and the three modules on the sides are equally tilted towards the sun at different time periods. The area between the modules are formed to ease runoff, with shapes of the edges similar to the existing solar cap, see Figure J.9.

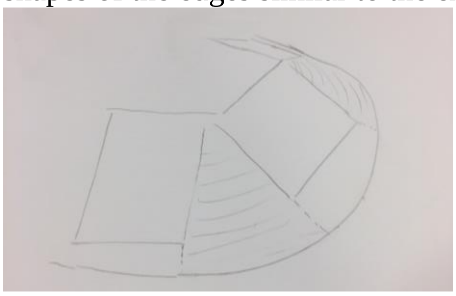


Figure J.9

Concept J

Concept J has four sides where solar modules of different sizes can be placed. The three sides are tilted, and the area at the top is not tilted. The two areas on the side are not rectangular, however, the solar cells placed on the sides are, see Figure J.10.

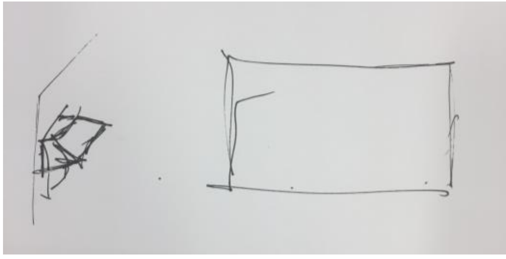


Figure J.10

Concept K

Concept K has four rectangular and tilted solar modules, which together also are tilted from the wall, see Figure J.11.

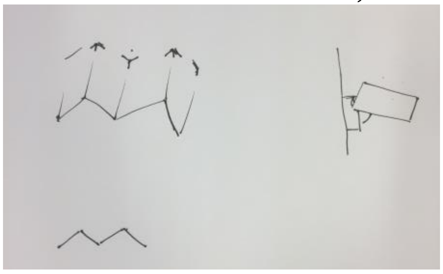


Figure J.11

Concept L

Concept L contains several small solar modules with equal quadratic forms, placed tilted and closely together. The edge is formed and bent to ease runoff, see Figure J.12.

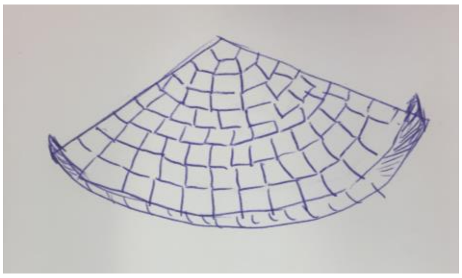


Figure J.12

Concept M

Concept M has one solar module with no tilt, perpendicular to the wall. The module is placed above the dome, see Figure J.13.

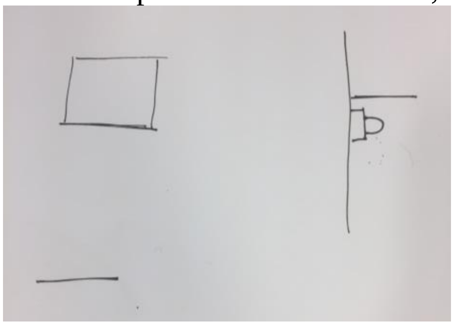


Figure J.13

Concept N

Concept N has two solar modules angled towards each other and placed over the dome, see Figure J.14.

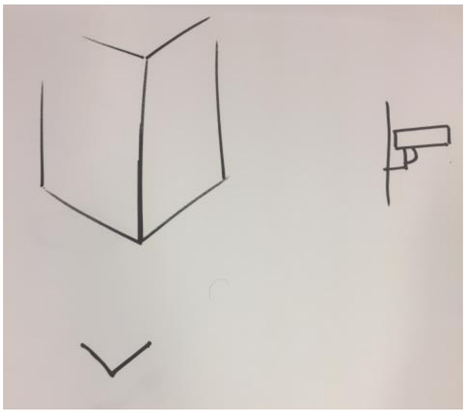


Figure J.14

Concept O

Concept O has a parabolic shape, attached to a surface over the dome. The parabolic shape contains flexible solar modules tilted towards the sun, see Figure J.15.

