MSc Program
Renewable Energy in Central and Eastern Europe

Monitoring of PV Plants

enhanced methods and yield forecasting

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **Stefan Beyer**, hereby declare

1. that I am the sole author of the present Master's Thesis, "Monitoring of PV Plants enhanced methods and yield forecasting", 62 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

In the past 20 Years Photovoltaic has evolved to be widely known as a reliable renewable energy source. The fact that a PV-plant can be realized without any moving parts, thus being very easy to maintain, makes this resource even more interesting for anyone interested in constant trouble free energy production. But - as in every power electric process - the conversion from light to power is still constantly under the threat of malfunction, due to various external and internal reasons. To minimise possible downtimes and to have the ability to exactly locate possible errors in order to fix them as soon as possible, automated monitoring systems have become more and more important in existing and newly erected plants. This is true not only for big installations but recently has become available also for small household installations.

The framework of this Master thesis is a detailed analysis of all possible errors that can occur in the PV power conversion. The first part describes the possibility of fast and exact detection of an error within a PV plant. Detection methods are discussed and evaluated by describing character and appearance of the error. The second part of the work is a detailed overview over the monitored parameters and the methods that can be used to evaluate the measured data. Diagrams and statistics are presented and discussed in order to understand their importance as a source for error localisation. The third chapter describes enhanced surveillance methods based on the capabilities of methods presented in the previous findings. Finally a possible method of yield forecasting is described and discussed. Based on meteorological data provided by ZAMG a calculation is made to evaluate the capability of such a forecasting method.

One outcome of this demo calculation is that it can be said that an exact yield forecast is nearly impossible because of the unpredictability of clouds. On the other hand it can be shown that under stable weather conditions the accuracy of prediction can reach more than 90%.

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1 Introduction

1.1 Personal Motivation

The motivation to choose this topic is my personal involvement in the field of PV power production and monitoring in Italy. Mangrovia, the company I am working for, is currently developing a monitoring system for PV plants erected and operated by partner companies in Italy. Through the necessity of the industry in needing reliable and stable monitoring systems and the fact that no "out-of-the-box" solution exists made my involvement in the topic more and more interesting. To fulfil the needs of a PV Plant operator an all-in-one solution is what seems to be needed but still missing in the market. Currently existing solutions cover different parts (Inverter monitoring, Surface monitoring, etc..) as island solutions but do not integrate the whole range of possible errors and problems. Therefore I began to evaluate and compare existing solutions and to define what the necessary items are that need to be covered by such a monitoring solution. By getting deeper into the matter I found out that through the usage of such a monitoring solution a lot of data is constantly produced and has to be stored. This data can be used to compare the internal and external states of a PV Plant with the yield of the Plant. As soon as this historical data is complete and available it is of course evident that – if the data is accurate – such a tool can also be used to predict an electric yield in the future. So I began to investigate the possibility to also include a forecast part into the monitoring system by taking into account that weather forecasts are becoming more and more accurate. In case these forecasts can actually be integrated in such a system it would have massive benefits for the operator. If it would be possible to predict the yield of a PV Plant approximately 12 – 24 hours in the future the electric energy could be sold at much higher prices at the energy exchange Market (EEX) than a mere flat feed-in-tariff (as it is the case for Italian PV Plants) could possibly gain for the operator. The findings of this thesis are a basis for the monitoring system that the company is now developing.

2 Utilization of solar radiation

To be able to understand the importance and the working principle of the monitoring of PV (photovoltaic) plants, it is necessary to give an introduction of all components, which are important in the generation of solar power. The following chapter will focus on the major PV components and their application in different designs of plants. Further on an overview over the possible errors that can occur in the power generation are listed and discussed.

2.1 History

Photovoltaic (PV) is the conversion of solar radiation into electrical energy by the use of solar cells. The term photovoltaic is a composition of the two terms Photos from the Greek word for light and Voltaic after Alessandro Volta, a pioneer of electrical engineering and emponym for the Unit of electrical tension. The principle of the photoelectric effect was discovered in 1839 by the French physicist Alexandre Edmond Becquerel. In 1954 it was possible to develop a practically usable solar cell. The first solar cells where used for power supply of satellites. The high cost of solar cells were negligible for the purpose of using them in satellites. Far more important was the high reliability, low weight and high efficiency. In the mid-70s PV became interesting for being used on earth for the first time. Since then the interest in this type of energy has increased tremendously. Feed in tariffs and financial insanities have led to such a fast growth of the PV industry, so that a steep learning curve could be realised. This was the base for a fast and global spread of PV technology

2.2 Design of Photovoltaic Plants

Photovoltaic systems can be basically divided into two groups. On the one hand, there are the so called autonomous systems, which receive their electricity entirely from the solar cells. To be able to utilize the time shift between generation and consumption the produced energy is stored i.e. in batteries. These plants are used where a connection to the public grid is not possible or advisable. Villages off the grid like on islands or in developing countries can be supplied with electricity without the need of building long transmission lines.

On the other hand there is the more common grid injecting, net parallel facility which is connected to the public grid. The size of plants can vary from some kWp to tens of Mwp. While smaller plants are mostly installed on or near houses . Big plants are realized mainly on the green field or on very big roofs. Nevertheless the main design of big and small plants is the same. Figure 1 shows a schematic configuration of a PV plant.

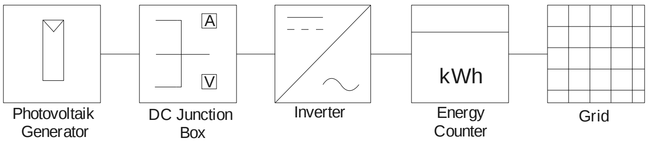


Figure 1: Schematic configuration of a Photovoltaic Plant

The main part of a PV plant are the photovoltaic modules which consist of photovoltaic cells connected in series as well as in parallel . They transform the solar radiation into electric current. In order to do so they have to be exposed to direct or diffuse beams coming from the sun. As already mentioned, they are typically mounted on roofs of buildings or on special mounting structures which are attached to the ground. But the range of possible applications is wide, so modules can be used as shading for car parks or be integrated in facades. Also used as mounting structures are so called solar trackers. The solar tracker is a device to align the PV modules towards the sun. It can follow the sun ether horizontally, vertically or both. An energy yield increase of 30% to 40% can be expected by using solar trackers.

Another very important part of the PV-plant is the inverter. It transforms the DC (Direct Current) energy generated by the plant to AC (Alternating Current) which is than metered and injected into the grid. Losses appear as in any kind of energy transformation. The efficiency of an inverter indicates how much energy is available after conversion . The efficiency of modern converters lies in the range of about 95%.

2.3 Working principle of the solar cell

A solar cell is a large area semiconductor diode. A semiconductor has a better electrical conductivity than an insulator but poorer than a conductor. Examples of semiconductor materials are silicon (Si), germanium (Ge), selenium (Se) Gallium arsenide (GaAs) or gallium phosphide (GaP). The most commonly used semiconductor material to produce PV cells certainly is silicon, It is sufficiently available and environmentally harmless . Silicon has four outer electrons, for a stable electron configuration it enters into a covalent bond with four neighbouring electrons. An impurity addition (doping) into the semiconductor crystal builds a p-n junction. If, for example the doping material are phosphorus-atoms the result is a so called n-region because the phosphorus-atom has five outer electrons. Four electrons are required for the crystal structure and the fifth is mobile and free. Vice versa for the p-region the crystal is doped with boron atoms. They only have three electrons. For the complete binding into the crystal one electron is always missing. This electron can be “borrowed” from the neighbouring atoms. In this way there is a positive “whole” mobile and wandering. If now an n-region is put together with a p-region, electrons diffuse into the p-regions and “holes” into n-regions. Therefore an electric field comes into existence in the former neutral junction (space-charge-region). It starts to increase until the further diffusion of carriers is avoided. [Kra06][Häb07]

2.3.1 The Photovoltaic Effect

In a solar cell,if photons or lower energy particles like infra red light (IR) hits an atom of the silicon crystal energy of the photon is possibly transferred to the electron. The photon is absorbed during this process. A electron-hole pair appears. Due to the eclectic field in the space-charge-region the electrons and wholes that appeared in this process wander to the respective other region. Between the contacts of the n-side and the p-side a tension can be measured. If the contacts are connected a current flows.

2.4 Energy conversion of a solar cell

Big losses appear during the conversion between light and electric energy. Not every wavelength of the solar radiation can be converted into electron-hole pairs. Electrons with a too low energy level can not produce electron-whole pairs. Electrons with a too high energy level simply pass through the solar cell without setting electrons free. Other factors like

- reflected light from the surface of the solar cell which cannot be used for power production
- leakage current
- electron-whole recombination which is caused by impure silicon
- self shading due to the contacts on the cell
- cell temperature

All of these factors lead to an efficiency of between 10% to 19% . Another important factor is the alignment of the solar cell with the sun. The solar cell should be mounted in a right angle to the sun. If light hits the cell in a flat angle the surface of the cell is smaller and therefore the energy production is lower. For the usability of light for different PV-cell materials see Figure 2. It shows different semiconductor materials and their specific energy absorption rate with the solar spectrum [Wat09]

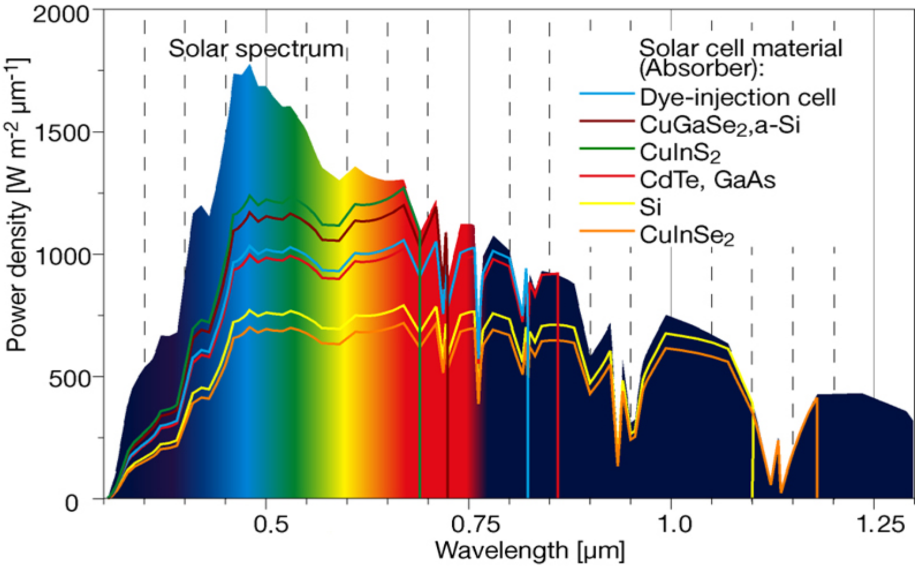


Figure 2: Energy usage of different cell materials in the solar spectrum (http://www.helmholtz-berlin.de)

2.5 Photovoltaic cell types

Solar cells can be categorised in different ways. The most common criterion is the thickness of the material which is categorised in thin film and bulk or thick film cells. A further criterion is the material of the used semiconductor. There is a lot of research and development happening is this field. The following chapter will state a short overview over the main cell types available on the market.

