A PHOTOVOLTAIC SYSTEM PERFORMANCE EVALUATION SOFTWARE

For evaluation of ten unique PV-system configurations in the middle of Sweden

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ABSTRACT

This thesis contains the development of a software capable of evaluating the performance of ten unique photovoltaic (PV) systems located 10 kilometers outside of Västerås, Sweden. The ten systems have different configurations according to this list:

1. Dual-axis tracking
2. Single-axis tracking with 30° tilt
3. Ground mounted, free-standing with 19° tilt
4. Ground mounted, free-standing with 41° tilt
5. Roof mounted with 19° tilt

Each of the above configurations exist with and without installed power optimizers adding up to a total of ten unique systems.

The development goal for the evaluation software is to provide the user with a variety of tools to determine which of the systems that has the best yield and performance. Integrated in the development of the software is therefore a literature study where it is investigate how photovoltaic systems operate and especially how their performance can be evaluated. Some of the frequently used parameters are; system yield, reference yield and performance ratio.

The software features are focused around presenting the data collected from the PV systems in a variety of graphs. The different types of graph are designed to let the user easy compare the data between the systems and thus find how and why a particular system is performing better than the others. The software is developed in a Matlab environment and has an intuitive user interface.

The thesis time-frame is too short for any conclusive result to be presented, but to showcase the software features a short-termed evaluation of the systems have been performed. The period evaluated is a three week period in the middle of May 2014. The short-termed evaluation highlights several scenarios and issues that can arise. It has been detected throughout the project that it is difficult to separate which effects that causes one system to be better than the other. Irregularities seen in the data can be caused by many factors. Some of the more evident are; installed power optimizers, differences in system configurations and shadow patterns. By using the software effects like array shading and inaccurate measurements has been discovered.

Keywords: yield, performance, comparison, electricity, production, array shading, software, user-interface.

Nyckelord: utbyte, prestanda, jämförelse, elektrisitet, produktion, modul skuggning, mjukvara, användargränssnitt.
PREFACE

This work is conducted within the master science program in sustainable energy systems at Mälardalen University. It contains the result of a development of an evaluation tool created with the purpose to handle and presenting the data collected from ten research PV systems located with the newly build 1 MW PV park outside of Västerås.

This thesis has been carried out with Bengt Stridh from ABB corporate research as the supervisor and with Eva Thorin as the examiner.

I would like to thank Bengt Stridh and Eva Thorin for the guidance and ongoing discussion that has been most helpful in the completion of both the software and the report. I would also like to thank and the guys over at Kraftpojkarna AB for the interesting days that I have spent in the PV park.

Västerås, June 2014

Alexander Sandberg
SUMMARY

Sweden is experiencing an upswing in the interest of photovoltaic systems and with it the interest of constructing them to generate electricity as efficient as possible and give a high yield. To determine the most favorable way of constructing PV system in Sweden a project conducted in collaboration with Mälardalen University, the Swedish Energy Agency, Mälarenergi AB, ABB AB and Kraftpojkarna AB is performed. The project spans over a longer time-frame than this thesis work. The purpose of this thesis work is to develop a software that can handle the data gathered from the ten unique research system located within the 1 MW plant that newly has been built 10 kilometers outside of Västerås. The research systems do all have different configurations according to the following list:

1. Dual-axis tracking
2. Single-axis tracking with 30°tilt
3. Ground mounted, free-standing with 19° tilt
4. Ground mounted, free-standing with 41° tilt
5. Roof mounted with 19°tilt

Every variation above exists with or without power optimizers installed. A power optimizer have the same functionality as a maximum power tracker (MPPT) usually found installed in the inverter. The MPPT monitor the power output of the modules connected to it and ensures that the modules operate at the optimal point.

The developed evaluation software provides the user with tool to easily analyze and compare the data between the systems. From the data collected by a variety of sensors and loggers in the park the program calculates are collection of performance parameters for the different systems. By examining how other PV systems have been evaluated and which parameters that have been used in other studies a selection of parameters describing the PV systems performance has been implemented into the software. Some of the most commonly used performance parameters are the system yield, reference yield and the performance ratio.

The system yield [kWh/kW] is the PV systems production divided by the system size. It thus represents the production normalized to the system size. This value is good to use when comparing systems of different sizes.

The reference yield represents the available radiation resource to the system in question. It has the unit hours that represent the amount of hours the system would have to operate at standard testing radiation to produce the actual amount of energy. It is dependent on factors like; array tracking methods, module tilt, local weather and seasonal effects. The reference yield is measured with the help of a reference solar cell attached to the same frame as the rest of the system modules. The value can be used to compare the available resources to different PV system regardless of their location and placement.
The performance ratio is the ratio between the two former parameters, it is the system yield divided by the reference yield. The is a dimensionless number between 0 and 1 that describes how well the system is to convert the available solar resource to electricity.

The software computes several additional performance parameters but to read further details of them it is best to continue to read the rest of the report.

The main features of the evaluation software are:

- Automatic data scanning and organizing.
- Show data as a function of time.
- Show two variables with separate axes in the same graph for easier comparison. This helps in the analyzing of the data, reasons why the data looks the way it does can easier be seen.
- Draw all of the systems in the same graph in a comparison plot. This method allows for quick and easy comparison between all systems in the same picture.
- Create a scatter plot where any of the recorded parameters can be plotted against each other. This method can be used to see correlation between parameters.
- Functions for saving the graphs.

To showcase the features of the software a short-termed evaluation of three weeks in May 2014 has been done. The result shown by this preview must be read with caution as the evaluation period is only three weeks. To come with any conclusive result a much longer period must be monitored and evaluated. Here follows some of the major discoveries from the three week evaluation of the ten systems.

- System yield
  - The dual-axis system has the highest system yield. 110 kWh/kW and 109 kWh/kW for the system with and without power optimizers respectively.
  - The single-axis systems have notably higher yield than the fixed, free-standing and roof mounted systems, they have the yield 99 kWh/kW and 83 kWh/kW respectively.
  - The lowest yield is found in the roof mounted system without power optimizers. The system yields for these systems are fairly similar, around 80 kWh/kW.

- Performance ratio
  - The ground mounted, free-standing system with a 41° tilt and with no power optimizers installed shows the highest performance ratio. This indicates that this system was best at converting radiation to electricity during the evaluation period.
  - The least performing system was again the roof mounted system without power optimizers.

During the evaluation several issues and problem where encountered. Using the tools developed and implemented in the software some answers as of why irregularities in the data was found. It was found that shading of the arrays makes it difficult to find a single reason to why unexpected data exists. Most of the arrays suffer from shading during the morning due to a close by forest. This forest is not that dense to block all sunlight, so some radiation will pass through the forest and causes some fluctuation in production during the really early
morning hours. The effect can easily be seen in the data from the dual- and single-axis systems since they better can follow the sun’s path. In the evening the arrays suffer from self-shading from nearby system trackers. It is in these situations the systems with power optimizers should show higher yield according to the manufacturer of the optimizers. Because the shadows are not as well documented as the rest of the parameters collected from the systems it is hard to determine if a higher yield is due to the optimizers or uneven shading of the arrays.

The evaluation itself could be a separate thesis work and the time that was available during this project was not enough to dive deeper into these issues. The developed software has proven helpful in the evaluation of the ten PV systems and have on some fronts more versatility than was expected from the beginning. Other parts of the development have been suffering but as always when developing something within a time limit there must be compromises.
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<th>Designation</th>
<th>Unit</th>
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<tr>
<td>A</td>
<td>Area</td>
<td>m²</td>
</tr>
<tr>
<td>CF</td>
<td>Capacity factor</td>
<td>h</td>
</tr>
<tr>
<td>E</td>
<td>Energy</td>
<td>kWh</td>
</tr>
<tr>
<td>G</td>
<td>Irradiance</td>
<td>kWh/m²</td>
</tr>
<tr>
<td>H</td>
<td>Irradiation</td>
<td>kWh/m²</td>
</tr>
<tr>
<td>I</td>
<td>Current</td>
<td>A</td>
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<tr>
<td>Lc</td>
<td>Capture losses</td>
<td>h or kWh/kW</td>
</tr>
<tr>
<td>Ls</td>
<td>System losses</td>
<td>h or kWh/kW</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
<td>W, kW or MW</td>
</tr>
<tr>
<td>P₀</td>
<td>Nameplate power</td>
<td>kW</td>
</tr>
<tr>
<td>PR</td>
<td>Performance ratio</td>
<td>-</td>
</tr>
<tr>
<td>PRₐ₀</td>
<td>Array performance ratio</td>
<td>-</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
<td>Ω</td>
</tr>
<tr>
<td>Sw</td>
<td>Wind speed</td>
<td>m/s</td>
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<tr>
<td>T</td>
<td>Temperature</td>
<td>°C or K</td>
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<tr>
<td>U</td>
<td>Voltage</td>
<td>V</td>
</tr>
<tr>
<td>Yₐ</td>
<td>Array yield</td>
<td>kWh/kW</td>
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<tr>
<td>Yₚ</td>
<td>System yield</td>
<td>kWh/kW</td>
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<tr>
<td>Yᵣ</td>
<td>Reference yield</td>
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## ABBREVIATIONS AND TERMS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>Array</td>
<td>Collection of PV modules in a plane that operates together</td>
</tr>
<tr>
<td>Azimuth angle</td>
<td>The angle between the south and the array plane orientation</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>Inverter</td>
<td>Device that converts DC power to AC power</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>OC</td>
<td>Open Circuit</td>
</tr>
<tr>
<td>Power optimizers</td>
<td>A DC to DC converter with MPPT used for optimizing PV performance</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic – method of generating electricity from sunlight.</td>
</tr>
<tr>
<td>SC</td>
<td>Short Circuit</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Condition</td>
</tr>
<tr>
<td>Tilt angle</td>
<td>The angle between the array plane and the horizontal plane</td>
</tr>
<tr>
<td>Tracking</td>
<td>Method used by the PV arrays to track the suns path over the sky</td>
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1 INTRODUCTION

1.1 Background

Sweden has an increasingly growing photovoltaic (PV) system market, both in the private and public sector. Compared to a few years ago there are many new manufacturers of PV systems. Many businesses use PV systems in commercial purposes to attract environmentally aware customers. With the subsidies made by the government to increase the interest in PV systems have made the energy cost comparable with other means of electricity production. These subsidies have been most important in the private sector where they have attracted many house owners to invest in PV systems. (Lindahl, 2012)

The PV costs are still considered too high for use in large scale utility plant without the help of subsidies, but for residential and commercial sector the levelized cost of energy for PV generated electricity can be lower than the Nord Pool spot price (Stridh, et al., n.d.). With the increasing number of PV systems in the country there is a need to monitor the performance of these systems to ensure that the construction of these systems are done in a way that yields both the highest profit and production. When constructing a PV system there is many factors that will have a direct impact on the performance of the system. Examples of such factors are different solar tracking solutions which control the angle of incident between the sunlight and the photovoltaic panels and thus the available radiation during the year. The choice of tracking system, if any at all, will have a big impact on the electricity production (Cichon, 2013). When no tracking systems are in place it is called a fixed system and the important factors for such systems will be the tilt angle and the azimuth angle these systems are constructed with. Something worth noting in this context is that with more accurate solar tracking more advanced equipment is required and an increased investment cost is unavoidable. For fixed systems there can be free-standing or roof mounted systems with the later commonly seen in the private sector. The roof is an unused space for many residences and by placing the PV system here it has a low visual impact for the ones living in the area. The free-standing systems have the advantage of free flowing air on both the front- and backside of the PV modules. The increased air flow around the modules results in a more efficient cooling of the modules, and because the performance of the solar cells is dependent on the cell temperature this will yield in a higher production (Cuce & Cuce, 2013).