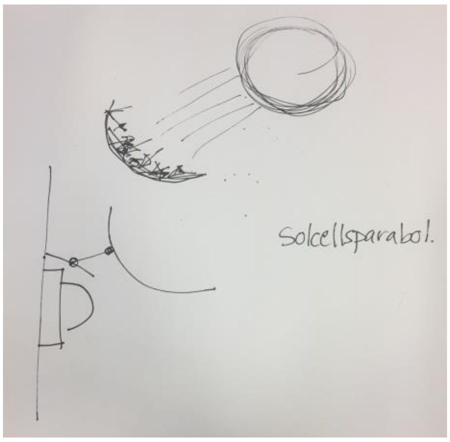


Figure J.15

Concept P

Concept P has five rectangular solar modules above the dome. The rectangular areas are tilted downwards and towards the center. The size of the rectangles can vary, see Figure J.16.

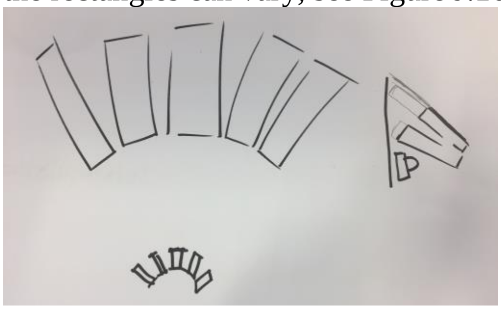


Figure J.16

Concept Q

Concept Q contains of six or more tilted solar modules, with triangular shapes and rounded edges towards the front of the dome. The edges are formed to ease runoff. The product is placed closely to the dome, to minimize the air volume between the product and the dome, see Figure J.17.

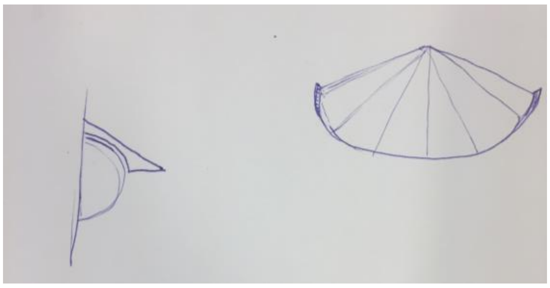


Figure J.17

Concept R

Concept R has four solar modules tilted towards each other and towards the sun, see Figure J.18.

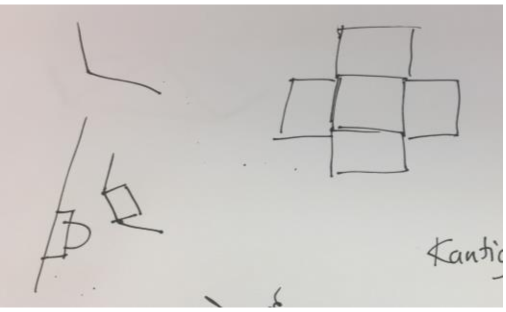


Figure J.18

Concept S

Concept S has three tilted and triangular shaped solar modules over the dome. The edges are formed to ease runoff, see Figure J.19.

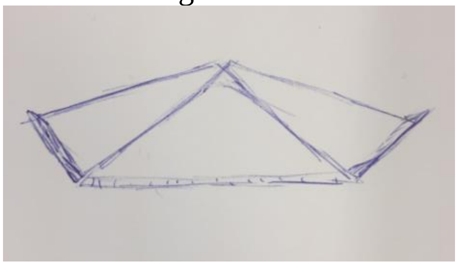


Figure J.191

Concept T

Concept T has a flexible solar module bent over the dome in a cylindrical shape, attached to the chassis, see Figure J.20.

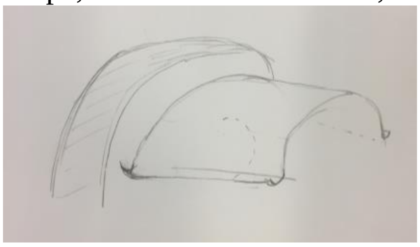


Figure J.20

Concept U

Concept U contains of several solar modules in different sizes, facing the sun at different time periods. Smaller rectangular solar modules are placed on the sides where the shape of the product is triangular, see Figure J.21.

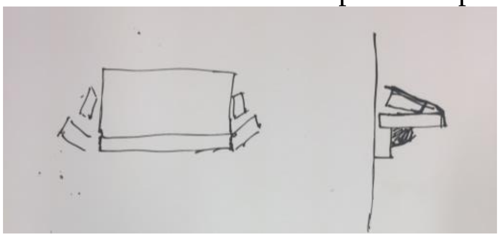


Figure J.21

Concept V

Concept V has five solar modules in different rectangular sizes. All modules are tilted towards the solar irradiation since the product is tilted downwards over the dome, see Figure J.22.