2.5.1 Bulk or thick film cells

It is called bulk or thick film cells because the semiconductor is sawed into slices of approximately 180 to 240 micrometers (wafers) which is much thicker than it would be necessary for the power production, but technically it is not possible to saw the wafers any thinner with today's technology. The wafers produced in such a way are soldered together to form the solar cell module. The only material that is used to produce bulk cells is crystalline silicon.

2.5.1.1 Monocrystalline Silicon cell

In monocrystalline or single crystal silicon the crystalline framework is homogeneous. It is pulled out of the high purity silicon smelter. These ingots are sawed to wafers. Its production is complex and more energy intensive than polycrystalline silicon cells. Nevertheless the efficiency of monocrystalline silicon cells is the highest of all single layer cell types.

2.5.1.2 Poly- or Multicrystalline Silicon cell

Silicon is cast to big ingots and carefully cooled down and solidified. Still the ingots have to be sawed to wavers. The complexity to produce polycrystalline silicon is a lot lower than monocrystalline but its energy efficiency is sufficiently lower as well.

2.5.1.3 Ribbon silicon

It is a type of multicrystalline silicone with the difference that the wafer are pulled out of the smelter. In this way thinner wafers can be produced and less silicon waste accrues. The production costs can be reduced but also efficiency of the cells is lower.

2.5.2 Thin film Solar cell

Various different thin film technologies are currently being developed. The benefits of this technology are smaller amounts of light absorbing material which is needed to produce solar cells, a bigger tolerance for shading and low irradiation and a better temperature coefficient. This leads to price reduction but again to lower efficiencies compared to bulk cells. Exceptions are multi layer thin films which reach efficiencies higher than bulk silicon cells but they are also more expensive.

2.5.2.1 Silicon thin films

Thin film cells made of amorphous or unstructured, non-crystalline silicon have a very thin layer thickness (0,5 – 2 µm) . The silicon is evaporated on a backing material like glass.

Microcrystalline and micromorph silicon is a mixture of amorphous silicon and very small silicon crystals. They have a better efficiency than amorphous silicon cells so they can compensate the disadvantages of amorphous silicon. They have a large energy potential if being combined with multi layer cells like a-Si/µc-Si.

2.5.2.2 Cadmium telluride cell (CdTe)

CdTe is an easy to deposit material that is suitable for big scale production. Because of the simple production process they are cheaper and therefore can help reducing the cost of plants. A lot of big plants are currently realised with CdTe modules because of the good cost-value ratio.

2.5.2.3 Copper-Indium-Selenide cell (CSI)

In CSI cells Copper Indium and Selenium are used in very thin layers instead of silicon to transform the irradiated light to electricity. They nearly absorb 99% of the irradiated light and therefore therefore appear deep black. The efficiency potential makes them very interesting as they can already be produced with 20% cell efficiency.

2.5.3 Concentrating photovoltaic (CPV)

CPV technology focuses light onto a small area with the help of lenses or mirrors. The concentrated light hits a small PV cell with high efficiency. These modules have to be used with a very exact sun tracker which always follows the position of the sun. Only direct irradiation can be utilised in this technology. The low cell material use and the high efficiency makes CPV very interesting for areas around the equator but also in the south of Europe.

Cell type	Cell efficiency in the laboratory	Cell efficiency production
Monocrystalline Silicon	24,70%	15 - 18%
Polycrystalline Silicon	19,80%	13 - 16%
Ribbon Silicon	18,00%	0,00%
Amorphous Silicon	13,00%	8,00%
Microcrystalline Silicon	14,50%	8,50%
CdTe	17,00%	10,70%
CSI	20,00%	11,00%
CPV	30,00%	25,00%

Table 1: Cell efficiency of different cell types [Kal06] [FCK09]

2.6 Possible sources of error in power generation

Whenever power electronics are involved in technical systems, errors can occur. Therefore one has to expect errors in complex facilities like Photovoltaic plants.

A small error or a failure of a little small part in the system, like a diode, can cause noticeable losses in power production of a PV system. This inevitably leads to an error search and correction of the error which can be very time and cost intensive. Additionally the constant meteorological changes complicate the quest. In the following chapter an overview of possible errors is given. The errors will be categorized according to the locations of the components of the facility (see Figure 1)

2.6.1 Errors in PV modules

To understand the errors which appear in the generator of a PV system one has to understand the design of solar modules. Solar modules consist of silicon cells. To be able to expose the cells to light the interconnected cells have to be packed in an enclosure to be protected against environmental conditions. This is realized by hermetically sealing the silicon cells closed between transparent plastic i.e. EVA (ethylene-vinyl-acetate),TPU (thermoplastic polyurethane), PVB (polyvinyl butyral) or silicones. Low iron glass (3 – 4 mm) with a very a high light transfer rate is mostly used as front coverage. The back is either covered with glass or plastic i.e. Polyvinylfluorid (tedla) and polyester.

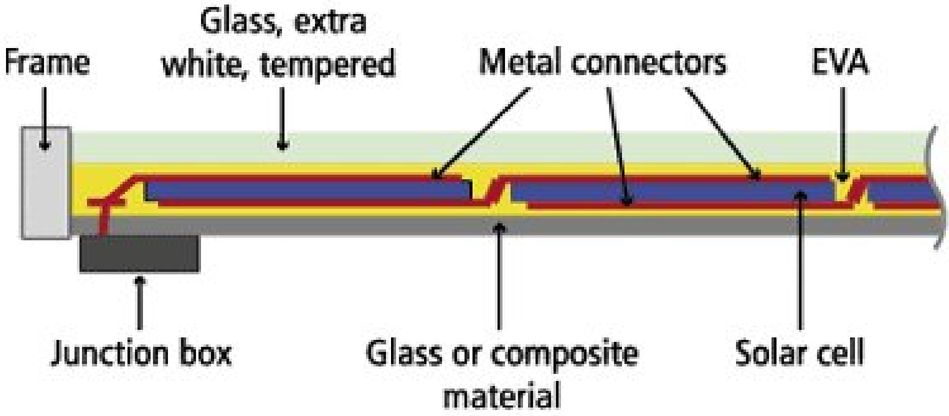


Figure 3: Assembly of a PV module (www.photon-magazine.com)

A junction box that normally also contains the bypass diodes is installed in order to connect the cells to the inverter, located in the back of the modules. Finally the classic module is framed with an aluminium profile that also serves as reinforcement, edge guard and mounting structure. If the module is used without framing the glass is much thicker (6 – 10 mm) since it has to provide the stability for the module .

As a matter of fact silicon cells produce an electrical potential difference of around 0,7 V. To reach a feasible voltage the silicon cells have to be connected in series. This forms so called strings where the voltages of the single cells sum up to the module voltage. Further more the strings are connected in parallel to increase the current. Normally every string is protected by a diode connected anti parallel. The voltage in a shadowed cell can surpass the negative breakthrough voltage. This can lead to a local power dissipation that could harm or even destroy the cell. This is called the “hot spot” effect.

Over the lifetime of the modules they are constantly exposed to all kind of environmental conditions. Like constant thermal stress, precipitation and constant irradiation. Therefore the enclosure,the cells, their interconnection or the isolation of the parts carrying current to the mounting structure can be damaged. The significant errors and their corresponding components are:

- flaking of the cell embedding
- blistering in the cell embedding

- discolouration of the transparent embedding
- ingress of moisture into the laminate
- fracture of a single cells
- defective electric conduction within the module
- bypass diode defect (shorted or disconnected)
- bypass diode not mounted or mounted the wrong direction
- short circuit between cells
- soiled modules due to dust
- soiled modules due to moss/algae, bird droppings

2.7 Inverter

Inverters are used to convert DC voltage to AC voltage. The output voltage form can be rectangle, trapezoid or sinus shaped. Modern inverters also have a **m**aximum **p**ower **p**oint (MPP) tracking unit to regulate the DC voltage to get the maximum energy out of the modules. See chapter 2.7.2

Inverters can be separated in two Groups.

- Inverters for autonomous operation
- Inverters for electrical grid injection.

In autonomous systems the generated energy has to be used at once. This can be done for example using the energy pumping water or store it in a battery bench. The inverters for autonomous systems can be separated in three categories. All of them are being used, depending on the appliance. For the sake of completeness all of them are mentioned here.

- Inverters that produce a rectangular AC waveform by changing the polarity of the DC with the needed frequency

- Inverters that produce a trapezoid AC waveform by switching to zero voltage over a period of time and changing polarity to reach a better approximation to the sine-form
- Inverters with a pulse width modulation (PWM) that produces a sinus like curve.

To feed electricity into the grid inverters have to produce a grid conform AC. To cover these requirements two types of inverters are available.

- Line commutated inverters
- Self commutated inverters

Line commutated inverters use very robust thyristors as electronic switches. The output current has to be filtered and compensated because of design reasons that makes these inverters more expensive but still economical beyond 100 kW .

Self-commutated inverters are built with detachable circuit breakers therefore no external grid is necessary. Again PWM is used to produce AC voltage. the difference is that they have to synchronize with the steady grid. If a system incident in the leading grid happens it is automatically cut from the grid to avoid overvoltage or other damages.

2.7.1 Inverter concepts

There is no general concept for the use of different types of converters. The concept always has to correspond with the specific plant situation. Inverters can be divided into three groups.

- Central inverter
- string inverter
    - multi-string inverter
- module inverter

Central inverters are connected to the entire solar generator over one line. The PV array consists of multiple stings that are connected parallel in the DC junction box. The generator consists of a combination of parallel and serial connected modules. They have to be illuminated equally and have to have a very small tolerance characteristics if the system voltage is high. If the system voltage is low (small number of serial modules is small) the tolerance for partly shading and characteristic variations is higher.

For big plants inverters up to 2.5 MW power are available. These inverters mostly are built modularly so that a module with a malfunction does not interfere with the rest of the system. Further on the inverter modules are switched on and off depending on the from the modules provided energy. The benefit of the central inverter concept is that plants in the MW range are made possible and there design is very robust. See Figure 4 for a schematic central inverter layout .