To drive the development of solar energy in Sweden a political interest and driving force is required. According to Uwe Zimmerman, researcher in solar energy at the University of Uppsala, the problem is that industries, companies and the general public that can invest in solar installation are unwilling to invest in something that won’t be profitable for the next 10 years. With political decisions that stride to develop the solar energy in Sweden not just in the short term but far into the future can convince unsure investors to start building. The
decision makers need to create a long-term goal and stand fast to it. As an example net metering has been adopted by other countries for example Denmark, with the result of a multiplication of the number of solar installations. (Axelsson, 2014)

Karl Steininger, professor in economics in Austria, says in the same article that investing in global solar installations in the world’s deserts it is possible to cover the world’s entire energy need. He is confident that is technical difficulties for such a project can be overcome but that the social and political issues and how to ensure that it is done in a sustainable way still are a problem. The energy market seems to at a crossroad. The energy supply can be produced on many levels; locally, on a national level, by collaboration neighboring countries or unions such as Europe or on an international level. There are many decisions to be made about how we want the future energy market to look like. Most likely will the end result be some form of compromise where all levels can interact and contribute to a sustainable society. The economical evaluations that are made for solar energy installation often use outdated price information. The fast dropping prices creates a misconception about the potential that can be drawn from solar energy. The price for solar modules has halved in the past three years. It is in the same article pointed out that the module price is not the only factor, but that the cost for the whole installation is just as important. With the module prices being as low as they are other cost will start to take up a larger portion of the investment cost. Seen on an installation level there are many factors that can reduce the cost, such as efficiency, installation costs and the lifespan of the solar modules. (Axelsson, 2014)

A report written by Can and Vasilis (2014) highlights the rapid expansion of the solar energy market. The authors aim to review the solar energy’s current situation and discuss the future potential prospects that can be made with the right policies. The report is aimed towards the US. In media the most important reason for investing in solar energy is the reduced emissions of greenhouse gases. In the report other, as the authors call it “hidden” benefits of solar energy is highlighted. Theses hidden benefits are increased energy security, increased number of high tech jobs, increased electricity availability. They further discuss methods and policies that can increase the solar energy market in the US. Feed-in-tariffs which aims to put the price for solar energy generated electricity comparable to already established power generators. They have been implemented successfully in numerous countries, such as Germany and Italy. Different forms of taxes, such as the investment tax credits that aims to help with the investment costs or the production tax credits which will generate an extra income per energy unit produced once the installment is operational. Other indirect ways of pushing the development of solar energy is a carbon or greenhouse gas tax program. By burdening the electricity production from non-sustainable fuels the interest in green energy will increase. (Can & Vasilis, 2014)

The long-term sustainability for large scale PV systems has been confirmed by Philips (2013) but with the concern that the solar energy to electricity conversion ratio is too low. According to his paper general opinion is that solar energy has the potential, in the long run to be a major part of the energy market, that with a small environmental foot-print. With such a large focus on the environmental benefits of solar energy, where it often is compared to different carbon based fuels the potential negative effects the production of solar modules and constructions of installation can be overseen. In a paper by Hernandez, et al. (2014) the
potential environmental effects of utility-scale solar installations are discussed. Topics that are discussed are the PV systems impact on biodiversity, water usage, dust generation and air quality and land use both on a local scale and on larger scales. Some co-beneficial suggestions are proposed by the authors. To decrease some of the negative effects with constructing PV systems on unused land it is purposed that already used land can be utilized. Some examples are pastures, landfills and mine sites and other already degraded areas. Even floating PV system is suggested to be used at water treatment plants.

From the above background it is clear that solar energy is here to stay but that there is a lot of work ahead to ensure that the end result is not only environmentally friendly energy but also sustainable on a socio-economic level. The general opinion of the researchers is positive for the technology but it is often pointed out that policies and regulation haven’t kept the same pace as the technology’s progression.

This report is a part of an investigation conducted at Mälardalen University in collaboration with the Swedish Energy Agency, Mälarenergi AB, ABB AB and Kraftpojkarna AB. The project is one of the ongoing projects that the university conducts within their Future Energy program. The project “Utvärdering av solelproduktion från Sveriges första MW solcellspark” aims to increase the knowledge of how PV systems should be installed in the most efficient way in Sweden. The study will be conducted at the newly built 1 MW PV plant outside of Västerås. At the plant ten research systems with different configurations is installed, all with different tracking systems and/or angles of incidents. To have this many unique systems at the same location creates favorable conditions to conduct an accurate comparison of the different PV systems. (Mälardalen University, n.d.)

This report is focused on the development of a computer program that can handle the gathered data from the PV systems and provide the user with a set of tools to compare and present the performance of the different systems. To understand which parameters that is important and useful in a comparison, a literature study covering the performance parameters of PV systems will be conducted.
1.2 Purpose

The evaluation tool developed to handle the data form the PV systems can when ready be used to display, analyze and present different performance parameters regarding the ten research systems located within the 1 MW PV plant. The tool will be designed to be versatile and have as many options and features as the time-frame for the development allows. It will be up to the user to make decisions of which parameters to analyze and how to present them. This design choice makes it possible to use the tool even outside of its original purpose.

During the course of the investigation some parameters, which at first appear irrelevant might become useful later down the road. Therefore the program is designed to handle all the available data gathered from the systems and leave it to the user to determine what to analyze. Even so, great care will be taken to ensure that the result presented in the program is relevant for the evaluation purposes.

Besides the development of the evaluation tool, a small comparison of the ten systems will be performed. A period between three to four weeks with good data availability will be analyzed. The comparison result will give a first preview of the performance of the different PV systems and show what the evaluation tool is capable of.

As this tool is to be used in the future and final evaluation of the PV plant it is important that it is robust and well documented so that it without complications can be used throughout the project.
1.3 **Scope and limitations**

The project will be limited to cover the production part of the PV plant, meaning that no economical evaluations will be done. The evaluation tool that will be developed will therefore focus on production and the parameters needed for calculations of different performance parameters.

Further the program is specifically developed to work with the data gathered from the PV plant. It will not be possible to use the same program for evaluations of other PV plants. This would add an immense amount of time to the development time and this feature is therefore outside of the scope of this project.

The evaluation of the ten systems performed in the report is meant as a preview of what the program can do. So any result and conclusions presented regarding the performance of the ten research systems is only valid within the period for which the evaluation was made.
1.4 Literature review

This chapter will summarize the knowledge acquired from the literature review. First some basics and background about solar energy and how photovoltaics work will be presented. This will be followed by a section about PV system monitoring and data collection. Finally the most used performance parameters for evaluation of different PV systems will be described and explained.

1.4.1 Solar energy generation

The power that can be harvested by using photovoltaic cells ultimately comes from the radiation that the sun emits. The energy produced by the sun originates from the nuclear fusion reactions that occur deep inside the sun, in its core, where hydrogen atoms are fused together to helium. In the process an enormous amount of energy is released which causes the sun’s surface to heat up to approximately 6000 °C. The highly energetic surface radiates its energy in all directions in the form of electromagnetic radiation. A small part of it hits the earth where roughly 30% is reflected back into space. Some of the 70% that is left makes its way down to the earth’s surface where photovoltaics can be used to generate electricity from the sun’s energy. (Boyle, 2004)

In Figure 1 the solar spectrum can be seen. The picture is taken from the Wikimedia collaboration and is used according to the terms posted with the image. The spectrum covers categories of electromagnetic wavelengths such as ultraviolet, visible light and infrared. Visible light have the highest intensity per square meter and the intensity gradually decrease as the wavelengths get longer and longer towards the infrared. The picture also demonstrates how the radiation above the atmosphere differs from the radiation at ground or sea levels. The differences are due to the absorption of various atmospheric gases, such as ozone, carbon dioxide and water vapor (Houghton, 1977).

![Figure 1: Solar Radiation Spectrum (Nick, 2008)](image)
1.4.2 Photovoltaics

Photovoltaics are the capability to harvest the energy of the sun and directly convert it into electricity within the same device. This differ to other solar power conversion technologies that first heat water to produce steam, which in turn is used to drive a turbine and generator. The end product is the same, but by using photovoltaics the number of steps is greatly reduced.

Photovoltaic cells are made from the second most abundant element in the earth’s crust, silicon. The basic component of a photovoltaic cell is silicon in its purest form, namely crystallized silicon. Silicon has four valance electrons, electrons in its most outer layer, and will in a crystal-silicon structure share one electron with one of its four neighboring silicon atoms. In this structure of pure crystalline silicon every valence electron is bound to another valence electron to form a valence bond between the atoms in the crystal. Due to this bond between the atoms there are very few free electrons that can conduct electricity through the material. As such the pure silicon crystal has a high electrical resistivity compared to metallic material but not as high as a good insulator like glass. Silicon has electric conduction properties between a good conductor and a good insulator and is therefore called a semiconductor. To explain what causes free electrons in a PV module and thus the conduction through the material, a deeper look into the nature of electricity is required. (Boyle, 2004)

For a material to be able to conduct electricity the electrons must in some way gain the appropriate amount of energy to be able to move from the valence bond to the conduction band. This energy can be obtained from light hitting the material or from thermal energy within the material structure. Many materials electrical resistivity decrease as the temperature increases. For example, at 0° Kelvin a semiconductor such as silicon would be a perfect insulator since all the electron is occupied in the valence bound between the atoms and no thermal energy is available to bump the electrons to a free state. This is assumed that only thermal energy can cause the valence electrons to move to the conduction band. This is why silicon can be seen as a semiconductor at temperatures well above the absolute zero. (Kittel, 2004)

Now that it has been shown how the flow of electrons in a silicon crystal can occur, the inner workings of a photovoltaic cell can easier be described. It is from this point forward assumed that the temperature is well above the absolute zero. In a pure silicon crystal some electrons are moving around freely due to excitations caused by energy provided from both photons and thermal energies. These electrons will only move inside of the silicon and are no use in regards to electricity generation. To be able to use the flow of electrons in an electric circuit some additional alterations and component are required.

This is where doping of silicon comes in. By taking a pure silicon crystal and replacing some of the atoms with impurities, such as phosphorus and boron, the electrical charge of the material changes. Phosphorus which has five valence electrons will when replacing a silicon atom provide one extra unbound electron to the crystal. If a small percentage of the silicon atoms are replaced with phosphorus atoms the excess of electrons will cause the material to be negatively charged. Boron on the other hand only has three valence electrons. As such,
they will when replacing a silicon atom cause an absence of electrons. This absence of electrons is also called “holes” and will make the material positively charged. Silicon doped with phosphorus is called an n-type semiconductor due to its negative charge and boron-doped silicon is thus called a p-type semiconductor. By joining the two types of semiconductors an electric field will appear in the junction of the materials. The electric field around the intersection of the materials causes the negative and positive charges to move in opposite directions. Because of this electric field the flow of electrons can be controlled and be used to power electric devices. (Boyle, 2004)

A photovoltaic cell is constructed with a thin layer of n-type crystal on top of a thicker layer of p-type crystal. On both the top and bottom there is a grid of metallic conductor connected to the external circuit through which the electrons flow and generate a current. Due to the electric potential between the crystals at the junction electrons tend to move towards the top of the cell and the holes tend to move towards the bottom of the cell. When an electron in the junction is excited by a photon it travels towards the top of the cell and through the external circuit to the bottom of the cell where it fills a hole. Not all photons will excite an electron. Light comes as illustrated in Figure 1 at different wavelengths. UV-light has short wavelengths and infrared has long. The amount of energy that a photon is carrying is related to its wavelength. A shorter wave is more energetic than a longer wave.