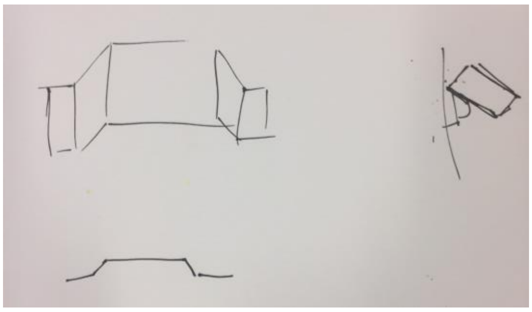


Figure J.22

Concept X

Concept X has one solar panel which is mounted on the existing cap. The panel is to be angled in the correct direction by the installation staff, see Figure J.23.

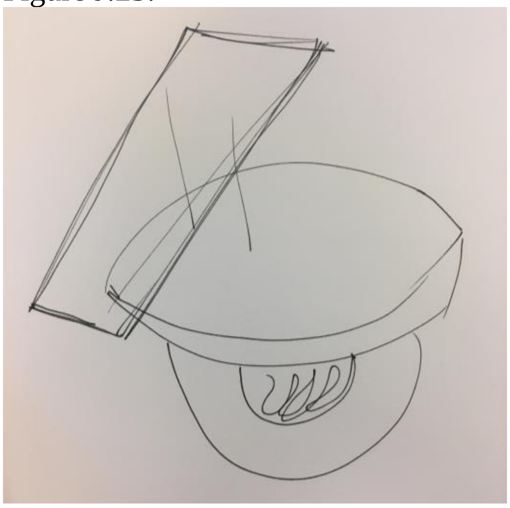


Figure J.23

Appendix K Concept Screening Matrix

Table K.1 Concept Screening Matrix

Urvalskriterier		Referens	A	B	C	D	E	F	G	H	I
Minimal skuggning		0	1	-1	1	1	1	0	0	1	1
Mellan 1-10 solcellsmoduler		-1	0	0	0	1	1	1	1	1	1
Maximering av solcellsarea (celler är fyrkantiga)		-1	1	1	1	1	0	0	0	1	0
Produkten är alltid vinklad mer än 0 grader mot marken		0	1	1	1	1	1	1	1	1	1
Genererar effekt även vid delvis skuggad		-1	1	1	1	1	1	1	-1	1	1
Försvårar droppbildning framför kameran		1	-1	-1	1	-1	1	-1	-1	1	1
Lika stor solcellsarea på alla **sidor**		-1	-1	-1	0	0	1	0	1	1	1
Skyddar kameran från solinstrålning		1	-1	-1	0	1	1	-1	1	1	1
Antal +		2	4	3	5	6	7	3	4	7	7
Antal 0		2	1	1	3	1	1	3	2	1	1
Antal -		4	3	4	0	1	0	2	2	0	0
Slutbetyg		-2	1	-1	5	5	7	1	2	8	7
Rangordning		9	6	8	3	3	1	7	6	1	1
	Ta vidare?						Kombinera med I			JA	Kombinera med E

Urvalskriterier		Referens	J	K	L	M	N	O	P	Q	R	S	T	U	V
			Koncept												
Minimal skuggning		0	1	-1	1	0	-1	-1	1	1	-1	1	0	1	0
Mellan 1-10 solcellsmoduler		-1	1	1	-1	0	0	0	1	0	1	1	1	0	1
Maximering av solcellsarea (celler är fyrkantiga)		-1	0	1	1	1	1	-1	0	-1	0	-1	0	1	1
Produkten är alltid vinklad mer än 0 grader mot marken		0	-1	1	1	-1	1	-1	1	1	1	1	-1	1	1
Genererar effekt även vid delvis skuggad		-1	1	1	1	1	1	0	1	1	1	1	-1	1	1
Försvårar droppbildning framför kameran		1	1	-1	1	-1	-1	-1	1	1	-1	1	1	1	-1
Lika stor solcellsarea på alla **sidor**		-1	-1	1	1	-1	0	-1	1	1	0	1	0	0	0
Skyddar kameran från solinstrålning		1	1	1	1	-1	-1	-1	1	1	-1	1	0	1	1
Antal +		2	5	6	7	2	3	0	7	6	3	7	2	6	5
Antal 0		2	1	0	0	2	2	2	1	1	2	0	4	2	2
Antal -		4	2	2	1	4	3	6	0	1	3	1	2	0	1
Slutbetyg		-2	3	4	6	-2	0	-6	7	5	0	6	0	6	4
Rangordning		9	5	4	2	9	8	10	1	3	7	2	8	2	4
	Ta vidare?								JA						

Appendix L Test Reports from Prototype Test

This Appendix presents the test reports from the prototype test.