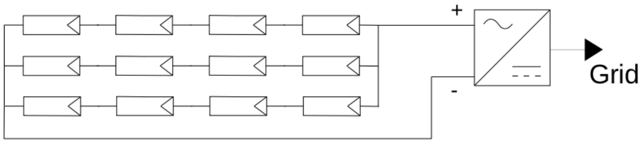


Figure 4: Central inverter layout with 3 strings parallel

String Inverters are connected to the solar generator in the same way as central inverters. The difference is that the generator always consists of only one string. String inverters are very efficient and are produced in big amounts and are therefore cheaper than central inverters. They are available in a wide power range, so they are starting to become an all round solution, big plants can also be realised using them. The big advantage of the layout of string inverters is it’s high efficiency. Strings with different orientation and shading are possible. The generator junction box can be omitted and the inverter can be mounted close to the modules. See Figure 5 for the schematic string inverter layout.

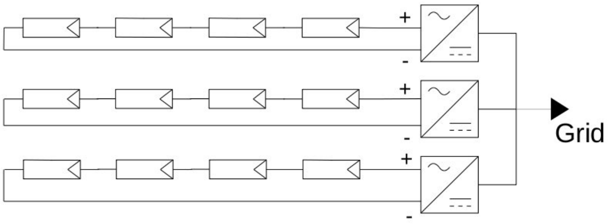


Figure 5: String inverter layout

Multistring inverter can be seen as a multiple string inverter on the DC side and like a central inverter on the AC side. They are mainly used in small plants where modules of different strings are illuminated differently, string sizes are differing or different module types are being used. The generator works more efficiently since every string has it's own MPP tracker and can work in it's optimal MPP. The benefit of multistring inverters is that non standard plants can be realised with them and the yield is higher than in central inverter layouts because of the use of multiple MPP tracking unites. See Figure 6 for a schematic multistring inverter layout.

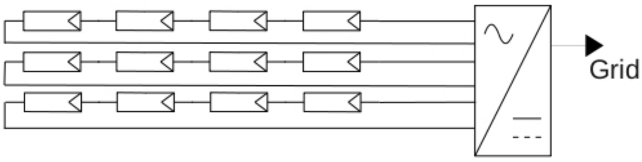


Figure 6: Multi string inverter layout

Module inverters are mounted directly onto the solar module. The DC power generator by the module is transformed to AC directly in the back of the module. The advantage of module inverters is that DC losses are being avoided as well as the problem that occur when high DC voltages are switched or cut (electric arc). Additionally the modules can be shaded individually, have different characteristics or can be differently orientated without influencing the total power production. [Dür08] See Figure 7 for a schematic module inverter layout.

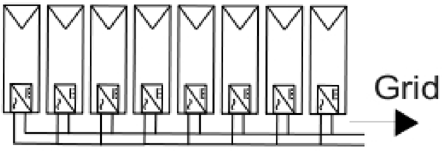


Figure 7: Module Inverter layout

2.7.2 MPP Tracking

The function of a **M**aximum **P**ower **P**oint **T**racking (MPPT) unit is to find the point on the current-voltage characteristic line where the product of current and voltage has it's highest value. At this specific point the array produces the highest power possible for the unit. Usually the used MPPT-algorithm locates the point of maximum power production in intervals of some seconds to several minutes. In order to do so the working point voltage is shifted up or down in small fractions. If the resulting current rises the working point voltage is shifted in the same direction again in the next step, otherwise it will be shifted in the other direction. The characteristic line is not constant. It depends on factors like irradiation conditions and module temperature. As shown in figure Fehler: Referenz nicht gefunden the current increase proportionally to the increase of irradiation while the voltage stays nearly constant. If the temperature increases the voltage decreases and the current stays nearly constant. [Kal06] [Dür08]

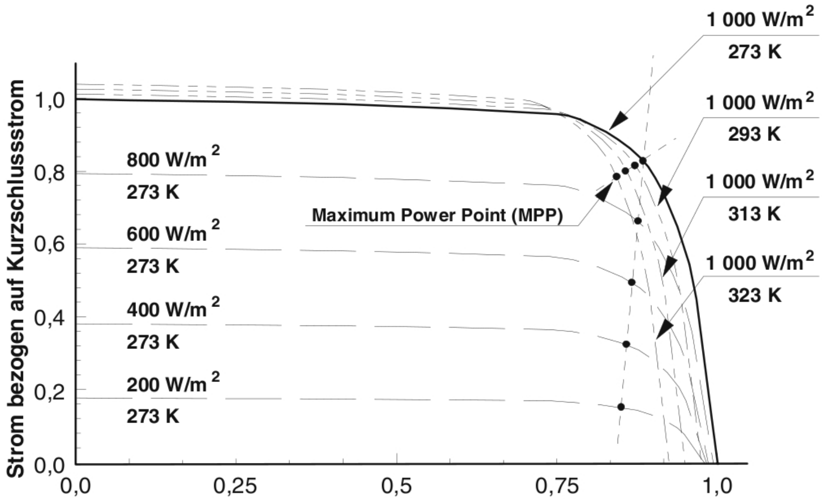


Figure 8: Current-voltage characteristic line with variable temperature and irradiation (horizontal axe is Voltage/ vertical axe is current) [Kal06]

2.7.3 Errors in the inverter

As mentioned in chapter 2.5 different facility concepts can be realized. The classic layout is the central inverter concept. The Inverter is connected to a generator that consists of stings of modules connected parallel. A relatively complex DC cabling is required and the facility is more sensitive to shading and mismatch within the generator. See chapter 2.7.1 Figure 4

Smaller string inverters are designed to be connected to just one string. The cabling is less complex and because of the shorter cabling distances the loss occurring on the DC side are considerably smaller. As a matter of fact smaller inverters can operate optimized with the string and can adapt better to irradiation conditions. See chapter 2.7.1 Figure 5

This is the core part of the facility because the MPP unit regulates the generator output. It is the path for the generated energy into the grid and also a monitoring interface. If a central inverter fails the whole plant can not feed any energy into the grid anymore. The advantage of string inverters is that the facility is divided into smaller units which makes the overall losses significantly smaller (in the case of a malfunction). The significant errors and the corresponding components are:

- MPP error – failure of the MPPT unit
- inverter detected accidental grounding
- over-voltage protection triggered on AC or DC side
- overheating
- power limitation (derating) as a result of a too high power production of the generator

2.8 Cabling

In big PV installations several hundreds to thousands of meter of cable are being installed. Modules are connected to strings, strings are combined to arrays and arrays are connected to the generator. Because of the constant stress and the high DC voltage the DC cabling has to fulfil certain requirements:

- short-circuit and earthing proof

- weather and UV resistant
- light and thin, with low conduction losses
- flame-retardant
- high voltage range

Figure 9: Photovoltaic cables, connectors and a module junction box [Häb07]

Figure 7 shows typical photovoltaic cable, connectors and a module junction box that should also contain the module diodes.

2.8.1 Errors in the cabling

Errors can occur in several thousand connections within the solar connectors and connection-terminals and the cable itself. Defective connecting-terminals can lead to disconnected parts of the generator and in the worst case scenario to arcs and eventually fire. To prevent this the solar connectors have interlocks but still can be disconnected accidentally. The cable itself can cause errors if it is not mounted properly or is for example mechanically damaged. The significant errors and the corresponding components are:

- corrosion on solar connectors or connecting terminals
- defective cables – short circuits, grounded circuits and therefore accidental bodily injury
- bad connections causing high resistance

2.9 Array/generator junction box

To minimize unnecessary long cabling bigger generators are separated in arrays. The strings of the arrays are connected in the **A**rray **J**unction **B**oxes (AJB) with string connecting terminals. The outbound array cables are connected to the generator in the **G**enerator **J**unction **B**ox (GJB) with generator connecting terminals. From there the DC main line is connected to the inverter. For lightning protection there are varistors that are monitored for heat and mounted in the AJB and in the GJB. Parallel to the power carrying cables there should be a potential equalization cable that is earthed at the inverter and connected to the mounting structure of the modules . In the AJB the strings are connected parallel. Every string has an element connected in series to protect the string against back current and overload current. This can be a diode (string diode, blocking diode) and/or a fuse or a automatic circuit breaker. To be able to disconnect the string from the rest of the generator there is often a DC disconnector. Last there are fuses on both sides of the string and disconnection terminals.

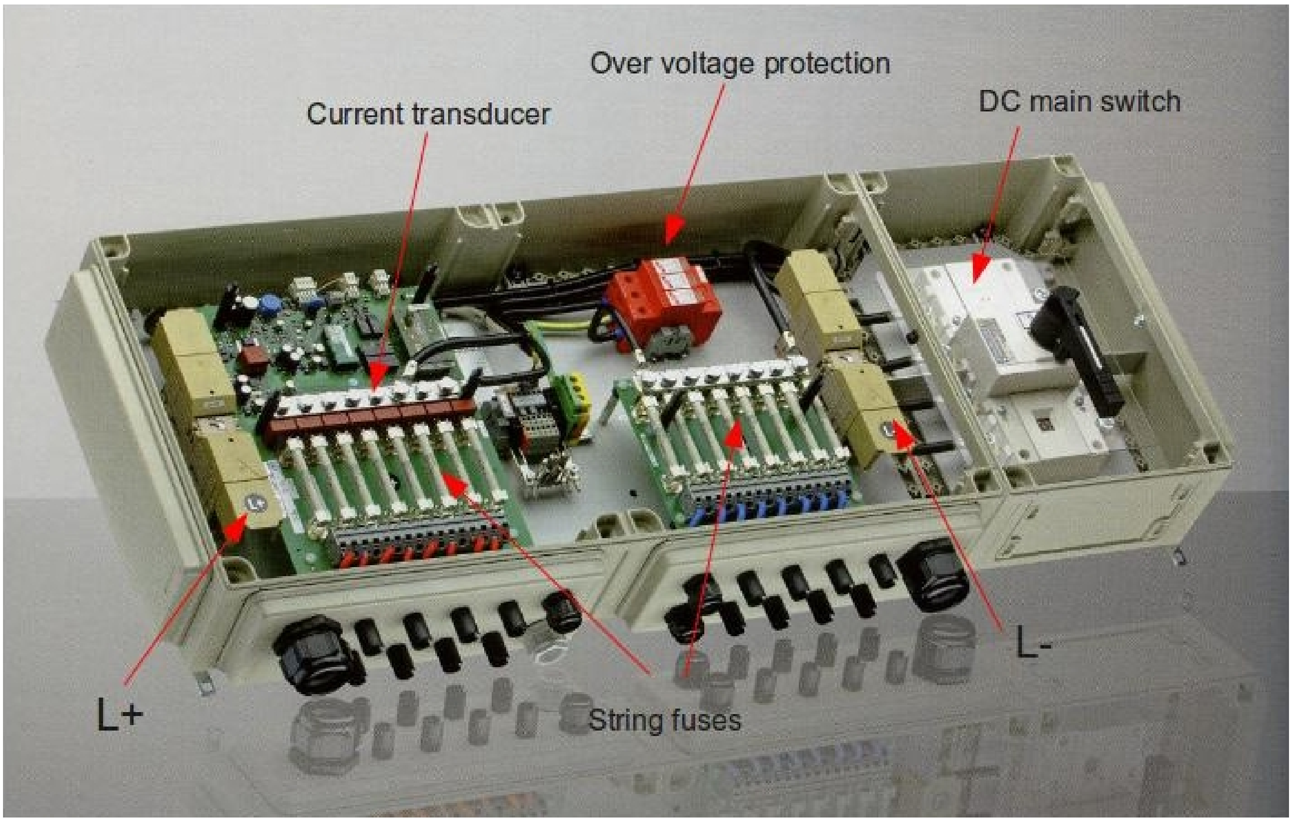


Figure 10: Array junction box with over voltage protection,power bus bars, string fuses and string current measuring unit. Modified by Stefan Beyer (SMA-Catalogue 2009/2010)

2.9.1 Errors in the array/generator junction box

In case of a failure of one string such as voltage reduction (caused by shaded modules, short circuit or short circuit to earth) the string diodes prevent the rest of the array to "feed" the defected string thus possibly destroying it. As mentioned above another possibility to prevent damage is a fuse or an automatic circuit breaker which is a bit more expensive but more secure and provides the possibility of switching the string without current. The automatic circuit breaker can also be switched remotely if a string current monitoring unit is integrated. The significant errors and the corresponding components are:

- shortened diode
- blown fuse
- triggered overvoltage protection
- high system resistance because of bad or loosened connections
- electric arc because of loosened connections

2.9.2 Errors from the grid

The grid is the connection to the consumer. It is very important that the facility does not harm the grid. As the grid is not a part of the plant I will only mention the most significant errors here.