There is yet another factor to consider. For an electron to be bumped up from the valence band to the conduction band a specific amount of energy is required. This energy is different for every element. According to Nordling and Österman (2006) the amount of energy required for silicon is 1.124 eV at 300° Kelvin. So the photons hitting the PV cell must at least have this energy level for an electron to be excited. There are a few scenarios that can happen when light hits the PV cell. Some of the photons have just the right amount of energy and will promote an electron to be free of its bond leaving behind a hole. The electron will travel towards the top of the cell to the conductor on the surface and the hole will move to the bottom of the cell. The electron goes through the external circuit to the bottom of the cell where it fills the hole again. If the photon has more energy than is needed to lift the electron over the band gap the electron will still be exited but only the 1.124 eV will be consumed by the jump. The rest of the energy will radiate as heat to the surrounding. If the photon has less energy than the band gap it will go through the cell without any interaction. A number of photons will not be able to reach the PV cell at all due to the metal conductor on the top, which will reflect and/or absorb the photons. Some additional photons will be reflected by the cell surface even if it has an antireflection coating. (Boyle, 2004)

As stated by Boyle (2004) a typical PV cell produces a voltage of around 0.5 V at a current of about 3 A. Using the power equation:

\[ P = UI \]  

Eq. 1

a single PV cell will generate 0.5 * 3 = 1.5 W. To generate a higher voltage and thus more power, many PV cells can be connected in series. Series of cells can then be assembled into modules and modules into arrays creating a network as big as required for the application.
1.4.2.1 PV cell characteristics

The above generated electricity is in laboratory testing conditions, or standard testing conditions (STC). Such a condition is defined as; when the PV cell is irradiated with 1000 watt per square meter and the cell temperature is held at 25 °C. In a real situation the light is rarely constant due to angle of incident towards the module plane, shadowing from external objects and clouds obscuring the light. PV cells do also behave differently depending on the amount of resistance that is applied to the external circuit. By connecting the external circuit of a PV cell with a variable resistance and meters to measure the voltage and current, the current-voltage characteristics of the PV cell can be determined. If an infinite resistance is applied to the circuit it would be as if the cell is not connected at all. Then the voltage across the cell will be at its maximum but no power is generated since the current is zero. This is called the open circuit voltage (\(U_{OC}\)). If on the other hand a zero resistance is applied to the circuit the current will be at its maximum with a zero voltage across the cell. It is as the circuit would be short-circuited and it is therefore called the short circuit current (\(I_{SC}\)). Again the power will be zero due to the non-existent voltage. Between these two extremes some power is generated and at one point the power reaches its maximum. This point is called the maximum power point (MPP).

The relationship between the voltage and the current in the cell circuit depends on many factors. The most important ones are solar irradiance, cell temperature and performance degradation due to material aging. The process can be modeled as a solar cell diode where the net current in the cell can be calculated as:

\[
I = I_{ph} - I_D = I_{ph} - I_0 \left( e^{\frac{e(V+I_{RS})}{mKT_c}} - 1 \right)
\]

Eq. 2

where:

- \(I\) – net cell current
- \(I_{ph}\) – photocurrent
- \(I_D\) – normal diode current
- \(I_0\) – the dark saturation current
- \(e\) – electronic charge
- \(V\) – voltage across the cell
- \(R_S\) – cell resistance (internal and connection)
- \(m\) – idealizing factor
- \(k\) – Boltzmann’s gas constant
- \(T_c\) – the absolute temperature of the cell

The diode acts as an energy barrier that corresponds to the valence gap in the silicon material. This makes only photons with high enough energy to produce electricity just as in a real solar cell. The underlying theory of diodes lies outside the scope of this report and any further detail into this will not be examined here. The equation does anyway show that the current-voltage relationship is connected to the cell temperature and light intensity. (Power Analytics Corporation, 2011)

The I-U characteristic of a PV cell is because of this never the same in real operation. A change in either the light situation or temperature of the cell will alter the shape of the curve.
To ensure that the cell is performing at an optimal condition, as close as possible to the instantaneous MPP, a maximum power point tracker (MPPT) is usually used.

### 1.4.2.2 MPPT

The effect that varying irradiance has on the PV cells I-U characteristics can be explained with the following example. If the intensity of the light drops down to 70% of the STC the I-U curve is scaled down as well. It will keep its general shape, but both the short circuit current and the open circuit voltage are lowered than their original values. It is basically the same shaped curve but the scale down by a factor dependent on the light intensity. With less light hitting the solar cell the lower will the OC and SC be. The same principle applies to the power curve. With lower light intensity the power curve keeps its general form but top of the curve is flattened resulting in a lower power output. (Green Rhino Energy Ltd, 2013)

In a similar way the module temperature affect the maximum power point of a PV module. With a higher module temperature than the one used at STC will result in a decreased power output. Reversely, if the temperature is lower than the STC power output will be higher assuming the solar cell is illuminated with the same light intensity.

In real operations both of these factors, temperature and irradiance, changes constantly. To keep track of the MPP an MPPT in installed to the PV cell-strings. This device can be installed in the inverter and will as such determine the MPP for the entire string of modules that are connected to the inverter. It can also be installed at each PV module, called an power optimizer. In that way all modules will operate at its own MPP. The theoretical benefit of this is that such a system is not as susceptible to uneven shadowing and irregular cell qualities. There are many different methods and algorithms that are used to track the MPP. The simplest of the methods works on the disturb and observe principle. Here the tracker change either the PV cell voltage or current and records how the power reacts. It the power increase as a result of the change the tracker keeps changing either the voltage or current in the same direction. If the power on the other hand gets lower as a result of the change the MPPT will as the next action make a change in the opposite direction. In this way it is ensured that the PV strings operates near the MPP. (Freeman, 2010)

### 1.4.3 PV system monitoring and evaluation

Since PV systems not have any moving parts and are associated with low maintenance it is easy to think that once the system is in place it will work throughout its lifetime. In fact there are many possible malfunctions the can occur in a PV system. It can be a disconnection of an entire string of PV modules or the malfunction of a single module that will reduce the production of the rest of the modules in that string. Inverter malfunctions and other system components failures are other examples. Woyte, et al. (2013) states that on average it occurs an system error once every 4.5 year in small scale residential PV systems. Inverter failures answered for 63 %, PV modules for 15 % and other components for 22 % of the total failures. These failures can cause a substantial production falloff for the system owner, and in a worst case scenario tip the financial scale to a negative result. If system errors and malfunctions can
be detected in real time or within days of them happening the problem can be corrected before a considerable part of the production is lost.

A positive side effect of adopting a proper monitoring system is data acquisition. The valuable data can provide a good foundation for future research towards eliminating failures and increased reliability for PV systems. A report by Marion et al. (2005) highlights the importance of continuous evaluations of PV systems for the whole industry. Everything from part manufacturers to political decision makers will benefit from a widely adopted monitoring and evaluation of PV systems. The report further emphasizes the importance of a general accepted guideline for how the data gathering and evaluations should be conducted. Such standards and guidelines have been developed by the International Electrotechnical Commission (1998) as an international standard and a guideline for the European market made by the PERFORMANCE project (n.d.), which is available as a webpage. For reliable evaluations of PV systems these standards should be followed as close as possible.

The encountered guidelines provide suggestions on which system parameters to monitor accompanied with suitable equipment to obtain accurate evaluation results. In the next section the standard performance and PV system parameters used for evaluations will be examined.

### 1.4.4 Performance parameters

The goal for performance parameters is to put a number on how a PV system is performing. Once such numbers have been derived they can be used to compare different types and configurations of PV systems. At first glance one might think that a record of the produced energy would be enough to determine the PV systems performance but when considering the highly fluctuating solar conditions over the world one starts to see that it is not that easy. Factors like latitude and weather conditions have great impact on the solar availability at the PV system location. One can with ease see the difficulties with comparing the performance of two differently sized systems using slightly different configuration with just the energy production available. Because of this several parameters taking account for these factors have been derived and some of the most commonly used will be described here.

The report written by Marion, et al. (2005) mention three of the IEC standard performance parameters that may be used to evaluate the overall system performance. These parameters determine the performance with respect to energy production, solar availability and system losses.

The first parameter is the PV system yield and is defined as

\[
Y_f = \frac{E}{P_0}
\]

where \(E\) [kWh] is the net energy produced by the PV system and \(P_0\) [kW] is the installed DC power of the PV modules, or name plate power. The unit is hours or kWh/kW with the later preferred as it both indicates how the value is derived and explains that it is produced energy in relation to the system size. It also represents the amount of hours the system would have
to operate at full capacity to produce the same amount of energy. As the system yield takes the system size in consideration it is an excellent value to use when comparing system of different sizes.

The second parameter is reference yield, denoted $Y_r$ and is derived as

$$Y_r = \frac{H}{G_{STC}}$$  \hspace{1cm} \text{Eq. 4}

where $H$ [kWh/m$^2$] is the total in-plane irradiation and $G_{STC}$ [kW/m$^2$] is the PV modules reference irradiance at standard testing condition. The reference yield represents the number of hours the system would need to operate at the reference irradiance to produce the amount of energy that was recorded during the test period. If $G$ is 1 kW/m$^2$ a reference yield of 10 would mean that the system would have to be operational for 10 hours with the irradiance 1 kW/m$^2$ to produce the same energy as represented by $H$ during the test period. The reference yield is a function of location, orientation of the PV system and weather variation over the year. It represents the solar resource available at the PV system location and can therefore be used to compare solar profiles at different location around the world.

The third parameter is the performance ratio (PR) which is derived as

$$PR = \frac{Y_f}{Y_r}$$  \hspace{1cm} \text{Eq. 5}

The performance ratio is the system size independent $Y_f$ normalized with respect to the available solar resource. The parameter is dimensionless and puts a number on the overall performance of the system. It basically is the ratio between the amount of energy the system has produced per installed capacity and the available solar resource at that location. For the performance ratio to be one the system would have to be perfect with no losses from any source. The performance ratio is a good value on the efficiency of the whole PV system regardless of the system size or location. It is therefore an excellent number to use when comparing different systems all over the world. As stated by Marion, et al. (2005), the value $1 - PR$ quantifies the losses in the PV system due to inverter inefficiencies, losses in cables, module temperature and soiling, snow-covering, system downtime and other component failures.

A group of researchers from Australia suggest in a report by Copper, et al. (2013) additional parameters than the ones mentioned above. Another yield parameter is introduced; array yield ($Y_a$) which is derived as
\[ Y_a = \frac{E_a}{P_0} \]  

Eq. 6

where \( E_a \) [kWh] is the produced energy on the DC side of the system. This is similar to the \( Y_f \) in that it represents the energy generated by the system normalized to the system size but is different in that only losses directly related to the modules, such as temperature, soiling etc., are incorporated in the value. These three yield values can be used to define two normalized loss parameters. The first is the array capture losses (\( L_c \)), defined as

\[ L_c = Y_r - Y_a \]  

Eq. 7

The array capture losses are the difference between the available solar resource and the actual captured energy by the PV modules. The losses incorporate occurrences like module temperatures different from the STC, module shading, high angle of incidents towards the module plane, cell and module mismatching, soiling and other covering effects and losses in array cables. Some other factors that are not as natural to find here are losses due to inaccurate maximum power point trackers and inverter failures or downtimes since no energy is generated during these periods. The authors therefore highlight the importance of preparing the data so that such losses can be attributed accordingly. The other loss parameter is system losses (\( L_s \)) and is defined as

\[ L_s = Y_a - Y_f \]  

Eq. 8

which represent the other losses in the system other than the capture losses. Inverter conversion efficiencies and system cable losses are the main losses that can be found here. (Copper, et al., 2013)

Similar to the array yield an array version of the performance ratio can be computed. The array performance ratio is defined by (Woyte, et al., 2013) as

\[ PRA_a = \frac{Y_a}{Y_r} \]  

Eq. 9

and represents the array performance, which is the system performance without the losses that are not related to the array and PV modules (System losses \( L_s \)).

Three efficiencies for different zones of the PV system can be defined. The array efficiency (\( \eta_a \)) represents the average DC energy conversion efficiency of the PV array. It is computed as

\[ \eta_a = \frac{E_{dc}}{A_a \cdot H} \]  

Eq. 10

where \( E_{dc} \) [kWh] is the DC energy generated by the array, \( A_a \) [m²] is the array area which is defined as the added module area including the frame of all the modules making up the array. \( H \) is the in-plane insolation per square meter during the recording time. The system efficiency (\( \eta_s \)) can be computed in a similar way but with the AC energy instead of the DC energy:
\[ \eta_s = \frac{E_{a.c}}{A_n H} \]  

Eq. 11

The third efficiency is the inverter efficiency (\( \eta_i \)) which is the ratio between the DC power in to the inverter and the AC power out of the inverter. It can also be defined over a time period and when the energy in and out of the inverter is used instead: (Copper, et al., 2013)

\[ \eta_i = \frac{P_{a.c}}{P_{d.c}} = \frac{E_{a.c}}{E_{d.c}} \]  

Eq. 12

One final performance parameter that is mentioned by Kymakis, et al. (2009) is the capacity factor (CF) which is defined as

\[ CF = \frac{V_r}{8760} = \frac{E_{a.c}}{P_0 \times 8760} \]  

Eq. 13

and is the ratio between the actual produced energy and the potential energy that can be produced if the PV system where to operate at rated power over the whole year. The capacity factor can be defined over any arbitrary time period. This parameter can be good to use for comparison between technologies and as a value on how good the system utilizes the installed capacity.