L.1 Existing Cap

L.1.1 Test 1

Temperatures report for P3225-VE Mk II

Generated by Temperatures 1.9.1
Model name: P3225-VE Mk II
Firmware version: CVP-18.50.2

2018-12-17 18:59:50 CET (+0100)
MAC address: ac-cc-8e-73-ea-e6
IP address: 192.168.0.90

Logger PT1000-1 at COM8 has program version 1.0.8

First measurement was done at 2018-12-17 15:46:28 CET (+0100)

with fan pv cells on

Sensor	Last value	Min value	Max value
PCB	54.0	27.2	54.0
Heater	52.66	21.6	52.66
Image Sensor	61.33	30.66	61.33
S1	51.91	25.68	51.91
S2	52.88	21.6	52.88
S3	48.38	21.47	48.39
S4	43.82	20.84	43.89
S5	34.66	20.02	36.85
S6	51.25	21.24	54.36
S7	59.55	20.61	60.24
S8	63.52	20.79	64.58
Ambient	24.22	19.81	24.22

2018-12-17 18:59:50+0100 PyTools report for ac-cc-8e-73-ea-e6 at 192.168.0.90 Page 1 of 2

Figure L.1 Measurements from Test 1.

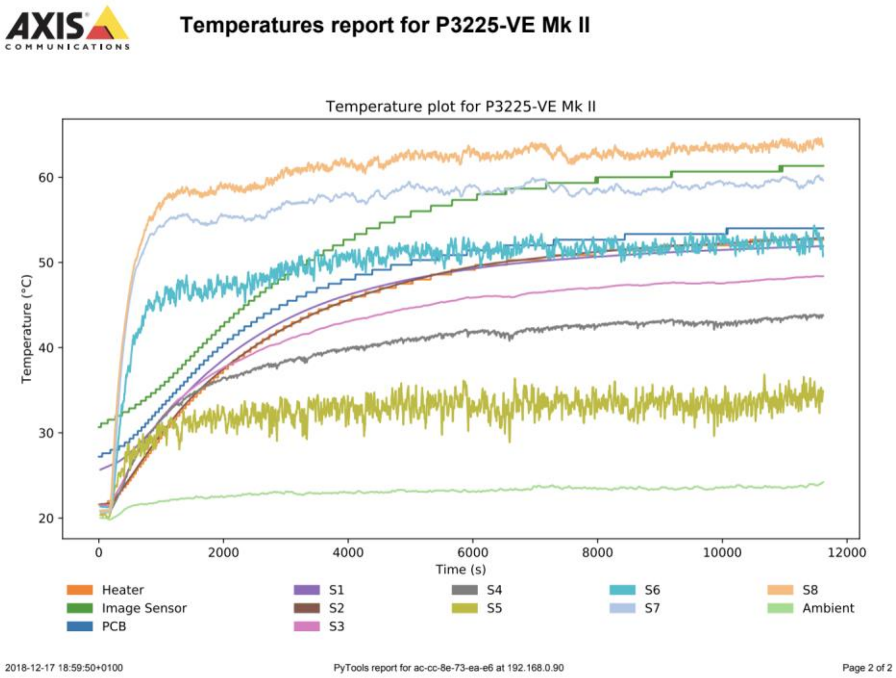


Figure L.2 Measurements from Test 1.