- disconnection caused by over/under frequency or voltage
- disconnection in result of outage of the grid

2.9.3 Summery

Chapter 2 shows that the production of energy with photovoltaic system is complex and the sources of errors are diverse. The power output depends mainly on the irradiated energy from the sun. But the design and dimensioning of the components are essential for the sufficient power utilisation. In chapter 2.6 is demonstrated that the detection of errors that can occur during power generation is complicated because of the amount of components and the similarity of symptoms caused by different problems, if the system is not provided with a proper monitoring system.

3 Monitoring

The following chapter gives an overview over the different sensors and functional characteristics that are essential for error detection in PV power generation. As well as the methods used for monitoring. A detailed discussion of the method of normalizing data utilized my monitoring devices and their interpretation follows.

As described above causes for malfunctions of PV plants may have diverse reasons. These can range from shading of modules, failure of a module or string, the breakdown of an inverter, a malfunction of the MPPT, etc. Every error has it's specific characteristics and can be detected more or less successfully. The failures can be very diverse and have to be analysed as the case arises.

In order to make a reliable monitoring system for PV Solar facilities it is necessary to install sensors that measure the parameters for the power generation and error detection. In order to interpret the measured data it is necessary to register and store the sensor's collected data. The more detailed the parts of the facility are being monitored and the shorter the intervals of the recordings, the better and faster is the possibility of an exact interpretation of the acquired data and therefore the localization of the failure.

3.1 Status quo

The Research centre in Ispra has introduced a document for monitoring guidelines in 1995 in the course of an EU project. The aim was to define parameters that are essential for the monitoring of PV plants for scientific and research matters. This Document can be seen as the basis for the current state of monitoring. Figure 11 shows a power flow diagram of a PV plant and the corresponding parameters which should be recorded for an analytical monitoring. The corresponding parameters are listed and described in Table 2 .

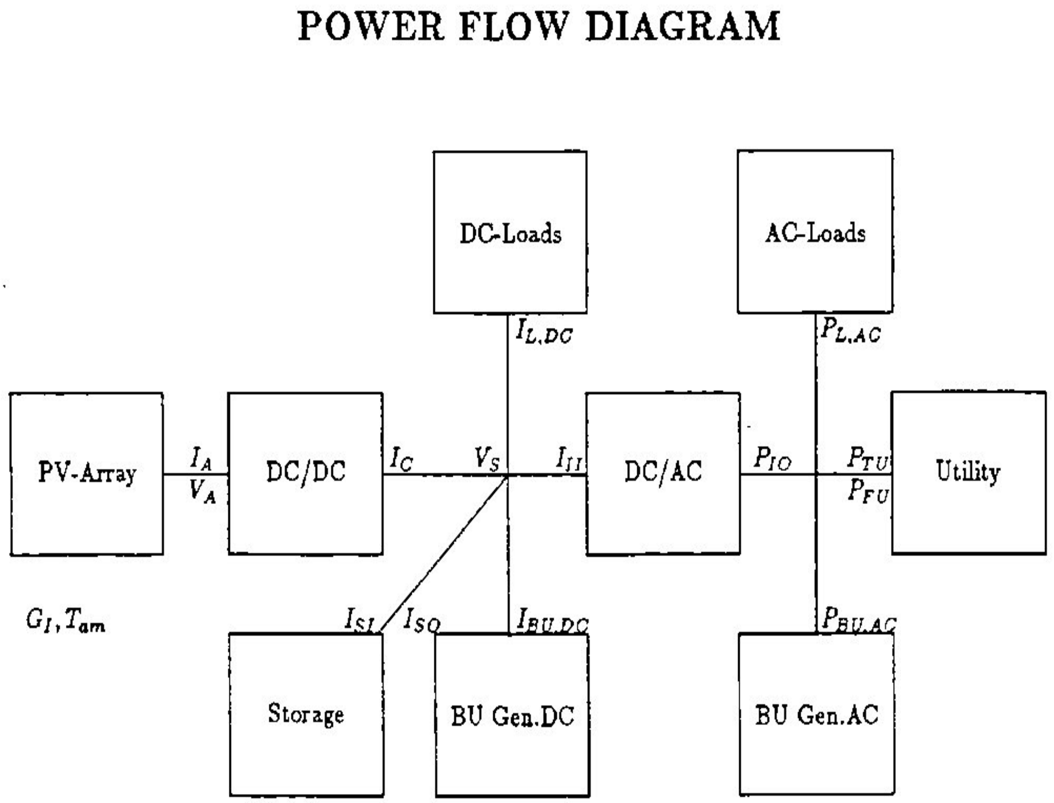


Figure 11: Power Flow Diagram [BM95]

PARAMETER	SYMBOL	UNIT
Irradiance, total (array plane)	G_I	W/m^2
Ambient temperature in the shade	T_{am}	°C
Array output voltage	V_A	V
Array output current (total)	I_A	A
Converter output current	I_C	A
Current input to storage battery	I_{SI}	A
Current output from storage battery	I_{SO}	A
dc line voltage (battery voltage)	V_S	V
Current to all dedicated dc loads	$I_{L,DC}$	A
Inverter/rectifier dc current (+/-)	I_{II}	A
Inverter/rectifier ac power (+/-)	P_{IO}	kW
Power to all dedicated ac loads	$P_{L,AC}$	kW
Power to the utility grid	P_{TU}	kW
Power from the utility grid	P_{FU}	kW
Power from auxiliary ac generator	$P_{BU,AC}$	kW
Current from auxiliary dc generator	$I_{BU,DC}$	A
Non-availability to load	t_{NAV}	hr

Table 2: Recorded parameters for analytical monitoring[BM95]

More or less all inverter producers provide a monitoring system that is capable of handling multi MW installations. Some independent companies and system integrators provide such systems as well. These systems mainly consist of:

- Data logger – collects analog and digital data collected from the inverter and the sensors. This data is mostly forwarded to a server that provides data analysis as well as a graphic output of the collected information .
- Inverters - giving information about their own status regarding power generation and conversion as well as the status of the grid (grid impedance)
- Sensors – collecting data from module thermometers, anemometers, pyranometers, reference cells, current sensors etc.

Various methods are being used for the monitoring of PV solar facilities. The bandwidth ranges from simply value input/output comparison to sophisticated numerical facility analysis . The most common methods are stated in chapter 3.3 Nevertheless all methods claim to fulfil the flowing functions.

- Identification of errors
- Location of errors
- Simultaneous readout of data during full operation of the plant
- Analysing data regarding the energy yield and efficiency of the plant
- User friendly maintenance

3.2 Monitored parameters

To be able to monitor PV plants it is essential to have detailed information about the current status and the history of the performance of the plant. The measured values concern the voltages, currents and power of strings and generators as well as the external influences on the plant and it's safety devices I.e. accidental grounding detection.

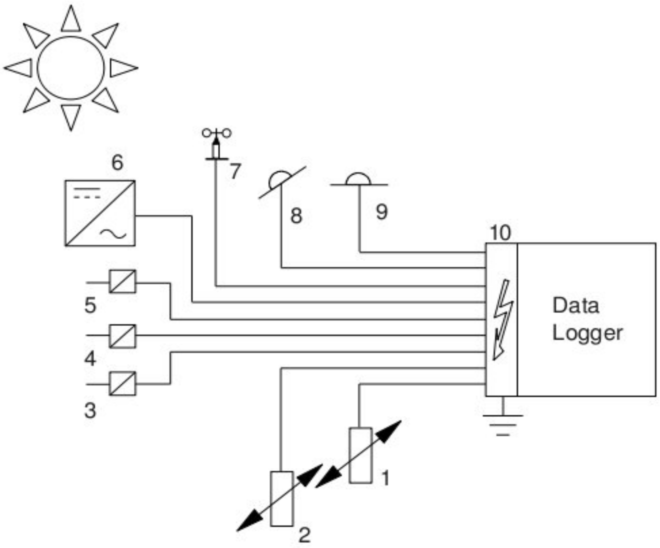


Figure 12: Schematic configuration of a monitoring unit

Caption of Figure 12:

1. Module temperature

2. Ambient temperature

3,4,5. Power, current an voltage measuring device

6. Inverter interface

7. Wind speed and direction

8. Irradiation on the module layer

9. Global irradiation

10. Over voltage protection

3.2.1 Devices to measure solar radiation

The solar radiation is the total spectrum of electromagnetic waves emitted by the sun. This is one of the main factors that gives us information about the theoretical output of the PV plant. With this data it is possible to compare the theoretical to the actual output of the plant. There are two common ways of measuring the solar radiation that is relevant for PV. Pyranometers are used to measure the entire solar radiation, irradiance sensor measure the irradiance effective on the sensors (insolation). The unit for the instantaneous irradiance is [W/m²]. The unit for isolation is [kWh/m² day] respectively [kWh/kWp*y] for photovoltaic.

3.2.1.1 Pyranometer

Pyranometer are instruments that measure the Solar radiation on a plane surface. They are mounted horizontally or in the same angle as the modules – if they should measure the incoming solar radiation which is seen by the PV modules and have a field of view of 180°. Usually they cover the spectrum of the solar radiation with a wavelength of 300 to 4000 nm. It consists of A thermopile sensor with black coating. The sensor is sensitive for irradiation with a range from 300 to 50 000 nm and is covered by a glass dome which limits the sensitivity (The irradiation from 4000 to 50 000 nm is filtered) and additionally shields the sensor from convection.