Many of the parameters described above have been used in similar PV system evaluations. Some such studies are written by Humphries (2013), Ma, et al. (n.d.) and Pietruszko, et al. (2009). Most commonly used are the system yield, reference yield and the performance ratio.

For the above parameters to be calculated a number of basic parameters are needed. The parameters in Table 1 are recommended by the IEA PVPS task 13 report to be recorded for any system that are to undergo monitoring and evaluation.

Table 1: Basic parameters that should be recorded for monitoring of PV systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-plane irradiance</td>
<td>G</td>
<td>W/m²</td>
</tr>
<tr>
<td>Module temperature</td>
<td>( t_{mod} )</td>
<td>°C</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>( t_{amb} )</td>
<td>°C</td>
</tr>
<tr>
<td>Wind speed</td>
<td>( s_w )</td>
<td>m/s</td>
</tr>
<tr>
<td>PV voltage</td>
<td>( V_{dc} )</td>
<td>V</td>
</tr>
<tr>
<td>PV current</td>
<td>( I_{dc} )</td>
<td>A</td>
</tr>
<tr>
<td>PV power</td>
<td>( P_{dc} )</td>
<td>W</td>
</tr>
<tr>
<td>Utility voltage</td>
<td>( V_{ac} )</td>
<td>V</td>
</tr>
<tr>
<td>Utility current</td>
<td>( I_{ac} )</td>
<td>A</td>
</tr>
<tr>
<td>Utility power</td>
<td>( P_{ac} )</td>
<td>W</td>
</tr>
</tbody>
</table>
2 PROJECT PROCESS

The project started with the finalization of building the 10 research system themselves. This work included installation of the final PV modules and setting up the logger equipment. Regarding the logger system some familiarization with the equipment was involved. For example some of the measurement equipment and logger systems were tested at the ABB office before they were taken out to the park for installation.

The main part of the PV plant, excluding the 10 research systems, had its opening the 5th of February 2014. After this the focus shifted towards the 10 research systems. This included installation of inverters, cable connections and logger systems, By mid-March these systems were up and running. At this point a data connection had been established with the PV plant and data could be acquired. Parallel to this work the literature review was conducted.

Once the flow of data was established, a substantial amount of time was taken to create a stable and organized data structure. With the base data structure complete the work continued with calculations of various performance parameters for the PV systems. Both of these subjects are explained in more detail further down the report.

At this point the development of the program user interface and functions began. With increased program functionality more and more performance parameters could be presented and reviewed. An ongoing discussion with Bengt Stridh regarding program functionality and parameter details occurred during the development. All of the computing and program development has been done in MATLAB. The program user interface has been created using MATLABs’ GUIDE tool, which is an interactive way of building interfaces for programs. MATLAB is a great computable program with additional capabilities to handle large quantities of data and tools for data visualization. All of the features that are required for the task at hand.

Once the program was mature enough the comparison of the systems could be started, result presented, followed by result analyzing. Form here the work consisted of a loop of presenting result and finding methods for how to analyze and make sense of the data. As stated in the purpose, the program is designed to be as versatile as possible. As such, many evaluations methods and performance parameters have been incorporated into the program. In the short evaluation performed of the PV systems in this report shows which methods and parameters that is relevant for this particular evaluation.
3 PV PLANT DESCRIPTION

The PV plant is located about 10 kilometers east of Västerås along the highway E18 towards Enköping. The majority, all except the ones included in the research evaluation project, of the plant modules are mounted on dual axis trackers. These trackers will track the sun across the sky in both the horizontal and vertical direction using an active tracker system. The park consists of 91 such trackers with 36 modules each. Every module consists of 72 mono-crystalline solar cells for a maximum power of 300 W per module. In Table 2 some general data for the modules are presented. With 36 modules per tracker and 91 trackers the rated power for this part of the plant is 982 800 W. In addition ten research systems of varying sizes are installed at the plant. Their combined rated power is 52 800 W, and thus the total rated power of the plant is 1 035 600 W or roughly 1 MW. This makes it the largest PV installation in Sweden.

Table 2: Module data and information (SANMU GROUP HUAMEI CABLE CO, 2008).

<table>
<thead>
<tr>
<th>Module data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power [W]</td>
<td>300</td>
</tr>
<tr>
<td>Length [m]</td>
<td>1.956</td>
</tr>
<tr>
<td>Width [m]</td>
<td>0.992</td>
</tr>
<tr>
<td>Area [m²]</td>
<td>1.940</td>
</tr>
<tr>
<td>Efficiency</td>
<td>15.5%</td>
</tr>
<tr>
<td>Cell type</td>
<td>Mono-crystalline</td>
</tr>
<tr>
<td>Cells #</td>
<td>72</td>
</tr>
<tr>
<td>Cell width [mm]</td>
<td>156</td>
</tr>
<tr>
<td>Cell length [mm]</td>
<td>156</td>
</tr>
</tbody>
</table>

Below in Figure 2 an overview of the plant is shown. The picture is taken by Bengt Stridh as is used with permission by Kraftpojkarna AB.

Figure 2: PV plant overview.
3.1 Tracking system

The dual axis trackers use a light sensing active tracker to expose the panels with as much of the suns radiation as possible. The sensor has three photosensors, each located on the side face of a pyramid, see Figure 3. The picture is taken by Bengt Stridh as is used with permission by Kraftpojkarna AB.

The pyramid's base is placed parallel with the plane of the modules. Each of the photosensors will measure the suns intensity. If one of the sensors records a higher value than the other two the sensor will call for a repositioning of the tracker. When all three sensors are exposed with the same intensity the pyramid apex and the normal of the array plane will point towards the direction of the sun. In case of a cloudy day the sensors only receive the diffuse light from the sky and will reposition the panels to a near horizontal position. Each dual-axis tracker has two of these light sensors installed, one at the top and one at the side of the modules. The one on the side will adjust the module inclination to the sun as explained above and the one at the top will help the tracker system to find the sun on the sky at different times during the day. For example, in the morning the sun often appears behind the tracker as it stops in an eastwards direction in the evening. In that case the sensor at the top detects the radiation coming from the back of the tracker and calls for a repositioning of the array.

3.2 Power optimizers

Each module besides a few research systems in the PV plant is fitted with a power optimizer. A power optimizer is a like a small maximum power point tracker that is moved from the standard location at the inverter to the module level. Instead of having one MPPT for each string into the inverter every module get an individual tracker.

According to SolarEdge Technologies (2013), who supply the optimizers to the plant, this solution can yield up to 25 % more energy in certain circumstances due to the ability to mitigate mismatch losses such as manufacturing inconsistencies, partial shading and module orientation differences. The increase in performance is explained by the smaller area for which the MPPT has to work. For example, if the regular inverter MPPT system is used the whole string is restricted to operate at the performance of the worst module in the string. If one module in the string is shaded or otherwise incapable to perform at its peak performance it will reduce the production of the whole string. In contrast by installing a MPPT for each module the string is unaffected by the performance of the other modules and a higher energy yield should be achieved. (SolarEdge Technologies, Inc, 2013)

As will be described in more detail below, half of the research systems will use these power optimizers and the rest will operate without them from comparison purposes.
3.3 The 10 research solar systems

Besides the system described above the PV plant has ten research systems installed. These systems are divided into five different configurations in regards to tracking method, tilt angle and installation method. In addition to that one system of each configuration has power optimizers installed and the other has not. In Table 4 the basic details for the systems are presented.

Systems one and two are both mounted on the same type of tracker as the rest of the park that is not included in the detailed research evaluation. The two systems share the same tracker with 18 modules per system. The rated power is thus 5.4 kW and the module area is 34.9 m².

The systems three and four utilize a single-axis tracker; see Figure 4, which is smaller than the dual-axis tracker. Each system has 10 modules installed for a rated power of 3.0 kW and an active area of 17.5 m². The tracker only follows the sun in one direction which is but not in a straight vertical or horizontal direction. The tracking orientation is illustrated by Figure 4 and has a tilt of 30°. The picture is taken by Bengt Stridh as is used with permission by Kraftpojkarna AB.

Figure 4: Single-axis tracker.

In Table 3 and Table 5 the types of inverters and power optimizers can be seen for each of the systems. In the table the accuracies and efficiencies of the instruments are also presented. The Euro-efficiency seen in the table is a weighted efficiency for the specific solar insolation in central Europe. It is commonly used for power converters in the industry and similar efficiencies are defined for other location such as the south-west regions of the US.
Table 3: Sensor models and sensitivities.

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Supplier</th>
<th>Model</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference solar cell</td>
<td>Mencke &amp; Tegtmeyer</td>
<td>Si-RS485-TC-T</td>
<td>± 5%</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>Kipp &amp; Zonen</td>
<td>CMP11</td>
<td>&gt; 3%</td>
</tr>
<tr>
<td>Power meter</td>
<td>Solar Log</td>
<td></td>
<td>± 1%</td>
</tr>
</tbody>
</table>

Table 4: Research systems details.

<table>
<thead>
<tr>
<th>System #</th>
<th>Tracking</th>
<th>Tilt</th>
<th>Azimuth</th>
<th>Power optimizers</th>
<th>Rated power [kW]</th>
<th>Modules #</th>
<th>Active area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>67-1</td>
<td>2-axis</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
<td>5.4</td>
<td>18</td>
<td>34.9</td>
</tr>
<tr>
<td>67-2</td>
<td>2-axis</td>
<td>-</td>
<td>-</td>
<td>No</td>
<td>5.4</td>
<td>18</td>
<td>34.9</td>
</tr>
<tr>
<td>92-1</td>
<td>1-axis</td>
<td>30°</td>
<td>-</td>
<td>Yes</td>
<td>3.0</td>
<td>10</td>
<td>19.4</td>
</tr>
<tr>
<td>92-2</td>
<td>1-axis</td>
<td>30°</td>
<td>-</td>
<td>No</td>
<td>3.0</td>
<td>10</td>
<td>19.4</td>
</tr>
<tr>
<td>93-1</td>
<td>Fixed</td>
<td>19°</td>
<td>South</td>
<td>Yes</td>
<td>4.8</td>
<td>16</td>
<td>31.0</td>
</tr>
<tr>
<td>93-2</td>
<td>Fixed</td>
<td>19°</td>
<td>South</td>
<td>No</td>
<td>4.8</td>
<td>16</td>
<td>31.0</td>
</tr>
<tr>
<td>94-1</td>
<td>Fixed</td>
<td>41°</td>
<td>South</td>
<td>Yes</td>
<td>4.8</td>
<td>16</td>
<td>31.0</td>
</tr>
<tr>
<td>94-2</td>
<td>Fixed</td>
<td>41°</td>
<td>South</td>
<td>No</td>
<td>4.8</td>
<td>16</td>
<td>31.0</td>
</tr>
<tr>
<td>95-1</td>
<td>Roof</td>
<td>19°</td>
<td>South</td>
<td>Yes</td>
<td>8.4</td>
<td>28</td>
<td>54.3</td>
</tr>
<tr>
<td>95-2</td>
<td>Roof</td>
<td>19°</td>
<td>South</td>
<td>No</td>
<td>8.4</td>
<td>28</td>
<td>54.3</td>
</tr>
</tbody>
</table>