L.1.2 Test 2

Temperatures report for P3225-VE Mk II

Generated by Temperatures 1.9.1
Model name: P3225-VE Mk II
Firmware version: CVP-18.50.2

2018-12-18 11:39:40 CET (+0100)
MAC address: ac-cc-8e-73-ea-e6
IP address: 192.168.0.90

Logger PT1000-1 at COM8 has program version 1.0.8

First measurement was done at 2018-12-18 09:00:08 CET (+0100)

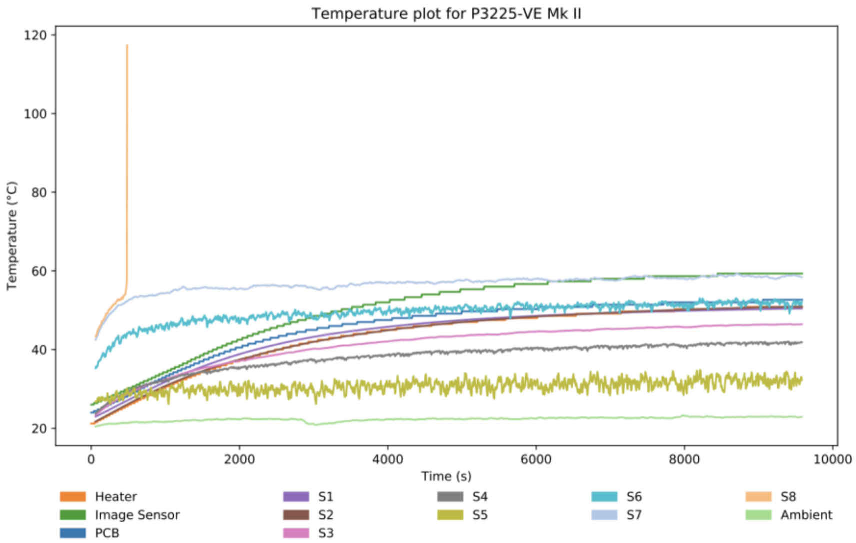
No fans, pv cells on

Sensor	Last value	Min value	Max value
PCB	52.66	24.0	52.66
Heater	50.85	21.2	50.85
Image Sensor	59.33	26.0	59.33
S1	50.45	22.98	50.45
S2	50.93	21.72	50.93
S3	46.44	23.44	46.48
S4	41.87	23.79	42.04
S5	32.24	26.13	34.84
S6	52.02	35.28	53.04
S7	58.39	42.53	59.28
S8	not connected	43.4	117.36
Ambient	22.92	20.46	23.28

2018-12-18 11:39:40+0100 PyTools report for ac-cc-8e-73-ea-e6 at 192.168.0.90 Page 1 of 2

Figure L.3 Measurements from Test 2.

Temperatures report for P3225-VE Mk II



2018-12-18 11:39:40+0100 PyTools report for ac-cc-8e-73-ea-e6 at 192.168.0.90 Page 2 of 2

Figure L.4 Measurements from Test 2.

L.1.3 Test 3

AXIS COMMUNICATIONS

Temperatures report for P3225-VE Mk II

Generated by Temperatures 1.9.1
Model name: P3225-VE Mk II
Firmware version: CVP-18.50.2

2018-12-18 15:54:11 CET (+0100)
MAC address: ac-cc-8e-73-ea-e6
IP address: 192.168.0.90

Logger PT1000-1 at COM8 has program version 1.0.8

First measurement was done at 2018-12-18 12:57:40 CET (+0100)

No fan, no pv cells

Sensor	Last value	Min value	Max value
PCB	53.33	28.44	53.33
Heater	51.42	27.2	51.42
Image Sensor	60.66	31.55	60.66
S1	51.33	27.2	51.34
S2	51.69	27.34	51.69
S3	47.17	25.41	47.32
S4	42.6	23.66	43.05
S5	34.15	20.97	36.64
S6	51.36	23.85	54.04
S7	59.12	22.32	59.94
S8	not connected	22.44	76.29
Ambient	24.09	20.68	24.68

2018-12-18 15:54:11+0100 PyTools report for ac-cc-8e-73-ea-e6 at 192.168.0.90 Page 1 of 2

Figure L.5 Measurements from Test 3.