Pyranometers are very precise in measuring the overall insolation over a longer period of time but have a very high inertia and are therefore important for data collection thus interesting for monitoring system. They cannot however measure shorter changes in solarisation. In order to be able to analyse the ratio between irradiation and power output irradiation sensors or reference cells are being used that have a substantially lower inertia.

Figure 13: Pyranometer (www.eijkelkamp.com)

3.2.1.2 Irradiation sensors

Figure 14: Irradiation Sensor (www.tritec-energy.com)

Irradiation sensors or reference cells consist of a silicon solar cell that is laminated between glass and Tedla foil. This is mainly the same design as in PV modules. Irradiation sensors are also sensitive to sensor temperature that has to be taken into account. The function of the sensor is based on the fact that the short-circuit current is proportional to the isolation. The characteristic of this sensor is similar to a PV cell and therefore it is the ideal sensor for an actual-theoretical comparison. The actual process of measuring the irradiation, is realized by measuring the short circuit current which is proportional to the irradiation. To compensate the thermal losses of the PV cell which is used in the irradiation sensor, the temperature has to be measured and taken into account. The detected temperature can be used as “module temperature “.

3.2.2 Wind measurement

The sensor that enables us to measure the wind is called anemometer. There are different designs af anemometers using different physical effects like the mechanical translation of wind pressure onto a display, thermally - a hot wire is cooled by the wind, acoustic and electromechanical, by measuring ultrasonic pulses or by measuring the volume flow.

The most common anemometer type used in PV monitoring is the cup anemometer. Three to Four hemispheric cups are mounted on the end of horizontal arms, the rotation axle of the cups is vertical. Therefore the wind pressure is translated into rotation regardless of the direction of the wind. The rotation is a function of the wind speed.

Figure 15: Anemometer

Figure 16: Anemoscope

In addition to the anemometer an anemoscope can be added to the system to measure the wind direction. A wind direction sensor can be regarded as a static system with only one mechanically stable state of equilibrium. The input element is asymmetrically mounted on the axe of rotation. The flag is always directed parallel to the wind direction.

3.2.3 Temperature

There are a set of possibilities for the electronic measuring of temperature. The most common once are stated in table 3.

Sensor	Parameter changed by the temperature
Resistance sensor	Resistance
Thermocouple	Voltage
Cut-off current on semiconductor junction	Current
Spectral pyrometer	Colour
Oscillating crystal with defined temperature behaviour	Frequency

Table 3: Types of Temperature sensors

The most important of the mentioned sensors that are used in the industry are resistance sensors on metal and semiconductor basis and thermocouple sensors. [Par08]

3.2.3.1 Module temperature

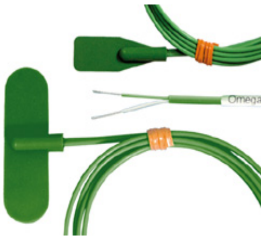


Figure 17: PT 100 Module tenperatur sensor (www.omega.de)

Module temperature is measured with a PT 100 sensor. PT 100 sensors are temperature sensors that are based on the change in resistance of platinum under the influence of temperature. PT stands for platinum and 100 for the resistance of the sensor at 0 °C The platinum temperature sensors are characterized by their nominal resistance of R0 at a temperature of 0 ° C. The resistance change is defined in DIN EN 60751 (2009-05). The advantage of standardization of nominal resistance and resistance change is the possibility to replace the temperature sensors, without the necessity to recalibrate the measuring chain. The sensors are used in combination with a temperature converter in order to convert a temperature value to an analogue process signal. In order to measure the temperature directly on a surface the sensor itself is designed as a self-adhesive foil.

3.2.3.2 Ambient temperature

PT sensors are being used here as well. Never the less the design of the sensor is different for this application. The sensor itself is installed in a cylindrical stainless steel housing. For an accurate measurement the sensor is placed into a polycarbonate housing with fins. This assures that enough air can pass by the sensor and thereby reducing missmeasurement. The sensor has to be mounted in shade e.g. on the side of the inverter container facing north.

Figure 18: Ambient temperature sensor housing (www.thiesclima.com)

3.2.4 Precipitation

Figure 19: Distrometer (www.thiesclima.com)

In order to measure precipitation usually rain gauges are in use. But with the use of rain gauges it is not possible to distinguish between different kinds of precipitation (rain, snow, hail, soft hail, etc.). Therefore it is better to use a distrometer, a device that detects different kinds of precipitation using a laser. This method gives detailed information of the amount, size and form of precipitation.

3.2.5 Measuring current, voltage and power

The ability to measure current and voltage is essential to measure most of the other electrical and non electrical values.

In devices measuring voltage, amplifying circuits are almost always being used. These test circuits have an input resistance which goes towards infinity. This makes the measuring nearly reaction-less in respect to the measured circuit.

To measure the current a shunt has to be integrated into the circuit to create a voltage drop. The voltage drop can be directly interpreted as measuring current. Very small shunts can be used here aswell, to keep the reaction minimal in respect to the measured value.

Another way of measuring the current is, to make use of the magnetic force that is created by the carrier current through a conductor. The magnetic field changes with the current and can be measured with a hall sensor. The hall sensor is typically integrated with a wound core or a permanent magnet surrounding the conductor. This measurement method has no influence on the measured value.

Figure 20: Current transducer (www.lem.com)

Figure 21: Measuring transducer (www.luconda.com)

To measure the voltage or current in an industrial scale measuring transducers are also being used. The input signal is transcended into a proportional output signal that can be interpreted. Mostly the interpretation is locally conducted and transformed in a bus signal and stored in the data logger.

The sensors for the measurement of the string voltages and currents are located in the array junction boxes where the strings are interconnected. The generator current and voltage is ether measured in the inverter, where mostly no information about the accuracy of the measuring process is available or in the generator junction box. The AC power, current and voltage is information available from the inverter or can be measured after the inverter.

The power of strings, the generator or AC power can be calculated when voltage and current are known.

$$P = U * I \tag{3.1}$$

$$P(t) = U(t) * I(t) \tag{3.2}$$

3.2.6 Inverter

The inverter is the core part of the plant. It has to measure DC current and voltage to control the MPP. The impedance, voltage and frequency of the grid has to be monitored as well. The data that can be read out is essential for a proper monitoring system, but the problem is that all inverter producers have proprietary data protocols. Some of them make the protocols available for third parties but others do not provide any information as to how to communicate with their inverters. Chapter 4.3 covers this problematic.

3.2.7 Arc detection

As electric DC arcs can have a very big influence on the power production of a plant, the detection of arcs will be addressed in this chapter. The problem with DC arcs in comparison with AC arcs is that they have no zero-crossings of current and therefore don't stop to burn. Especially in PV systems electric arcs can occur because of the high voltages and currents. A substantial number of fires were caused by such arcs already, which have lead to expensive damages.

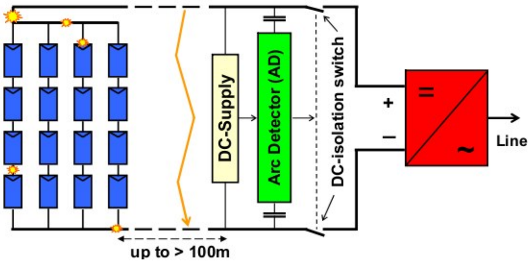


Figure 22: Schematic of an arc detector integrated in a PV plant [Häb07]

Figure 22 shows the diagram of an arc detector integrated in a PV plant. The detector measures radio frequency disturbance, caused by electric arcs and switches the DC isolation switch. This leads to the quenching of the arc.

3.3 Methods of PV monitoring

Different methods of PV monitoring can be implemented depending on the size and the economic possibilities of a plant. Every method has its specific benefits and disadvantages. Small plants normally don't have very sophisticated monitoring systems, since they because of the lower number of components. It is important that possible malfunctions are detected fast and roughly located. Bigger plants need a more complex monitoring system which gives more detailed information about the location of errors or malfunctions.

3.3.1 Monitoring by comparing the yields

This method is suitable for small facilities where a sophisticated system is not economical. The necessary data can be stored manually or with a data logger. The collected data is standardised by taking the size and specific design of the plant in consideration, which means that the size of the plant gets irrelevant. This way a comparison of different plants is possible. Nevertheless this method is not very exact since only facilities for similar design and geographic location can be compared. Differences in the read out data would indicate malfunction. Unfortunately the data that is obtained this way only allows very rough comparison because of the different system designs of plants like participial load efficiency or different inverters or module technologies (silicon, thin film, etc.). There is a platform in Europe www.sonnenertrag.eu which offers a service to compare various facilities online and for free.

3.3.2 Monitoring over pattern detection

The idea behind this method is to detect patterns within the operating range of the plant. The operating characteristics of the inverter can be clearly defined. These patterns are the result of measured values like current and voltage and should be observed again during the operation of the plant. It is an indication for a possible failure if a difference between the predefined pattern and the actual pattern occur. This implies that any failure also has a corresponding failure pattern. For example a constant DC characteristic is a sign for a failure in the MPPT of the inverter. The benefit of this method is that no additional devices are needed. The inverter can provide all necessary data. All standard patterns that occur through the day are known and fast changes can be interpreted rapidly. The downside of this method is that slow changes can cause misinterpretation.

Principally it is thinkable that adaptive systems that are used in informatics are able to learn new patterns, specific to any particular plant. An example for this would be partial shading of a PV plant. This specific pattern can not be predefined but only adapted to because the patterns are different for every plant.

3.3.3 Monitoring over forecasted yields

This is the main method to monitor PV facilities. With the help of external devices like pyranometer, temperature sensors and other external sensors a yield forecast can be predicted. This prediction heavily depends on the accuracy of the measured data. The predicted data is compared with the real measured yield. If the two values do not match an alarm massage is initiated. This approach enables the monitoring system to give a very detailed error analysis based on the comparison of predicted and given yield characteristics. Possible causes of malfunctions can be located very accurately and the operator gets detailed information about the source of error.

Data from satellites can also be used to get irradiation values but this data is not as accurate as if it is locally measured. However the project PVSAT-2, which is supported by the European Commission, is developing such a system for small to middle size plants. The aim of the project is a monitoring system with automated error detection based on a data logger at the plant and interpolated data from satellites and meteorological stations.