Table 5: Inverters and power optimizers used for each of the systems.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Supplier</th>
<th>Model</th>
<th>Euro-efficiency</th>
<th>Used for systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter</td>
<td>Solar Edge</td>
<td>SE10k</td>
<td>97.6%</td>
<td>95-1</td>
</tr>
<tr>
<td>Inverter</td>
<td>Solar Edge</td>
<td>SE5k</td>
<td>97.3%</td>
<td>67-1, 93-1, 94-1</td>
</tr>
<tr>
<td>Inverter</td>
<td>Solar Edge</td>
<td>SE3k</td>
<td>97.6%</td>
<td>92-1</td>
</tr>
<tr>
<td>Inverter</td>
<td>SMA</td>
<td>Tripower 8000 TL20</td>
<td>97.6%</td>
<td>95-1</td>
</tr>
<tr>
<td>Inverter</td>
<td>SMA</td>
<td>Sunny Tripower 5000 TL20</td>
<td>97.1%</td>
<td>67-2, 93-2, 94-2</td>
</tr>
<tr>
<td>Inverter</td>
<td>SMA</td>
<td>Sunny Boy 3000 TL20</td>
<td>96.0%</td>
<td>92-2</td>
</tr>
<tr>
<td>Power optimizer</td>
<td>Solar Edge</td>
<td></td>
<td>98.6%</td>
<td>95-1, 92-1, 93-1, 94-1, 95-1</td>
</tr>
</tbody>
</table>

Systems five and six are fixed free standing systems, see Figure 5, with 16 modules each for a rated power of 4.8 kW and an area of 28.0 m². The array is mounted with a 41° tilt and oriented directly south. The picture is taken by Bengt Stridh as is used with permission by Kraftpojkarna AB.
Systems seven and eight are also fixed free standing systems, see Figure 6, with the same orientation and size as systems five and six. The difference is that these two arrays are installed with a 19° tilt. The picture is taken by Bengt Stridh as is used with permission by Kraftpojkarna AB.
The final systems, nine and ten are fixed roof mounted systems with the tilt angle 19°, see Figure 7. The picture is taken by Bengt Stridh as is used with permission by Kraftpojkarna AB. These are the largest of the research systems with 28 modules each for a rated power of 8.4 kW and an area of 49.0 m$^2$. These are also oriented directly to the south.

Each of the systems is installed to a separate inverter. All systems that have power optimizers installed are connected to inverter from SolarEdge, while the others are connected to SMA inverters. The details are presented in Table 5.
3.3.1 Equipment and resources

It was in the literature review suggested that to be able to perform a proper evaluation, some base variables should be recorded from the PV systems, see Table 1. To record these values for the systems specified above a logger system was installed at the plant. A logger system made by the company Solar-Log is used. Due to some technical restriction together with the requirement of the acquisition of reliable data one logger had to be installed for each PV system. The result is a more complex data handling as more files and data must be structured. Some values are logged by the inverter, such as voltage, current and power values, and are recorded by the loggers. Other values, such as wind speed and temperatures are recorded by external instruments supplied by Solar-Log.

Besides covering just the basic variables mentioned in Table 1, some additional equipment has been installed to record additional data for comparison and validation of data quality. For example, Woyte, et al. (2013) states the many inverters on the market do not have the necessary measuring quality for the data to be used in an evaluation such as this.

3.3.1.1 Measurement equipment

The systems are grouped into pairs. For example, system one and two are identical except that one system has power optimizers and the other has not. They are also placed parallel to each other; see pictures in previous chapter, with the same array tilt angle and azimuth. Therefore it would be redundant to install instruments for each of the systems. It would only result in two data sets almost identical to each other. Because of this only one set of measuring instruments were installed per system pair. As they are located so close to each other the data can represent both of the systems.

![Power meter](Power_meter.png) ![Pyranometer and wind meter](Pyranometer_and_wind_meter.png) ![Reference solar cell](Reference_solar_cell.png)

Figure 8: Measuring sensors.

The in-plane irradiance, module temperature, ambient temperature and wind speed for each system group is recorded by a supplementary sensor box supplied by Solar-Log, see Figure 8. The picture is taken by Bengt Stridh as is used with permission by Kraftpojkarna AB. The box contains a mono-crystalline silicon solar cell that registers the solar irradiance. These boxes are installed on the same framework and in the same angle as the array modules. Within each
box there is a temperature sensor that records the module temperature. To record the ambient temperature an external temperature sensor is attached to the box. Connected to the box is also a cup anemometer that records the wind speed. The anemometers are all but one placed in a horizontal orientation. For the single axis tracking system group the installation method used to ensure that the wind-meter stays horizontal when the tracker tilts was not compatible, it is therefore statically installed in the same angle as the array framework. The result is that when the tracker tilts the anemometer will also tilt. The box is in turn connected to the logger and transfers the data from all the devices to the logger database.

The voltage, current and power values are all recorded, or can be computed from the recorded values, by the inverters. As mentioned before the inverters are not as accurate as one could hope and because of this it was decided that one additional power meter should be installed on the AC side of the inverter. The data provided by this meter can be used to validate the data from the inverter. It is here the logger restriction comes in. The loggers from Solar-Log does only support one power meter per logger and thereby forcing the installation of ten logger systems.

In addition to the above equipment a pyranometer, see middle picture in Figure 8, from the company Kipp & Zonen with a separate logger system in installed on the roof in a horizontal position. The pyranometer is of similar quality to the ones used by SMHI, the Swedish weather agency. They are also recommended by Woyte, et al. (2013) as a well suited irradiance recorder for PV system evaluation purposes. For comparison purposes a Solar-Log sensor box is also installed in a horizontal position on the roof together with the pyranometer so that the differences between the two devices can be determined. Below in Table 6 a summary with the details of the instruments used in the PV park. By following the links in the sources more information about the devices can be obtained.

Table 6: PV plant measurement instrument summary.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Model</th>
<th>Supplier</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar-Log logger</td>
<td>Solar-Log 1000</td>
<td>Solar-Log</td>
<td>(Solare Datensysteme GmbH, a, 2014)</td>
</tr>
<tr>
<td>Pyranometer logger</td>
<td>GP1</td>
<td>Delta-T Devices Ltd</td>
<td>(Delta-T Devices Ltd, 2014)</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>CMP11</td>
<td>Kipp &amp; Zonen</td>
<td>(Kipp &amp; Zonen, 2014)</td>
</tr>
<tr>
<td>Power meter</td>
<td>Inepro 1250D</td>
<td>Solar-Log</td>
<td>(Solare Datensysteme GmbH, b, 2014)</td>
</tr>
<tr>
<td>Sensor Box</td>
<td>Commercial</td>
<td>Solar-Log</td>
<td>(Solare Datensysteme GmbH, c, 2014)</td>
</tr>
</tbody>
</table>

Sensor box manufacturer: Mencke & Tegtmeyer

The data gathered from the systems can be acquired through a remote connection to the PV plant. It is thereby easy to refresh the data for the evaluation program whenever required.

In addition a web-camera is installed at the plant for the purpose of recording how the shadows and snow falls on the arrays. All the systems are not covered by the camera but the four free standing and the two dual-axis systems are within the cameras field of view.
4 DATA ANALYSIS

Data is collected from several sources with different format. The purpose of this section of the report is to explain how to data is gathered and structured into an easy to handle and functional database.

4.1 Available data

All of the ten Solar-Log loggers generate a data set based on the inverter type and sensors attached to it. In general the data from the loggers can be places into two groups, one for the SolarEdge inverters and one for the SMA inverters. The values that these manufacturers record differ in a few ways, in Table 7 the available data from the two sources can be seen. Like mentioned before there are only five sensor boxes divided over the ten systems and they have been connected to the loggers associated with the SolarEdge inverters. One more difference is that the SMA inverters do not log the current on the DC side but this value can be calculated by using the recorded DC power and DC voltage.

Table 7: General available data values from Solar-Log loggers.

<table>
<thead>
<tr>
<th>Value [unit]</th>
<th>Device</th>
<th>SolarEdge data</th>
<th>SMA data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>Power meter</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Power AC [W]</td>
<td>Sensor box</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Irradiance [W/m²]</td>
<td>Sensor box</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Module temperature [°C]</td>
<td>Sensor box</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Ambient temperature [°C]</td>
<td>Sensor box</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Wind speed [m/s]</td>
<td>Sensor box</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Power AC [W]</td>
<td>Inverter</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Power DC [W]</td>
<td>Inverter</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Voltage DC [V]</td>
<td>Inverter</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Inverter temperature [°C]</td>
<td>Inverter</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Voltage AC [V]</td>
<td>Inverter</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Current AC [A]</td>
<td>Inverter</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Besides this difference in data between the inverter and sensor boxes there are some alterations in the data within the same inverter group. This is due to the fact that the single-axis systems are divided into two strings while others are only one string. This causes additional data to be logged and further complicates the organizing of the data.

Since the pyranometer is not compatible with the Solar-Log logger system a separate logger were needed to handle this data. The two systems use different recording periods. The recording period is the interval for which the logger calculated a mean value. The logger samples data at a much higher rate than the recording rate to save memory space. If the logger where to save information at the same rate as the sampling period the amount of data will would be too big. One important consideration for all data gathering project is to find a good balance between the amount of data and the recording period. As stated in the literature review the appropriate record interval is five minutes. This interval is adopted by the Solar-
Log loggers but not by the logger used for the pyranometer. It instead records the values on a five second basis since no data averaging function was available in the logger software. This means that this data need to be recalculated to five minutes mean values to match the rest of the data.

4.2 Data structure

The data is structured into MATLAB matrix files, one file for each of the ten systems. The data for each system is designed to include all the relevant data for that system. This means that the data from the sensor box associated with each system group is copied to the corresponding systems data file. The same reasoning applies to the irradiance data from the pyranometer and the horizontal sensor box located on the roof. In this way the separate data from each system can be used without any other files, which simplifies calculations and results in a faster experience when using the program.

With the installment of the power meter on the AC side of the inverter, two values of AC power are obtained from inverter and the power meter, respectively. Rather than choosing one value over the other to use in calculations both are used and all parameters that are derived with these values are labeled accordingly. For example, the accumulated energy production is calculated using the AC power. This system property will be calculated two times using power readings from the inverter and power meter respectively. This applies to all parameters using the AC power in the calculations, see chapter 5 for more details. The main reason to why both values are used in the program is to give the ability to evaluate the differences between the power reading of the inverter and the power meter.

The data acquired from the SMA and the SolarEdge inverters are different from each other, which mean no general script or code can be written for all the data. Additionally minor differences do exist for the systems with the same inverter manufacturer. So the code used to organize the data is unique for most of the systems. No specific editing of the data is done in the code. The main purpose of the code is to organize the data as it is recorded. Any editing or filtering of data is done within the user interface of the developed software.
5 CALCULATIONS

In this chapter the calculations and formulas used by the program is presented. The main
purpose of the program is the give the user the ability to evaluate the systems performance by
providing many parameters and way to compare them to each other. In the literature review
it has already been explained how the performance parameters are derived and what they
stand for so in the chapter they will not be described as thoroughly. The first section will take
a look at how parameters other than the performance parameters have been calculated.

This chapter is not meant to be very descriptive, but used as a complement to the user and
foremost the user of the evaluation tool. It is meant to be as a lexicon with the formulas used
to compute the data values used by the program.

5.1 Basic calculations

Current
The data collected from the inverters does not contain the values for the DC current, but the
DC power and voltage does so the current can be calculated. It is done as:

\[ I_{DC} = \frac{P_{DC}}{U_{DC}} \text{ [A]} \]  \hspace{1cm} \text{Eq. 14}

where \( P_{DC} \) and \( U_{DC} \) is the DC power and voltage respectively.

Voltage
The roof mounted system without power optimizers (number 95-2) is the only system with
the modules divided into two strings. Because of this the inverter data naturally contains two
values for the DC voltage. To get a single voltage value for the system the average voltage
between the two strings has been calculated as:

\[ U_{DC,average} = \frac{U_{string 1} + U_{string 2}}{2} \text{ [V]} \]  \hspace{1cm} \text{Eq. 15}

This value is in turn used in the calculations for the DC current above.