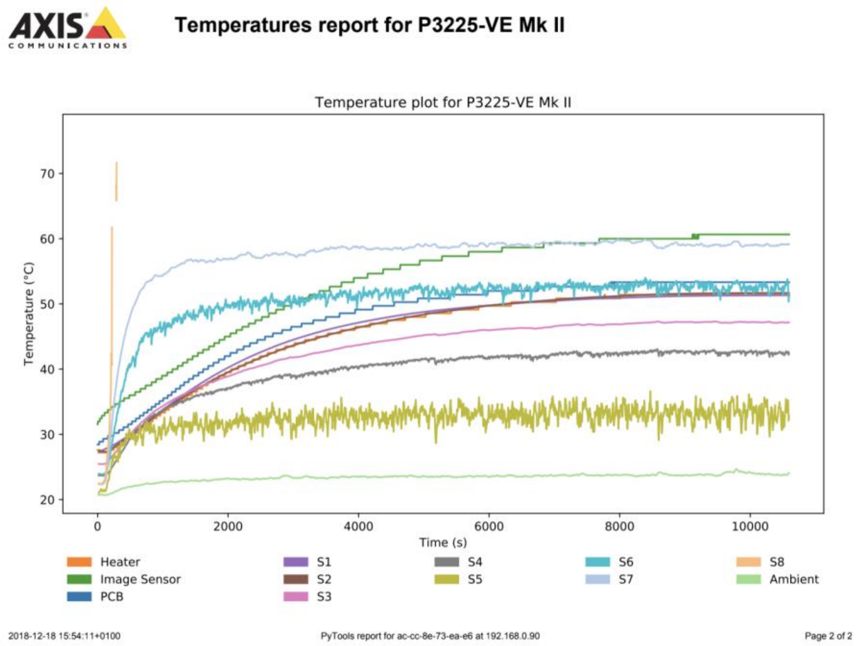


Figure L.6 Measurements from Test 3.

L.2 Prototype

L.2.1 Test 1

AXIS COMMUNICATIONS **Temperatures report for P3225-VE Mk II**

Generated by Temperatures 1.9.1
Model name: P3225-VE Mk II
Firmware version: CVP-18.50.2

2018-12-17 18:59:43 CET (+0100)
MAC address: ac-cc-8e-73-ea-57
IP address: 192.168.0.90

Logger PT1000-1 at COM4 has program version 1.0.8

First measurement was done at 2018-12-17 15:46:29 CET (+0100)

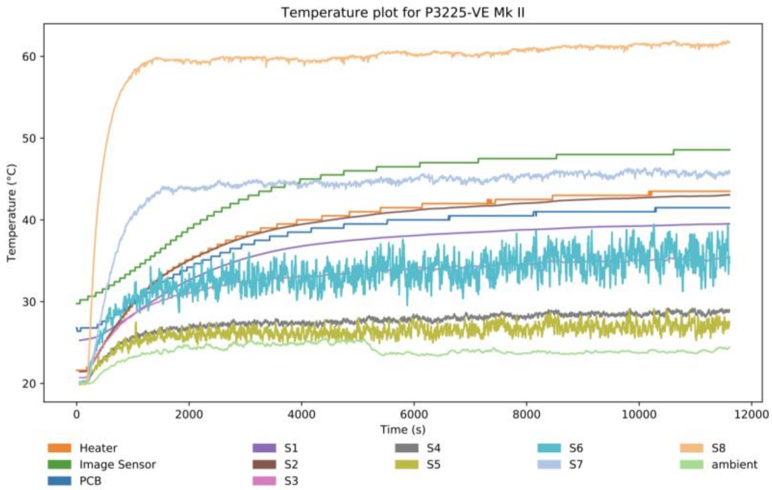
With fan & PV cells ON

Sensor	Last value	Min value	Max value
PCB	41.5	26.39	41.5
Heater	43.5	21.6	43.5
Image Sensor	48.57	29.77	48.57
S1	39.53	25.27	39.53
S2	43.07	21.44	43.07
S3	35.39	20.69	35.43
S4	28.92	19.99	29.2
S5	27.21	19.84	29.15
S6	36.03	20.15	39.46
S7	45.71	20.03	46.36
S8	61.59	19.96	61.88
ambient	24.41	19.96	25.58

2018-12-17 18:59:43+0100 PyTools report for ac-cc-8e-73-ea-57 at 192.168.0.90 Page 1 of 2

Figure L.7 Measurements from Test 1.

Temperatures report for P3225-VE Mk II



2018-12-17 18:59:43+0100 PyTools report for ac-cc-8e-73-ea-57 at 192.168.0.90 Page 2 of 2

Figure L.8 Measurements from Test 1.