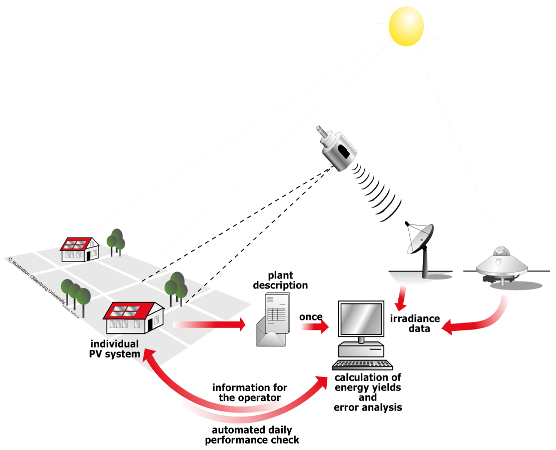


Figure 23: Schematic overview of the PVSAT method

The collected data from the data logger at the plant is transmitted to a server where the design of the plant is stored as well. Predicted yield and measured yield are compared, analysed and interpreted. Picture Figure 23 gives a schematic overview of the process. [He+05]

3.4 Estimate of yield by normalizing yields

To analyse the operating behaviour of a PV plant all relevant measured data has to be normalized. To do so the Joint Research Centre based in Italy provides a methodology to normalize data from PV plants. The following chapter gives a detailed overview over that method. [BM05] [Häb07]

The measured data has to be standardized in order to be comparable. The method not only normalizes data but defines additional values which give the ability to make a conclusion of the operating status of the plant. With the calculated data, diagrams over a variable time (daily, weekly, monthly or yearly) can be generated. These diagrams enable the detection of malfunctions in the plant operation.

3.4.1 Normalized yields, losses and Performance ratio

To eliminate the influence of the facility size the yield of the plant over a certain time τ is divided through the nominal power P_0 at STC (" Standard Test Conditions" G=1 kW/m², AM 1,5 , cell temperature 25°). τ is a variable time and can be chosen freely. Usually the time frame is a day, a month or a year. The result is the specific yield which is separated in the final yield Y_F (full-load hours of P_0) and the array yield Y_A (DC yield of the generator).

$$Y_F = \frac{E_{USE}}{P_0} \qquad y_F = \frac{P_{USE}}{P_0} \tag{3.3}$$

$$Y_A = \frac{E_A}{P_0} \qquad y_A = \frac{P_{DC}}{P_0} \tag{3.4}$$

For the detailed analysis shorter values (i.e. 5 minute midpoint) are used. These normalized instantaneous values are named analogue to the normalized yields with lower case letters. Thereby y_F is the normalized useful power, P_{USE} is the momentary useful power and P_{DC} is the power on the DC side. In Grid connected plants the yield $E_{USE} = E_{AC}$ which is the yield on the AC side and the same is valid for $P_{USE} = P_{AC}$.

To consider the site specific irradiation influences another value is defined. Y_R which is the reference yield. It equals the time which the sun has to shine with G_0 at STC, which is fixed to 1kW/m², to irradiate the energy H_G onto the solar generator. H_G is is the energy irradiated in module layer during the acquisition period. For the normalized instantaneous irradiation y_R the global irradiation in the module layer G_G [kW/m²] is divided by G_0.

$$Y_R = \frac{H_G}{G_0} \qquad y_R = \frac{G_G}{G_0} \tag{3.5}$$

Additionally to the irradiation value, if the module temperature T_C is measured, the temperature corrected irradiation power y_T can be calculated. The module specific temperature coefficient c_T is introduced and as reference point the temperature T_0 (25°C) at STC .

$$y_T = y_R * [1 + c_T * (T_C + T_0)] \tag{3.6}$$

Normalized Losses

With the defined normalized yields and powers the normalized losses of a PV plant can be calculated. The difference of the reference yield Y_R and the generator yield Y_A is defined as L_C which are the generator losses. The generator loss can be divided in temperature caused losses L_{CT} (cell temperature which is normally above 25°C) and in not temperature caused losses L_{CM} (wiring, string diodes, low irradiation, dirty modules, mismatch, MPPT errors etc.)

$$L_C = Y_R - Y_A = L_{CT} + L_{CM} \quad (3.7)$$

and

$$l_C = y_R - y_A = l_{CT} + l_{CM} \quad (3.8)$$

The normalized instantaneous temperature caused losses l_{CT} and the not temperature caused losses can be calculated as follows.

$$l_{CT} = y_R - y_T \quad (3.9)$$

and

$$l_{CM} = y_T - y_A \quad (3.10)$$

The difference between the generator yield Y_A respectively the normalized generator power y_A and the final yield Y_F resp. the normalized usable power y_F is the system loss L_S resp. l_S. All losses which are connected with the DC conversion are included here.

$$L_S = Y_A - Y_F \quad (3.11)$$

and

$$l_S = y_A - y_F \quad (3.12)$$

Performance Ratio

The performance ratio is a quotient from final yield Y_F and the irradiation yield Y_R. The corresponding is valid for pr.

$$PR = \frac{Y_F}{Y_R} \quad (3.13)$$

and

$$pr = \frac{y_F}{y_R} \quad (3.14)$$

The irradiation yield Y_R resp. the irradiation y_R is used as reference and is always bigger then the final yield Y_F resp. the normalized usable power y_F. The reason for that is that the losses which occur in all components of the PV system are responsible that not all of the irradiated energy can be converted in usable energy. As result of this the value of PR can have a range between 0 and 1. If a PV system is optimally planned and build the value should be as close as possible to 1.

Yield calculation with normalized instantaneous values

With the normalized instantaneous values y_R, y_T, y_A, y_F and the normalized instantaneous losses l_{CT}, l_{CM} ,l_S it is possible make an integration and calculate the values Y_i resp. L_i for the corresponding day.

$$Y_i = \oint_0^T y_i * d_t = \sum_k y_{ik} * \Delta t \tag{3.15}$$

resp.

$$L_i = \oint_0^T l_i * d_t = \sum_k l_{ik} * \Delta t \tag{3.16}$$

With this relation it is possible to calculate also daily values for Y_T (temperature corrected irradiation resp. reference yield), L_{CT} the temperature caused generator losses and L_{CM} temperature independent generator losses.

3.4.2 Diagrams and statistics

Diagrams are an important tool to understand pv systems and the dependency of the different values. With the in chapter 3.2.1 described normalized yields, diagrams can be drawn. For the illustration of the monthly and yearly yields bar diagrams are used. Figure 24shows the statistics of a plant in Switzerland on the Mont Soleil with 555 kWp in march 2009.

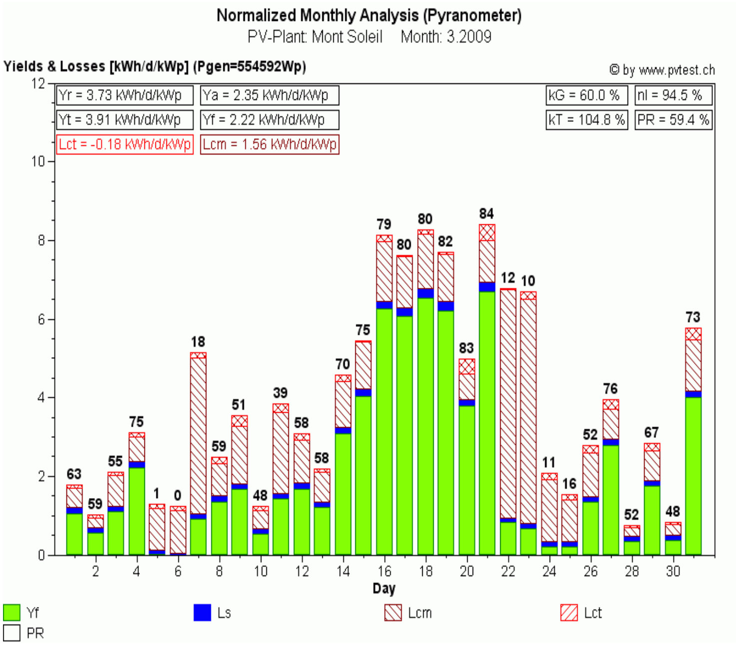


Figure 24: Graph of a normalized monthly analysis

The bar diagram shows that the generator was completely shaded on the third and fourth. This can be identified because Y_f and PR are nearly zero and L_{CM} is big, which are indicators for a not temperature caused malfunction. On the 7,11,22,23,24,25 Y_f and PR are small but not zero which can be an indicator for partial shading. The reason for this was snow coverage of the generator. For the rest of the month there are no noticeable problems. The lower PR on some days is connected to the lower efficiency of the inverter at partial load caused by low irradiation. It is normal that inverters show this behaviour.

For the ability of a detailed diagnose it makes sense to look more closely into the daily statistics of the plant. With an hourly resolution it is possible to detect the exact moment of a failure and the corresponding values. An example is Figure 25 which is a normalized diagram of the plant on Mont Soleil.

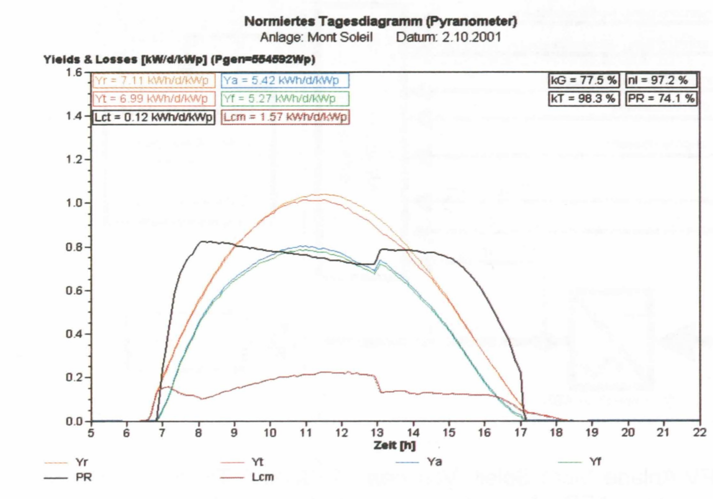


Figure 25: Graph of a Normalized daily analysis

The graph shows a normalized diagram with partial failure. The PR decreases over the day because of the increasing irradiation. L_{CM} is increasing correspondingly. The reason was that one of the 11 arrays of the plant is disconnected from the inverter. At 1 pm the array is connected to the rest of the generator again. Until that time L_{CM} is to high. The PR rises for about 7% and L_{CM} goes back accordingly.

The graphs can indicate errors. However, the interpretation of the graph is complex and requires experience. Also other measured values can give valuable information. For instance in the case of Figure 24, the information of a precipitation sensor can give important information for the correct interpretation of the graph.

4 Enhanced surveillance capabilities

Based on the findings of chapter 3 it is possible to say that an advanced monitoring system is a descriptive reproduction of the plant and, the more exact all production parameters are known the better the monitoring system works. This leads to the following three conclusions respectively extension suggestions:

- The possibility to detect the pollution grade of the modules. The problematic and the design of such sensors is discussed in chapter 4.1
- The problematic of the proprietary communication protocols of inverters which appearers if an independent monitoring system shall be used . In chapter 4.3 an open standard will be introduced and discussed .
- The possibility of yield forecast by means of the monitoring data and meteorological forecast data. The possible potential of a forecasting system will be discussed in chapter 4.4

4.1 Pollution measurement

As polluted modules can cause considerable losses, a detector which can measure the pollution will be discussed in this chapter.