Irradiance data
The irradiance data from the sensor boxes are in the unit \( W/m^2 \). The program does calculates
the accumulated irradiation the reference solar cell is exposed to. This is done by first
converting the average power reading to an amount of energy. The average power readings
are done once every 5-minutes (one twelfth of an hour) so to convert the irradiance to
irradiation the following calculation is done:

\[ H_{sensor \ box} = \frac{G_{sensor \ box}}{12 \times 10^{-3}} \text{ [kWh/m}^2\text{]} \]  \hspace{1cm} \text{Eq. 16}

where \( G_{sensor \ box} \) is the sensor box irradiance reading. The energy values are stored as an
accumulated total irradiation. These formulas are used to calculate the accumulated energy
recorded by all six of the sensor boxes in the park. A corresponding calculation is done for the
pyranometer data to calculate the accumulated energy recorded as 5-second values.
Energy
Both the DC and AC power readings are converted to an energy amount. Since the AC is measured by both the inverter and the power meter there are in total three energy values calculated as:

\[ E_{DC} = \frac{P_{DC}}{12 \times 10^3} \text{ [kWh]} \]  \hspace{1cm} \text{Eq. 17}

\[ E_{AC} = \frac{P_{AC}}{12 \times 10^3} \text{ [kWh]} \]  \hspace{1cm} \text{Eq. 18}

The energy values are the amount of energy recorded every 5-minutes since the power data is 5-minutes averages.

AC power meter readings ratio
As mentioned several times the AC power is recorded with two devices for each of the systems in the PV farm. Those are the inverter and an external power meter. To determine if and how the data gathered from the two devices differ the ratio between the values is calculated as:

\[ P_{AC \text{ ratio}} = \frac{P_{AC \text{ inverter}}}{P_{AC \text{ power meter}}} \text{ [-]} \]  \hspace{1cm} \text{Eq. 19}
5.2 Performance parameters

System Yield
The system yield is calculated as:

\[
Y_f = \frac{E_{AC}}{P_0} \left[\frac{kWh}{kW}\right]
\]

Eq. 20

where \(P_0\) is the combined module nameplate power of the system for which the system yield is to be calculated for. Because of the two data recordings to the AC power per system there are a total of 20 data sets of the system yield, two to each system.

Array Yield
The array yield is calculated as:

\[
Y_a = \frac{E_{DC}}{P_0} \left[\frac{kWh}{kW}\right]
\]

Eq. 21

Reference Yield
The reference yield is calculated as:

\[
Y_r = \frac{E_{sensor box}}{G_{STC}} [h]
\]

Eq. 22

where \(E_{sensor box}\) is the energy received by the reference solar cell during the time period for which the reference yield is calculated. \(G_{STC}\) is the irradiance for which the modules have been tested with to determine its performance. STC stands for standard test conditions. For these modules \(G_{STC} = 1000 \frac{W}{m^2}\) or \(1 \frac{kW}{m^2}\).

Performance Ratio
The performance ratio is calculated as:

\[
PR = \frac{Y_f}{Y_r} [-]
\]

Eq. 23

For each system two versions of the system yield \(Y_f\) is calculated because of the two recording of the AC power. Therefore the performance ratio is also computed with data based from both of the data sources.

The performance ratio can also be computed for the array side of the system. It is then calculated as:

\[
PR_a = \frac{Y_a}{Y_r} [-]
\]

Eq. 24

Inverter Efficiency
The inverter efficiency is calculated for each system as:
\[ \eta_i = \frac{P_{AC}}{P_{DC}} [-] \quad \text{Eq. 25} \]

Just as other parameters based on the AC power readings the inverter efficiency is computed with both available data sources for each system.

**System Efficiency**

The system efficiency is calculated as:

\[ \eta_s = \frac{E_{AC}}{H_{sensor \ box} \cdot A_a} [-] \quad \text{Eq. 26} \]

where \( A_a \) is the array area including the module frames. According to the data in Table 2 the area of one module is 1.94 \( m^2 \) and the array areas are presented in Table 4. The system efficiency is calculated in two versions for each system, one with the AC power data from the inverter and one with the AC power data from the power meter.

**Array Efficiency**

The array efficiency is calculated as:

\[ \eta_a = \frac{E_{DC}}{H_{sensor \ box} \cdot A_a} [-] \quad \text{Eq. 27} \]

**Capacity Factor**

The capacity factor is calculated as:

\[ CF = \frac{E_{AC}}{P_0 \cdot t} [-] \quad \text{Eq. 28} \]

where \( t \) is the duration for which the capacity factor is calculated for. The current data set uses 5-minutes average values so the duration in this case is one twelfth of an hour: \( t = 1/12 \).

**Capture Losses**

The capture losses are calculated as:

\[ L_c = Y_r - Y_a [h] \quad \text{Eq. 29} \]

**System Losses**

The system losses are calculated as:

\[ L_s = Y_a - Y_f \left[ \frac{kWh}{kW \cdot hr} \right] \quad \text{Eq. 30} \]
6 RESULTS

The result below will firstly consist of a system comparison of the ten research systems over a period of three weeks. Here the differences in production and available solar resource will be presented. The comparison will mainly be focused on the parameters that are related to the production of the systems and that can be derived from the AC energy output. Because of the questionably accuracy of the inverter power readings the comparisons will rely on the data collected by the power meters, which is believed to have a higher accuracy. A side effect of this is that some parameters, like inverter efficiencies and array yield, are not reliable in this context. The difference in accuracy of the data on the DC to the AC side of the inverter is too large for an accurate comparison. Using the DC values from the inverter and the AC values from the power meter, inverter efficiencies over 100 % can and do often occur in the data. Therefore in the evaluation all AC power data has been done using only data collected by the power meters. This does not however mean that this is the only data used. Some parameters like the reference yield rely on data from the sensor boxes and are used in the calculations required for the evaluation.

Some of the performance parameters presented in the literature review is left out from the evaluation. The capture losses, system losses and several efficiencies that rely on the inverter power reading are not used. The reason for this is that the majority of these parameters; see

\[ L_c = Y_r - Y_a \quad \text{Eq. 7} \]

\[ L_s = Y_a - Y_f \quad \text{Eq. 8} \]

\[ \eta_a = \frac{E_{d.c}}{A_{a} H} \quad \text{Eq. 10} \]

\[ \eta_i = \frac{P_{a.c}}{P_{d.c}} = \frac{E_{a.c}}{E_{d.c}} \quad \text{Eq. 12} \]

use the array yield or the energy production on the DC side when calculated. It has therefore been decided that the time is better used to evaluate the parameters with more accurate values in more detail. The capacity factor is another parameter that is not mentioned in the report other than in the literature review. As this value better serves as a performance value over longer periods it is only implemented into the evaluation tool for use in any future evaluations but the value does not make any major contribution to the evaluation performed in this report.

The second section will look more detailed on

6.1 A three week comparison

The period for which the systems have been
Figure 9: Horizontal solar irradiance from the 5th

Figure 10: Horizontal solar irradiance from the
6.1.1 System Yield

The system yield is the system production over the three week period normalized to the installed capacity for each system. The system yield is calculated according to $Y_f = \frac{E}{P_0}$ Eq. 3 and the data used is the AC energy recorded by the power meter located after the inverter. In Figure 12 this parameter can be seen, for easier comparison the systems with the same configuration except for the power optimizers are grouped together. Below the chart the individual numbers for each system is displayed for clarification.

The immediate thing that can be seen in the chart is that the systems with dual-axis tracking produce the most energy per installed power. Both of the dual-axis systems have produced roughly 110 kWh/kW. In this case the power optimizers have the difference of 0.6 % between the systems performance is within the measurement accuracy of the power meter. The single-axis tracking systems have produced less than the dual-axis. The system with optimizers has yielded 5.7 % more than the system without optimizers. The free standing systems and the system on the roof with 41° and 19° tilt has yielded about 80 kWh/kW. The free standing system with optimizers has yielded a bit more than the systems without, but for the fixed system on the roof the opposite is true. Here the system without optimizers has produced more than the one with optimizers.
In Figure 13 a ranking of the systems is shown. In the figure the two systems with similar tracking is separated with the notation of (PO), which stands for power optimizers. The graph shows that both the dual-axis tracking systems yield the most. On rank three and forth is the single-axis tracking systems, with and without power optimizers respectively. The free standing system with a 41° tilt and without optimizers produced a similar amount as the roof mounted system with optimizers. The system that yields least energy is the roof mounted system without optimizers.

Figure 13: System yield ranking.
6.1.2 Reference yield

Another interesting result is how much radiation that the different system groups are exposed with. The reference yield is a value that tells how much solar resource that is available on the specific location. In this case when all the systems are in the same location, factors like weather differences and seasonal effects are equal for the systems. Therefore the reference yield will reflect factors such as array tilt angle, mounting methods and tracking techniques much clearer. The data presented below is recorded by the reference solar cells sensor boxes located in the same plane as the PV arrays.

In Figure 14 the system groups are ranked based on the in-plane irradiation. The dual-axis tracking system receives the most radiation. It has received a total amount of 132.5 kWh/m². The three fixed systems have little variation in solar resources and have received about 94 kWh/m². The single-axis system is placed between these two groups with the radiation 114 kWh/m².

The small differences in the fixed systems are at least to some extent due to self-shadowing in the park. The roof mounted systems are higher up from the ground which reduces the chance of self-shadowing from other arrays in the park, but this will be looked at in the discussion further down the report.

The values for the free standing systems with tilt 19° and 41° indicates that even though the angle difference is high, the amount of radiation is adding up to the same. This observation can also be seen in the irradiation data calculated by an online tool (PVGIS). This tool says that the average daily irradiation is 5620 W/m² and 5600 W/m² for the plane angles 19° and 41° respectively.

<table>
<thead>
<tr>
<th>Reference Yield Y [h]</th>
<th>2-axis</th>
<th>1-axis - 30°</th>
<th>fixed roof - 19°</th>
<th>fixed free - 19°</th>
<th>fixed free - 41°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Yield [h]</td>
<td>132.53</td>
<td>114.46</td>
<td>96.44</td>
<td>93.56</td>
<td>93.00</td>
</tr>
</tbody>
</table>

Figure 14: Reference yield ranking.
### 6.1.3 Performance ratio

In Figure 15 the performance ratio for the ten research systems are presented. In the figure the y-scale has been reduced to only show the relevant data and so that the differences between the systems easier can be seen. An effect of this is what seems like a big difference between some of the systems is actually only a few percentages.

![Figure 15: System comparison of performance ratio.](image)

The dual-axis systems do perform similar to each other. The difference of 0.5% is well below the measurement accuracy for the electricity meter and therefore any real differences between these two systems can’t be observed. The single-axis systems along with the roof mounted systems shows a larger difference between the use of optimizers and no optimizers. For the single axis system the difference is 4.6% and for the roof mounted system it is 6.1%. The two free standing systems show an increased performance for the systems which are without power optimizers.

The ranking of the systems performance ratio is shown in Figure 16. The three best performing systems are in decreasing order;

1. Fixed, free standing with 41° tilt without power optimizers
2. Fixed, free standing with 19° tilt without power optimizers
3. Single-axis tracking with power optimizers

The worst performing system is the roof mounted without power optimizers. The best system can convert 89.1% of the available solar resource to electricity while the least performing system can convert 79.7%. That is a difference of \(0.891 - 0.797 = 0.094\) or 9.4% percentage units.

---

<table>
<thead>
<tr>
<th></th>
<th>With Optimizer</th>
<th>Without Optimizers</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-axis</td>
<td>0.831</td>
<td>0.826</td>
</tr>
<tr>
<td>1-axis - 30°</td>
<td>0.863</td>
<td>0.817</td>
</tr>
<tr>
<td>Fixed free - 41°</td>
<td>0.858</td>
<td>0.891</td>
</tr>
<tr>
<td>Fixed free - 19°</td>
<td>0.853</td>
<td>0.865</td>
</tr>
<tr>
<td>Fixed roof - 19°</td>
<td>0.858</td>
<td>0.797</td>
</tr>
</tbody>
</table>
In Figure 17 the same performance ratio ranking as in Figure 16 is shown but together with the total system losses. The y-scale has also been adjusted so that the losses better can be seen relative to the energy converted by the PV systems. The losses are the available solar resource that is not converted to electricity by the modules. The losses can be calculated as
\[
\frac{\text{Reference yield} - \text{System yield}}{\text{System yield}} = \frac{Y_r - Y_f}{Y_r} = 1 - \frac{Y_f}{Y_r} = 1 - PR.
\]

Figure 17: System performance ratio and total losses percentages
6.2 Detailed comparison

Above an evaluation of the systems have been done over a longer time period. It is also interesting to see how the systems behave over shorter timespans. Below two specific days with unique weather condition will be evaluated in more detail. Firstly a sunny day with lots of solar resource will be analyzed. This will be followed by a day with low radiation and high cloud density. The two dates have been chosen within the three week period and is the 11th and the 23rd of May. The result will mainly focus on differences between the systems yield and solar irradiance.