L.2.2 Test 2

Temperatures report for P3225-VE Mk II

Generated by Temperatures 1.9.1
Model name: P3225-VE Mk II
Firmware version: CVP-18.50.2

2018-12-18 11:39:45 CET (+0100)
MAC address: ac-cc-8e-73-ea-57
IP address: 192.168.0.90

Logger PT1000-1 at COM4 has program version 1.0.8

First measurement was done at 2018-12-18 09:00:18 CET (+0100)

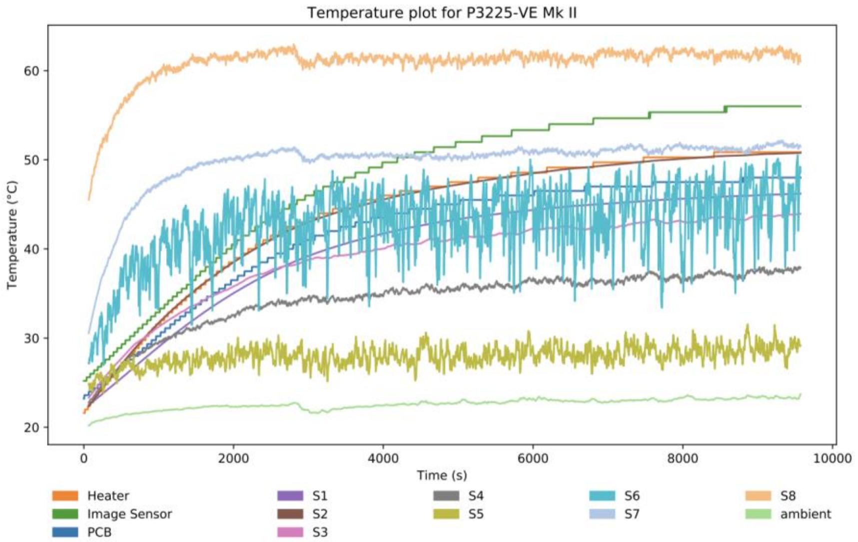
No fans, PV cells ON

Sensor	Last value	Min value	Max value
PCB	48.0	23.2	48.0
Heater	50.85	21.6	50.85
Image Sensor	56.0	25.2	56.0
S1	46.21	22.53	46.21
S2	50.78	22.35	50.78
S3	43.96	23.31	43.96
S4	38.03	22.79	38.03
S5	29.53	23.86	31.55
S6	48.92	26.98	50.52
S7	51.61	30.55	52.18
S8	61.43	45.51	62.95
ambient	23.79	20.19	23.79

2018-12-18 11:39:45+0100 PyTools report for ac-cc-8e-73-ea-57 at 192.168.0.90 Page 1 of 2

Figure L.9 Measurements from Test 2.

Temperatures report for P3225-VE Mk II



2018-12-18 11:39:45+0100 PyTools report for ac-cc-8e-73-ea-57 at 192.168.0.90 Page 2 of 2

Figure L.10 Measurements from Test 2.

L.2.3 Test 3

Temperatures report

Generated by Temperatures 1.9.1 | 2018-12-18 15:54:17 CET (+0100)
Model name: | MAC address: ac-cc-8e-73-ea-57
Firmware version: | IP address: 192.168.0.90

Logger PT1000-1 at COM4 has program version 1.0.8

First measurement was done at 2018-12-18 12:57:16 CET (+0100)

No fan, no pv

Sensor	Last value	Min value	Max value
PCB	48.0	27.6	48.0
Heater	51.42	26.79	51.42
Image Sensor	56.66	29.77	56.66
S1	46.2	26.92	46.2
S2	51.14	26.71	51.14
S3	44.33	24.54	44.61
S4	38.1	22.85	39.11
S5	29.22	20.56	32.49
S6	48.03	23.15	51.9
S7	51.64	21.79	52.53
S8	61.48	21.39	63.27
ambient	24.59	20.63	25.37

2018-12-18 15:54:17+0100 PyTools report for ac-cc-8e-73-ea-57 at 192.168.0.90 Page 1 of 2

Figure L.11 Measurements from Test 3.