The problematic of permanent module pollution is that dust or other particles sediment on the modules. This leads to shading of the modules. If the modules are not cleaned periodical the dust can further lead to heavy dust layers and in the worst case to primary fouling. Mostly this dust layers are situated on the bottom of the module where the aluminium frame is mounted. Rain washes the dust from the modules but on bottom the dusty water stays and forms a thicker film of dust.

As described in [RH03] the pollution caused losses can range around 10% of the yield, if the plant is cleaned in a 2 year period. This value depends very much on the periodic time and the location of the plant. For instance the normal time period in Italy to clean a PV plant is 3 month but still in the south the losses can become noticeable much faster then 3 month, if for example sand from the sahara sediments on the modules. [Wag10] describes the problematic of dust on modules in Dakar, Senegal.

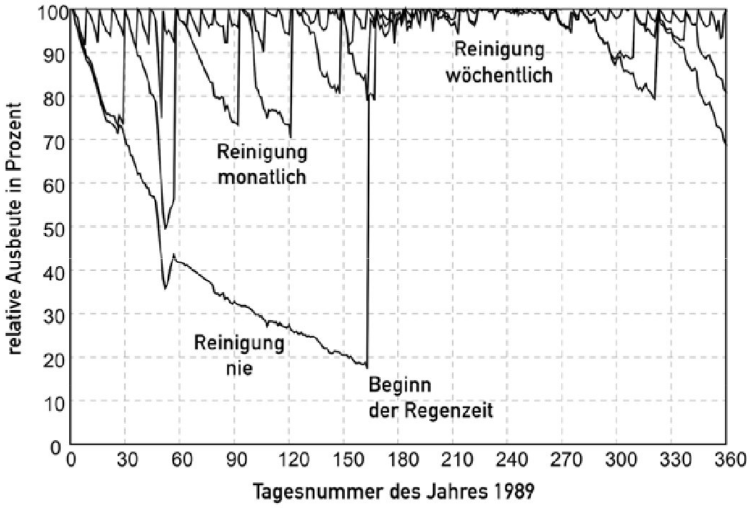


Figure 26: Relative Energy yields caused by dust (horizontal axe is number of day in the year 1989/ vertical axe is relative yield in %) [Wag10]

Figure 26 shows the relative energy yield of an PV test field in Dakar, Senegal. Four PV Modules of the same type where mounted with the same orientation to the sun. All modules where cleaned at the beginning of the long term test. Three of the modules where cleaned in different time intervals (daily, weekly, monthly) the fourth module is not cleaned any more. Figure 27 shows the test arrangement in Dakar. The 4 different pollution grades of the modules is very well visible.

Figure 27: Test arrangement in Dakar

In Europe the situation is different but near industry, roads, railways and also agriculture dust can appear which is more adhesive than sand and therefore it is not washed away like sand in the sahara (see Figure 27 day 160) .

Also the interpretation of the data generated from the sensors of the monitoring system can give information of the pollution grade of the modules. But the fact that the pollution happens mostly very slow makes its detection harder.

4.1.1 Pollution detection with a CCD sensor

A CCD-sensor (Change Coupled Device) is an electronic device which consists of a matrix of photo diodes. CCD sensors are used in digital cameras of mobile phones, therefore they are a mass product and very inexpensive. If a lens is attached to the sensor it can be used as optical sensor. The optical sensor can be attached to the PV module to scan a part of the surface of the module. The dumped data has to be interpreted by a software to be able to measure the factor of pollution of the module.

The sensor would have to be integrated in the module. Module producer could provide special modules with integrated sensors. Or a “dummy” module is produced for measuring reasons only .

4.1.2 Classic Rain sensor as pollution detector

A classic rain sensor is used in the car industry to detect water on the windscreen. The concept is is based on a optoelectronic measurement where a LED (light emitting diode) is used as the illuminant and a detecting photo diode. The physical laws of reflection are used in the way that light is sent in an angle of 45° into the PV module glass, dust or dirt is absorbing the light. The photo diode measures the reflected light beam. The amount of absorbed light is proportional to the pollution grade. Again the sensor has to be integrated in the module.

4.1.3 Pollution detection with photo diodes

The idea is to attach three photo diodes to a module. Each diode is sealed in a metal tube. In one metal tube there is also a LED which is illumining the module. The photo diode which is attached, measures the intensity of the LED. The opposed photo diode measures the direct reflection and the diffuse reflection. The third photo diode measures only the defuse reflection. Before the very short measuring procedure the operational amplifier attached to the photo diodes have to be neutralised to prevent measuring errors. After the measuring process the data is evaluated and the total reflection can be calculated. The reflected amount of light is proportional to the grade of pollution.

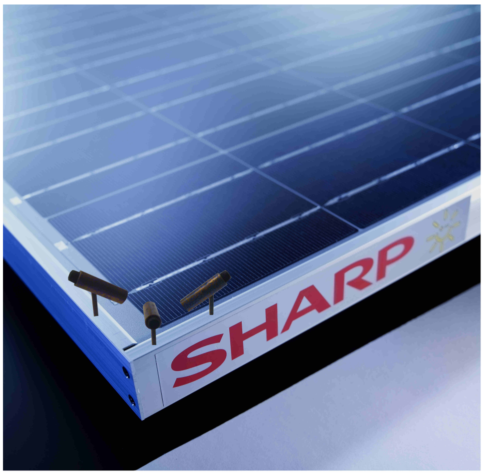


Figure 28: Module with pollution detection sensor

4.2 Conclusion

If a module producer would provide a module with an integrated sensor the CCD sensor solution would be preferable because of the small dimensions of the sensor. It could be integrated in a standard module. Also the rain sensor is a good solution with the disadvantage of the size of the sensor. A dummy module would have to be produced. The photo diode sensor is the least developed solution but probable the cheapest one.

However the software for the data interpretation has to be developed for all three solutions.

4.3 Inverter communication

A problem which shows up by designing an independent monitoring system is that inverter producer do not use standardized communication languages. This is also a problem if inverter specific monitoring systems are used together with different inverter producers. Some of the inverter producer announce their protocols but some others don't. So ether the inverters of producers which keep the protocols proprietary can not be used, or multiple monitoring systems have to be installed. This makes the monitoring of a plant usually more cost intensive, complex and harder to maintain.

In the last years inverter producer tend to include Ethernet interfaces to their inverter's. This gives the possibility to standardise the communication between the inverter and other devices over Ethernet. In an optimal way this communication language is an already existing open standard that everybody can use and implement in their individual system.

The target of this chapter is to provide a solution for a possible communication language standard with the help of an example. After interviews with companies which apparently design new monitoring systems and interfaces the best solution appearers to be the XML standard.

4.3.1 XML

XML (Extensible Markup Language) is a communication language for representing hierarchically structured data sets in form of text data. The goal of XML is to emphasize simplicity, generality and usability. It was specified by the World Wide Web Consortium (W3C) in 1998 and since that time the XML standard is widely used. Also as base for a big number of user defined languages.

XML documents consist of text characters. *By definition, an XML document is a string of characters. Almost every legal Unicode character may appear in an XML document.* [W3.org] This fact makes it possible for a human and a machine to read and understand the generated file easily and directly.

4.3.1.1 XML example

```
<?xml version="1.0" encoding="UTF-8" standalone="yes"?>
<index>
     <title>Monitoring Parameters</titel>
     <entry>
          <header>Irradiation</header>
          <entry_text>The irradiation is the main  ...</entry_text>
            <actual_value>10</actual_value>
     </entry>
     <entry>
          <header>Cell temperature</header>
          <entry_text>The cell temperature has an influence...</entry_text>
            <actual_value>22</actual_value>
     </entry>
</index>
```

This xml file is just a simple example which shall show that the xml file itself is easy to read for a human being. It consist of a structure element which can be freely chosen. The free defined values have to be defined in an the DTD (document type definition).

In the stated XML example it is very easy understand the contend of the transferred file. The header gives information about the device from where the following information is coming from. The entry text can be any text like status or such. The actual value carries the output of for instance a PT100 sensor.

The idea is that a standard based on the XML language is defined by a consortium of all inverter producers. The standard could be additionally implemented to the proprietary communication protocol of every inverter producer.

4.4 Yield forecast

In this chapter will be discussed if a yield forecast is possible with the help of meteorological forecast data and the in chapter 3.2 defined method to analyse the yield of a PV plant. So the aim of this chapter is to find out if, and how accurate it is possible to predict the energy yield of a PV plant.

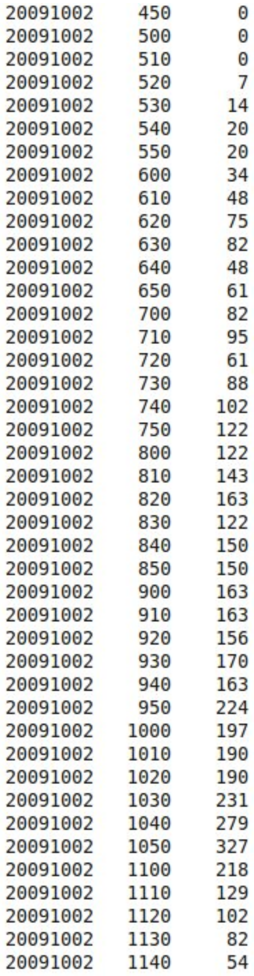
Yield forecast can be interesting for owners of big plants as also for alliances of owners of smaller plants and grid owners. On one side in countries like Italy where the conto energia is in force which is the Italian feed in tariff law, it is possible to trade the energy. The subsidy is not paid for the physical energy itself but for the production of energy. So the energy can be used on site or traded. For instance at the EEX (European Energy Exchange) it is possible to trade energy on the spot marked one "day ahead". This means that the energy is traded 24 hours in advance or "intra-day", where the contract has to be closed 75 minutes before the energy is provided. If a plant owner or a community of owners want to sell their energy there they have to know how much energy they will produce. Therefore the exact prediction is important. If to much or to less energy is provided the provider has to pay penalty. [eex.com]

On the other side also for the grid operator it can be interesting to know how much energy is going to be feed into his grid. This possibility is going to be more and more interesting. It already is for instance in Bavaria where in rural areas a big amount of energy comes from private PV plants on roofs of farmers and private investors. There so much energy is fed into the grid, that it is overloaded. [pho09]

However, essential for the accuracy of the forecast is the dataset on which the calculation is based on. The Austrian ZAMG (Zentralanstalt für Meteorologie und Geodynamik) provides a service which is called INCA (Integrated Nowcasting through Comprehensive Analysis). INCA is a weather forecast and can predict the irradiation and the temperature 24 hours in advance. In the following a calculation with a dataset from ZAMG is used to make a comparison between forecast and measured data. It has to be taken into account that the accuracy of the forecasting weather data is depending on the general weather situation. This means that in anticyclone respective cyclone periods the prediction of irradiation data is more precise than in unstable weather situations.