6.2.1 A sunny day 23rd May

First off it is good to take a detailed look at the available solar resource during the day and its differences between the systems. In Figure 18 the irradiance measured by the in-plane reference solar cell is shown for each of the systems. The naming of the systems seen in the chart legend is a system that is used at the PV park and to keep it consistent the same naming system is used here. To see what system that corresponds to which PV configuration you are referred to Table 4, where the system details are presented.

![Figure 18: In-plane irradiation comparison for a sunny day (23rd May).](image)

Of the five system groups the most illuminated is the dual-axis tracking system (red) followed by the single-axis systems (black). Between these systems there is a larger difference in the morning than in the evening. The reason for this could be explained by the limitations in movement of the single-axis systems, but this will be looked at closer in the discussion. The fixed systems have more or less a similar solar profile across the day. The graphs above have a parabola like shape with some noise or irregularities. For a perfect sunny day none of the spikiness would be present. During the three week period this was the day with the least clouds and other solar obstructions.
Knowing how the solar profile looks like, it can be seen in Figure 19 that the systems yield of the systems follow the same shape with some exceptions. In the graph not only the differences between the system groups can be seen but also the differences between each individual system.

Comparing the systems yield with the irradiance in Figure 18 one big difference is the decrease in yield for the single-axis system around 18 o’clock. It is suspected that this is due to shadowing of at least part of the array as the same pattern can be seen at the same time on the 20th through the 22nd of May, see Appendix I.

For both the dual-axis and the single-axis tracking systems the yield for the modules using the optimizers are higher in the morning. Just like the evening shadowing effect seen in the single-axis system this is a pattern that can be seen throughout the three week period, see Appendix I. This morning effect does not show in the data gathered for the fixed systems. Here other patterns can be seen instead.

The blue lines representing the roof mounted system displays a lower yield for the system without optimizers (blue, dotted line). The effect is stronger as the irradiance gets higher during the day; therefore the biggest effect can be seen in the middle of the day. This effect is not expected and the reason for the effect is not clear, it has to be investigated further.

The most stable system group, meaning where the differences between using and not using optimizers is smallest, is the free standing systems with 19° tilt. Here the lines are drawn almost on top off each other. This is consistent with the result for the whole three week period described in the previous section. In the system yield ranking graph (Figure 13) it can be seen that the difference between the two systems are just above 1 kWh/kW during the three week period. The results indicate that during this period the use of optimizers has little effect for this system configuration.

Figure 19: System yield comparison for a sunny day (23rd May).
The last system, the free standing with 41° tilt (green) does show a similar but opposite effect like the roof mounted system, namely that the system without optimizers has a higher yield. The effect is not as distinct as for the roof mounted system but is never the less consistent throughout the examined time period when the irradiance is high.

6.2.2 A cloudy day 11th May

The typical cloudy day is not as interesting as the sunny day. This is best illustrated with another graph, in Figure 20 the in-plane irradiance recorded by the reference solar cells are shown for each system for a cloudy day. The differences in solar resource are almost nonexistent. This is an expected result since the diffuse irradiation during cloudy days do not have any particular direction. The lines for the dual and single-axis tracking systems are hard to see because the other line has been drawn on top.

![Figure 20: In-plane irradiation comparison for a cloudy day (11th May).](image)

Just as for the sunny day the system yield, shown in Figure 21, follows the general pattern of the solar resource and in this particular day the two types of graphs are hard to distinguish from each other. They are so similar to each other that no conclusions can be drawn. The only thing that can be said is that the PV system configuration becomes less important as the irradiance gets lower.
Figure 21: System yield comparison for a cloudy day (11th May).
6.3 Result summary

The result presented in chapter 6.1 is scattered over many pages and is thus complicated to grasp and draw any conclusions from. This is especially true when trying to evaluate the potential effects of the power optimizers. Because of this the most relevant result has been summarized in Error! Reference source not found. In the table the result is divided into the five system groups and further separated by the installment of optimizers. The same system data, reference yield, system yield and performance ratio that can be found in the previous graphs is present in a compact format.

The different rows under system yield show the difference in both percentage and kWh/kW between the systems with and without power optimizers. All of the systems are also compared to the worst performing system in the park, the roof-mounted system without power optimizers. The high difference between the two systems on the roof (7 %) is a deviation compared to the other systems. This can indicate on some module malfunction or nameplate power mismatch for the modules in the system. The difference between the two systems on the single-axis tracker (5.4 %) is also large enough to notice. Some potential factors are as of why are discussed further down in the report.

Table 8: Summarized result over the three week period in mid-May 2014 with comparison against the worst performing system (WPS).

<table>
<thead>
<tr>
<th>System Group</th>
<th>Installed Optimizers</th>
<th>Dual-axis</th>
<th>Single-axis</th>
<th>Fixed free 41°</th>
<th>Fixed free 19°</th>
<th>Fixed roof 19°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Yield [h]</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>132.5</td>
<td>114.5</td>
<td>93.0</td>
<td>93.6</td>
<td>96.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Yield [kWh/kW]</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>+ % effect</td>
<td>0.6%</td>
<td>5.4%</td>
<td>3.6%</td>
<td>1.4%</td>
<td>7.1%</td>
<td></td>
</tr>
<tr>
<td>+ kWh/kW</td>
<td>0.6</td>
<td>5.1</td>
<td>2.9</td>
<td>1.1</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>+ % vs. WPS</td>
<td>30%</td>
<td>30%</td>
<td>22%</td>
<td>18%</td>
<td>4%</td>
<td>7%</td>
</tr>
<tr>
<td>Performance Ratio</td>
<td>0.831</td>
<td>0.826</td>
<td>0.863</td>
<td>0.817</td>
<td>0.858</td>
<td>0.891</td>
</tr>
<tr>
<td>+ % -units</td>
<td>0.5%</td>
<td>4.7%</td>
<td>3.2%</td>
<td>1.2%</td>
<td>6.1%</td>
<td></td>
</tr>
</tbody>
</table>
7 DISCUSSION

I want to make it clear right from the beginning of this section that the result retrieved during this project is based on a small time period. The three weeks in May used for the system evaluation is a too short period for any conclusive facts to be established regarding what type of PV systems that performs the best in the Swedish environment. The work conducted and presented in this report is meant to be a first preview of the data possible to gather from the research systems. As stated earlier in the text; one of the main goals for this project was to develop a tool, with which a continuous evaluation of the ten PV systems can be conducted. The result presented in this report is thus only representative for the current evaluation period, the middle of May 2014. This also holds true for any of the subsequent discussion and conclusions that are related to the specific result presented in this report that can be read in the following sections.

The following text will discuss some of the most important issues and problems that arise when the data evaluation is conducted. It is important to not trust the results as facts and push them forward as conclusions without reflecting over why the result looks the way they do. When analyzing the result one should have the following factors in mind:

- Measuring accuracy of the equipment
- Different inverter types and efficiencies
- Uneven shading of the systems
- Differences in real and nameplate power of the modules
- Higher module temperatures for tracking systems and thereby lower module efficiency due to increased radiation exposure

These factors are especially important for PV systems where external conditions like weather and seasons create many unique situations over long periods of time. When evaluating the performance of a system where external factors that can’t be controlled or predicted it is important to continue the evaluation for at least one cycle of, in this case, the seasonal effect. This would translate to one year as an appropriate evaluation period.

7.1 The effects of array shadowing

It is mentioned in the result that shadowing is suspected to cause some of the irregularities in the result. The decrease in yield for the single-axis systems in Figure 19 is a reoccurring phenomenon throughout the evaluation period for days with reasonable high irradiation. This particular system is not recorded by a web camera like the dual-axis and the four free standing systems so the array shading can’t be followed as detailed for this system. In Figure 22 the same decrease in yield as in Figure 19 is shown in greater detail and isolated from other systems. It can be seen that the system without optimizers has a higher yield about half an hour before the decrease also occurs for this system.
Figure 22: Suspected shadowing of the single-axis system in the evening.

Knowing that, seen from the photo of the array the evening shadow in the park first hits the left side off the array, see Figure 23, and that the systems located to the left side have power optimizers installed the data in the above figure is not surprising. In Figure 23 the shadowing of the dual-axis system illustrates this phenomenon in the evening on the 23rd of May. The graph shows that the decrease in yield occurs about one hour earlier than what is shown in the picture for the dual-axis system, but it seems possible that the single-axis systems suffers from shadowing a bit earlier. This explains why the system with optimizers experiences the decrease in yield earlier than the neighboring system. Since the shading starts to the left of the array it is expected that the left system will experience a production decrease before the same happens to the right system.

This is one example of shading of the arrays that is known in the park. The particular example above has been chosen because of it relation to the graphs used in the result. All the systems suffer from self-shadowing, that is shadows cast by the arrays located in front of the research systems. It is especially notable in the mornings and the evenings. Other examples of array shadowing can be seen in Appendix II.

The surrounding forest, both to the south and to the north does act as solar obstructions during the day causing additional shading for the system with trackers. The forest seen in the back of Figure 23 does cast some shadows during the morning. This forest is not very dense or thick so some radiation does get through. This can be seen by the high irregularities in yield during the early morning hours especially in the dual-axis tracking system, see Appendix I. The forest to the south is on the other side of the highway and is denser and thicker, but it is also further away from the arrays than the forest to the north. Because of this it does not cause as much problem. The effect of the southern forest is a higher horizon and therefore an earlier sunset.
During the evaluation period the forest to the south is not the cause of evening shadowing. During this period of the year the sun's path over the sky is high enough to not be affected by the forest in this side of the road. There are plans for removing large parts of trees that are causing shading in the park on both the north and southern side of the park.

Even though the system groups are constructed to be as identical as possible, except for the difference of the power optimizers and inverters, the data shows differences that are hard to determine the cause of, especially when the arrays are experiencing scattered radiation between the northern trees or uneven shading. If the array shading could be monitored with the same precision as the rest of the data it would be easier to determine if these differences is caused by uneven shading or by the power optimizers. Once the forests have been removed the effects of the shadows can easier by determined. One shading problem will continue to affect the arrays and that is the self-shading from nearby system trackers. These shadows can however be predicted by calculating the path of the sun and the relative position of the arrays. With that data the impact of the power optimizers could better be determined.
7.2 Performance ratio as a result

In the detailed section of the result the performance ratio is not presented and the reason for this will be discussed here.

In Figure 24 the performance ratio for the sunny day, the 23rd of May can be seen. The performance ratio is a value that should have a value between zero and one but judging by the figure this is not the case for the gathered data. In the graph several spikes of high performance ratio exists, some as high as six. One reason why this happens is because of the time resolution of the data. In the figure and most other graphs in the report is drawn with 5-minute average values. With such a short time interval the performance ratio gets more sensitive. The performance ratio is a function of the system yield and the reference yield, see

\[ PR = \frac{Y_f}{Y_r} \quad \text{Eq. 5.} \]

The reference yield is measured by the reference solar cell located on top the arrays and if this box is shadowed while a large part of the array is not shadowed this can cause the performance ratio to get a value above one.