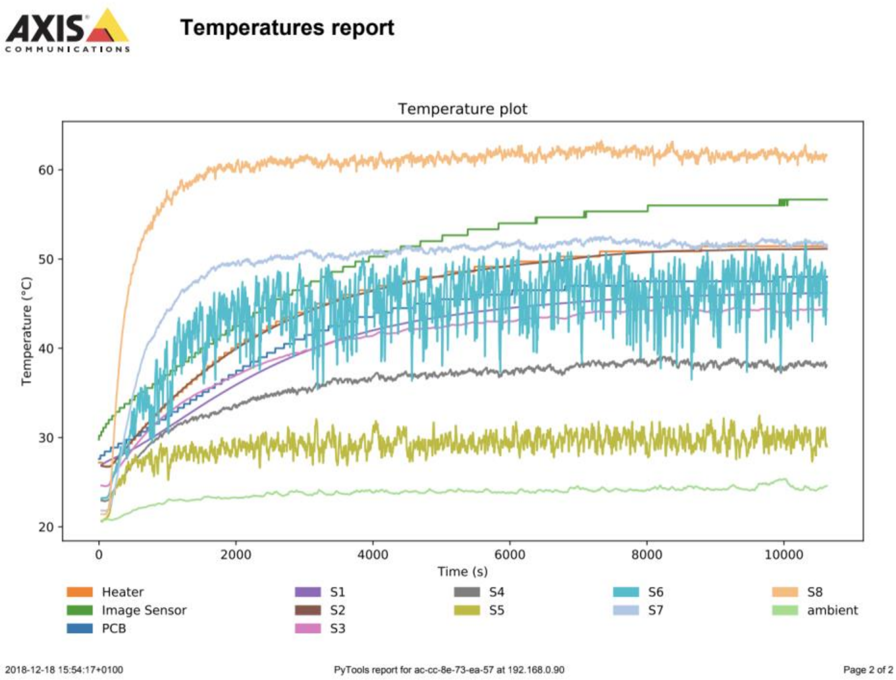


Figure L.12 Measurements from Test 3.

Appendix M Power Output at worst case

Appendix M presents the calculation of the power output at worst case scenario conditions in Dubai.

From the weather data analysis, it can be shown that the worst-case scenario is when the temperature is 44 °C, the DNI is 700 W/m^2 and the elevation angle is 77°. The following calculation estimates the power output of the prototype under the worst-case scenario conditions.

$S = DNI * \sin(\alpha + \beta)$ [W/m^2] (Equation 1)

$P = S * \eta * (1 + T_{coeff}(T_m - T_{standard}))$ (Equation 2)

Where,

S = The perpendicular irradiation on a solar module surface. If the term $\alpha + \beta$ is zero, the surface is directly facing the sun. [W/m^2]

DNI = Direct normal irradiance [W/m^2]

α = Elevation angle [degrees]

β = The tilt of the solar module surface [W/m^2]

η = The solar cell efficiency [22 %]

T_{coeff} = The temperature coefficient, estimated to -0.4%/°C according to (PV Temperature Coefficient of Power, n. d.).

T_m = The solar module temperature [72 °C]

$T_{standard}$ = Standard testing temperature [25 °C]

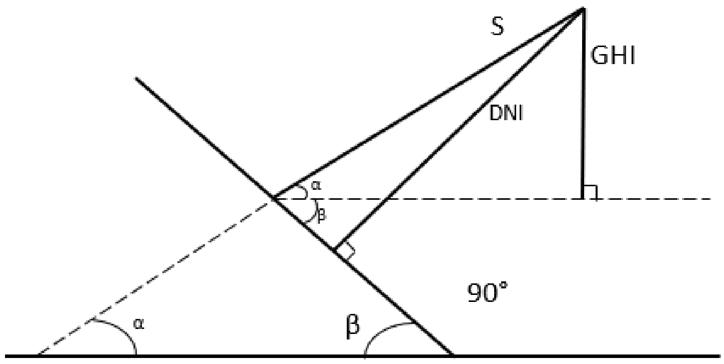


Figure M.1 Solar angles.

The top plate of the prototype has an angle of 10° from the horizontal plane. The perpendicular irradiation on this surface is calculated according to equation X to 699.04 W/m^2. According to equation Y this resulted in a power output of 124.88 W/m^2. The chosen PV modules are not fully covered by PV cells. The PV cell area per module was approximated to 0.0049 m^2. By multiplying the area with the power output per square meter, the power output expressed in watts was calculated to 0.612 W.
Since the two side plates of the prototype and the top plate are equally tilted from the wall by 100° (10° from the horizontal plane), these are assumed to receive an equal irradiation. This means that these three solar modules together produce $0.612 \cdot 3 = 1.836$ W.
The front plate is tilted 30° from the horizontal. According to equation 1 the perpendicular irradiation on this surface is 669.4 W/m^2. The power output is calculated according to equation 2 to 119.58 W/m^2 and expressed in watts, 0.586 W.
Adding the power output from the four PV modules, the total power output of the prototype under the worst-case scenario conditions is 2.42 W.