![Figure 24: Performance ratio comparison for a sunny day.](image)

By looking at the pictures taken by the camera located in the park and comparing what is seen in them with the graph above there is some correlations with shadowing and high performance ratio. For the dual-axis system in the graph there is a spike at 6 o’clock and in Figure 25 the shadowing of the array can be seen from 6:00 am to 6:30 am. The pictures are used with permission by Kraftpojkarna AB. For the pictures it can be seen that the sun is coming out from behind the trees behind the arrays at this time of the day. As the sun come out, the radiation starts to hit the array on the right side seen from the picture perspective. Knowing that the reference cell is located at the middle of the array it is natural that the main part of the 67-1 system will receive the suns radiation before the reference cell is fully exposed. This will cause the effect seen in the graph.
A similar effect is present for the free standing systems as well. In the pictures above the shadow can be seen in on the system with 19° tilt angle on the far right side. It is not hard to see that the shading must affect the performance ratio.

The effect is by far strongest for the single-axis systems. With the knowledge of how the array tracks the sun, see Figure 4, it is understandable that the effect is strongest for these systems. Just as for the dual-axis array the sun hits the right side of the arrays first. This translates to the bottom of the single-axis array and causes the reference solar cell to be exposed by the light last. In Figure 24 it is mainly the single-axis systems with optimizers installed that show the high spike in performance ratio. The performance ratio gets higher either with a low reference yield or with a high system yield. In this case a combination of the two can be the explanation. The optimizers make the array less sensitive to string shadowing and will according to the manufacturer SolarEdge Technologies (2013) produce up to 25 % more than arrays without optimizers during conditions with partial shading. The optimizers might help the array to achieve a higher production compared to the neighboring system. At the same time the sun path causes the reference solar cell to receive little light, resulting in a low reference yield and thus a high performance ratio.

This pattern of spikes in the performance ratio is common throughout the evaluation period in the mornings and the evenings. By analyzing Figure 24 again the main part of the day has stable performance ratio values below one showing that when no or very few sun obstructions exist the performance ratio is much more stable. It is stated by Marion, et al. (2005) that the performance ratio usually is reported on a monthly or yearly basis, but that a performance ratio on a smaller time scale down to one day can be useful to identify component errors. Knowing now from the above example that the performance ratio is sensitive to array shadowing of these systems, the 5-minute average values of the performance ratio should be used with caution during evaluations. This parameter is better used on a longer time scale as in the three week evaluation done in chapter 6.1.
7.3 Instrument inaccuracies and their implications

Some other parameters not mentioned in the result are the numerous efficiencies and losses calculated over different parts of the PV systems. The capture losses and system losses do rely on that the array yield $Y_a$ is accurately calculated. The array yield is the specific production on the DC side. As stated before the AC side is measured with a dedicated power meter, but the DC side relies on the measurements of the inverter. In the report by Woyte, et al. (2013) it is stated that many of the inverters on the market do not live up to the standards required for these types of evaluations. Their measuring accuracy is accurate enough to identify malfunctions but does not serve as a high level monitoring device. For this they suggest using power or true-rms meters for both DC- and AC-power. The accuracies for which theses values are measured are thus different. This means that the array yield is calculated with a lower accuracy than the system yield and according to $L_c = Y_r - Y_a$ Eq. 7 and $L_s = Y_a - Y_f$ Eq. 8 the losses are computed using the array yield. Therefore the losses are not reliable enough to be part of the result in this evaluation.

The same is true for the inverter efficiency. It is the ratio between the production on the DC and the AC side of the inverter. With the less accurate values on the DC side the inverter efficiency values do when calculated often go over 100%.

These parameters have because of the reason stated above been omitted from the report result. If used as result, the time it would take to analyze if the inaccurate values or some other reason is the cause to the effects seen in the result would far outweigh the information these parameters would return.

7.4 Understanding the results

Displaying and presenting the result is one thing but understanding why the result looks the way it does is much harder. It is also often these questions that have the most valuable answers. To say that the one system is better than the other systems with a graph or number is not enough to make it true. There might be circumstances not obviously shown in the strict result that are causes to that particular outcome. To strengthen and back up the result a broader and deeper evaluation is required.

In the report so far the result has been discussed and backed up mainly by the comparison graphs and this is fine when looking at effects like immediate shadowing or fast changing parameters such as the 5-minutes averages of the performance ratio. To detect other possible causes to why some systems is better than others over a longer time period other methods are required. In the report by Woyte, et al. (2013) a method of monitoring how certain system parameters changes over weekly time periods is used. It is a visual evaluation method where the performance parameters are plotted against each other in a scatter plot. The data for each week is plotted as a separate series. A linear trend line is added for each of the series to display the average performance of that particular parameter. Each graph usually consists of four weekly data series and four trend lines.
This is easier understood by looking at an example. In Figure 26 the system yield have been plotted against the reference yield in a scatter plot with four data series in each graph. To the left the system behaves normally and the trend lines overlap with each other indicating that the average system performance ratio is unchanged from week to week. In the right graph though it is a distinct change is the system. In the first week the systems operates normally but during the next week one string is disconnected from the inverter resulting in a lowered production. This radical system change is seen in the next coming weeks in the graph as the lower line of data.

Other parameters can be plotted against each other to see other and the same effects. In Figure 27 the same string disconnection can be observed in a plot where the performance ratio has been plotted against the module temperature. Here the performance reduction is clearly seen by the reduced performance ratio in the later weeks in the graph to the right.
disconnected string and its module do still exist on the array and will therefore contribute to the same module temperature as before. The difference is that the module string will not contribute to any production.

Many similar graphs can be plotted to detect other system malfunctions within the systems. Below are a list of selected parameters from the report written by (Woyte, et al., 2013) and what kind of malfunctions the plots can detect.

- **System yield vs reference yield**
  - Defective string and inverters
  - Effects of shading
  - Cell performance degradation (aging)
  - Undersizing of inverters
- **Performance ratio vs. module temperature**
  - Defective string and inverters
  - Effects of shading
  - Cell performance degradation (aging)
  - Undersizing of inverters
- **Differences between module temperature and ambient temperature \((T_{mod} - T_{amb})\) vs. system yield**
  - Detect accumulation of insulating material between the back of the modules and the roof
- **DC voltage vs. module temperature**
  - Uneven array illumination
  - Power limitation by the inverter
  - Short-circuited solar cells or bypass diodes

This method is most useful for evaluations of longer periods where enough data is available to establish a baseline of how the systems perform during normal operation. The groundwork for this method has been implemented in the evaluation tool developed but due to time limitations this particular feature did not get as developed as planned. In the current version any parameter recorded or calculated from the systems can be plotted against each other but this feature needs some additional work to be used in a productive way.
8 CONCLUSIONS

The purpose of the work conducted here was to develop a software which can handle the data collected form the PV plant and allow the user to visualize the data and perform evaluations. The goal was to create a versatile application with many features and evaluation methods used in the field today. The evaluation done for the three week period serves as a preview of what the program can do. The program has in its current state several method of evaluation the data, both for short-term and the foundation for long-term evaluation. The later needs some improvement for it to be used in a productive way. The main features of the program are summarized in the following list.

- Automatic data scanning and organizing.
- Show data as a function of time.
- Show two variables with separate axes in the same graph for easier comparison. This helps in the analyzing of the data, reasons why the data looks the way it does can easier be seen.
- Draw all of the systems in the same graph in a comparison plot. This method allows for quick and easy comparison between all systems in the same picture.
- Create a scatter plot where any of the recorded parameters can be plotted against each other. This method can be used to see correlation between parameters.
- Functions for saving the graphs.

The three week period used in the comparison of the ten PV systems is too short for any general conclusions to be made about the different system configurations. For any real conclusions about that data for a least a year should be analyzed. This does not mean that the result presented in this report isn’t valuable. The subjects presented and discussed here have illuminated some of the major problems in the PV park early in the monitoring process.

One problem that has been illuminated by this study is the difficulty to use data gathered from sensors with different accuracies. In this case it was the inverter power readings contra the reading from the power meter. When comparing the data series of the AC power between two devices it can be seen that the differences is larger for low irradiation. The DC power is only monitored by the inverter and as such the parameters derived with the DC power suffer of the same inaccuracy. These parameters have because of this been omitted from the comparison in this report. This issue can be illuminated by installing another power meter on the DC side or make a deeper analysis of when the inaccuracy is the largest and keep that data out of the evaluation.

Some conclusions can be made regarding the production and performance of the PV systems for the monitored period. The most conclusive fact is that the dual-axis tracking system has the highest yield, followed by the single-axis system. The fixed systems have generated about the same amount of electricity and any separation regarding which of the system that is better can’t be done. With an exception of the roof mounted system without power optimizers, it has a notable lower yield than the rest of the systems with is suspected to be caused by some module malfunction. The system with the best performance ratio is the fixed, free-standing system with 41° tilt. Again the roof mounted system without the optimizers is the worst performing system.
When evaluating the system performance on a shorter time scale, by analyzing the 5-minute average data from the systems, it can be hard to determine the cause of the irregularities seen in the data. This has shown to be more difficult when the arrays suffer from shading. The shadows introduce yet another factor to consider when evaluating the systems. The fact that the shadow is not monitored as closely as the rest of the data it becomes hard to determine if the shading is the cause of the irregularities seen in the data.

There is still room for improvements in the program. The development time for the program was limited during the work since much time was taken to create the data structure and writing the report. Some features like the long-term evaluation method discussed in chapter 7.4 has suffered because of this and is not fully implemented in the program. Despite this the program is versatile and fulfills the goals set up for it in the beginning of the work.
9 SUGGESTIONS FOR FURTHER WORK

In this section suggestion on what features that can be added to the evaluation tool is presented. The goal of the tool is to be versatile and therefore all the features that have been considered valuable for the read literature is written here. Some of the features is not explained in detail due to the unnecessary information to the reader. Instead, references to the where the features have been seen is presented. In that way the ones interested can continue to read about it in those texts. The following proposals have the highest priority.

- Data availability.
  - It is important to know how much data that is available when the system evaluation is performed. When comparing several systems as done in this report it is important that the same amount of data is available for all the systems. This means that if one of the ten research systems are experiencing downtime the corresponding production data for the other systems should be omitted from the evaluation. Otherwise the evaluation would return an unjust result of the systems performance. Therefore a function in the evaluation tool should be implemented that takes these issues into consideration.

- Improved data handling by the program.
  - As time goes on the data gathered from the PV systems pile up. In the current state of the program the data handling is not optimal and is not optimized to handle amount of data 2-3 times larger than the currently available data. The algorithms for this section of the program need editing and rethinking.

- Data extraction from the program.
  - Even though the tool is designed to be as versatile as possible every possible future plot or data usage can’t be predicted. Therefore a feature that allows the user to extract the data that is shown in the graph can be very useful. The optimal way to implement this would be to let the user choses from what data her or she wants and when deliver this data in a familiar format, such as in an Excel workbook or MATLAB data file.

- Comparable monthly plots.
  - Just as the existing comparison plots where the systems can be compared to each other are useful, a comparison of the systems on a monthly basis can be useful.

- It would be of interest to investigate if results became more consistent if only hours of the day without shadowing on any the systems were used for the evaluation. That could be done by excluding early morning and late evening hours or to exclude data points with low irradiance.

- Further investigate the production differences for the two roof-mounted systems.

- 4-weak plots.
  - Further develop and complete the 4-week plot discussed in the report. See further details in section 7.4 and in the report by Woyte, et al. (2013).

- Stamp collection.
  - In the report by IEA task group 13 a collection of selected plots are aggregated to a small page to give a quick overview and comparison. More details in the report by Woyte, et al. (2013).

- Use IR-camera to see if there are problems with some modules, particularly for the roof mounted system without power optimizers.
10 LIST OF SOURCES


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[Accessed 20 5 2014].


APPENDIX I: System yield from 17th to 25th of May

A series of graphs showing some patterns seen in the data discussed in the report.

May the 17th:

May the 18th:
May the 19th:

![Graph for May 19th]

May the 20th:

![Graph for May 20th]
May the 21st:

![Graph for May 21st with data from 21/05/2014 to 22/05/2014 showing System 67-1 to System 95-2.]

May the 22nd:

![Graph for May 22nd with data from 22/05/2014 to 23/05/2014 showing System 67-1 to System 95-2.]

3
May the 23rd:

May the 24th:
May the 25th:
APPENDIX II: Examples of array shading in the PV park

Shading on a sunny day (23rd of May 2014)