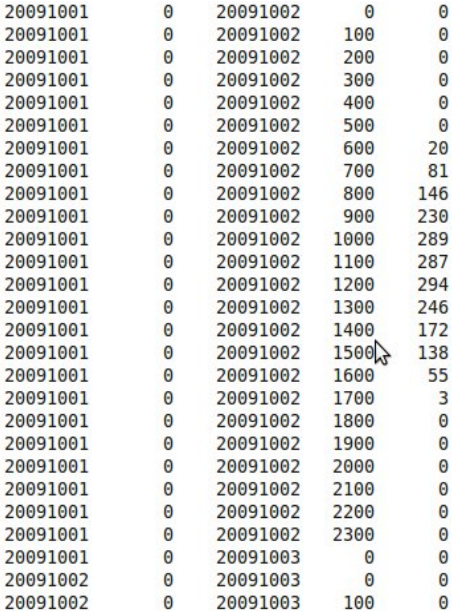
4.4.1 Methodology

The allocated data is from the 2. October 2009 till the 2. November 2009. The measured irradiation data has a resolution of 10 minutes and the foretasted data of 1 hour. The temperature data sets have the resolution of 1 hour. All data provided from ZAMG comes in a text file. Table 5 shows the form of the file for the foretasted data and Table 4 shows an abstract of the measured data file.



```
20091002    450     0
20091002    500     0
20091002    510     0
20091002    520     7
20091002    530    14
20091002    540    20
20091002    550    20
20091002    600    34
20091002    610    48
20091002    620    75
20091002    630    82
20091002    640    48
20091002    650    61
20091002    700    82
20091002    710    95
20091002    720    61
20091002    730    88
20091002    740   102
20091002    750   122
20091002    800   122
20091002    810   143
20091002    820   163
20091002    830   122
20091002    840   150
20091002    850   150
20091002    900   163
20091002    910   163
20091002    920   156
20091002    930   170
20091002    940   163
20091002    950   224
20091002   1000   197
20091002   1010   190
20091002   1020   190
20091002   1030   231
20091002   1040   279
20091002   1050   327
20091002   1100   218
20091002   1110   129
20091002   1120   102
20091002   1130    82
20091002   1140    54
```

Table 4: Text file for measured irradiation data (ZAMG)



```
20091001    0   20091002      0     0
20091001    0   20091002    100     0
20091001    0   20091002    200     0
20091001    0   20091002    300     0
20091001    0   20091002    400     0
20091001    0   20091002    500     0
20091001    0   20091002    600    20
20091001    0   20091002    700    81
20091001    0   20091002    800   146
20091001    0   20091002    900   230
20091001    0   20091002   1000   289
20091001    0   20091002   1100   287
20091001    0   20091002   1200   294
20091001    0   20091002   1300   246
20091001    0   20091002   1400   172
20091001    0   20091002   1500   138
20091001    0   20091002   1600    55
20091001    0   20091002   1700     3
20091001    0   20091002   1800     0
20091001    0   20091002   1900     0
20091001    0   20091002   2000     0
20091001    0   20091002   2100     0
20091001    0   20091002   2200     0
20091001    0   20091002   2300     0
20091001    0   20091003      0     0
20091002    0   20091003      0     0
20091002    0   20091003    100     0
```

Table 5: Text file for irradiation data forecast (ZAMG)

In the first step the data is imported in a calculator program (Open Office Calc). Then the data is controlled and filtered to minimise the data amount and minimise error sources. In the next step the percentaged error is calculated by using formula 4.1

$$E=\frac{H_v}{H_m \div 100} \tag{4.1}$$

The percentaged error E is the foretasted irradiation H_V divided by 1% of $H_{m.}$ In this way H_m is taken as 100% and E describes the relative error of a single moment.

The average irradiation for a day, for the forecast irradiation and the measured irradiation is calculated by using formula 4.2 and formula 4.3. The daily forecast irradiation H_{Dv} is calculated by dividing the hourly data through the number of measuring intervals (see Table 5). The same approach is used with the measured irradiation H_{Dm} which is divided by every minute measuring intervals (see Table 4).

$$H_{Dv}=\frac{H_{v1}+H_{v2}+H_{v3}.....H_{vn}}{n} \tag{4.2}$$

$$H_{Dm}=\frac{H_{m1}+H_{m2}+H_{m3}.....H_{mn}}{n} \tag{4.3}$$

Figure 29 shows the percentage error distribution of the 32 analysed days. In 53 % of all days the total error is under ± 20%.

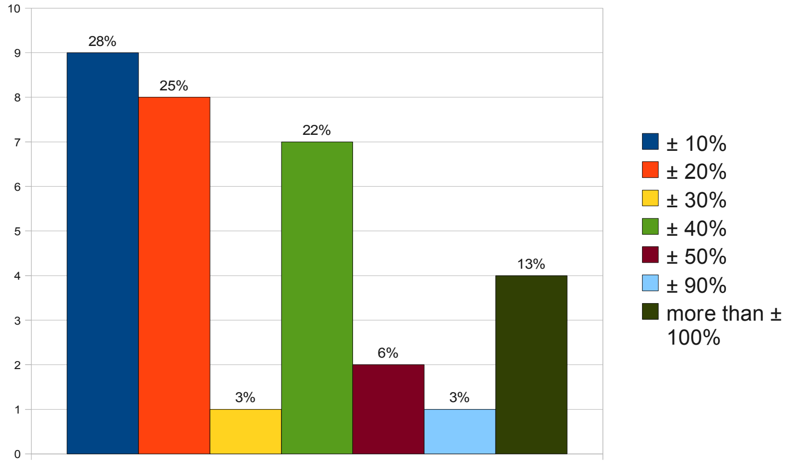


Figure 29 : Percentage error distribution (horizontal axe is the error [%] of the forecasted irradiation in 10 % steps/ vertical axe is the absolute number of days)

This calculation shows the total error over a period of time. But the difference between foretasted and measured output can be even bigger if the time frame is shortened. Figure 30 shows the forecast and measured irradiation over one day. This diagram makes the real occurring problems visible. The error considered over the day is very small but in smaller time frames the error gets up to 100 %.

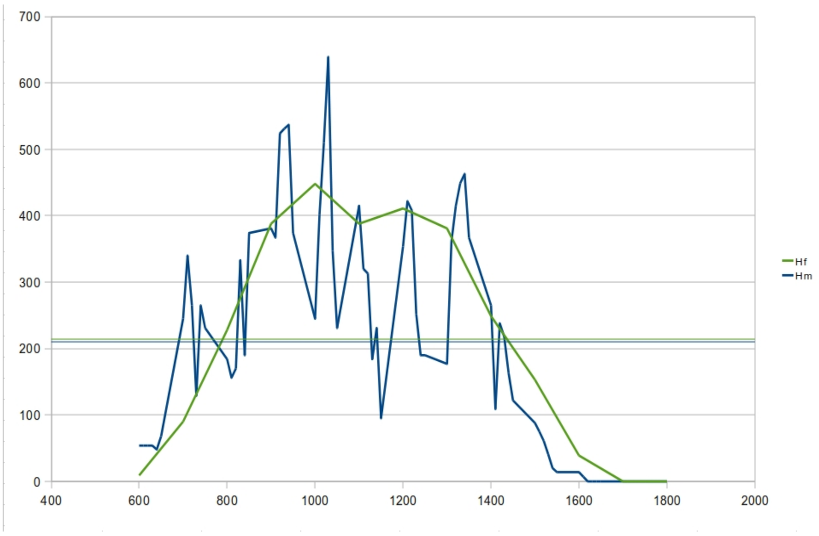


Figure 30: Measured and foretasted irradiation on the 11.10.09 (horizontal axe is the time [min]/ vertical axe is the irradiation [W/m²])

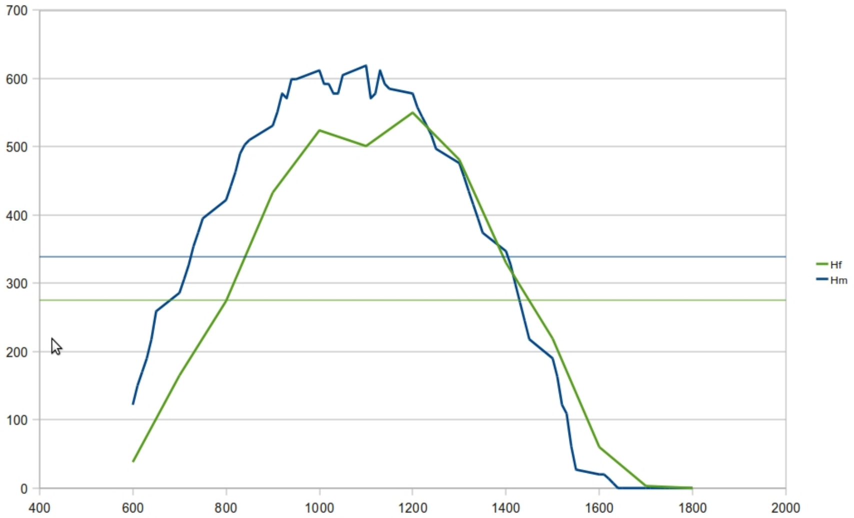


Figure 31: Measured and foretasted irradiation on the 04.10.09 (horizontal axe is the time [min]/ vertical axe is the irradiation [W/m²])

Figure 31 shows that on clearer days the situation is different and the prediction is much better. But still the forecast is not correct. The error over the day is in a range of 20% . In general it appears that a prediction of the irradiation is more precise on very sunny days or very cloudy days. Days which are mixed in sun and clouds make the precise prediction nearly impossible. [zamg]

4.4.2 Conclusion

The fact that the prediction of clouds is not possible, is responsible for the results of the study. The forecast and the measured irradiation data defers in 47 % of the reviewed days more than 30%. In 13% of the cases the error is more then 100%. It is not possible to trade all the energy on an energy exchange marked. For the estimation of the yield it can be sufficient depending on the requirements. However for small PV energy providers it is not sufficient to trade or even predict there energy conversion exactly. For bigger facilities it can be a good method to forecast there energy conversion because a certain base load can always be provided. The amount of this base load depends very much on the location of the plants and the season.

4.5 Final Conclusion

To be able to design a PV monitoring system the whole internal energy conversion process and all the involved parts of the plant have to be equipped with sensors and measured permanently. Furthermore the external influencing factors such as wind, irradiation, and temperature have to be watched and put in relation with the internal states. The more exact and the higher frequent the resolution of the stored data, the better is the possible alignment and interpretation of the so won data. Furthermore it is vitally important that all data is collected in the same temporal resolution. If not all data is recorded in the same moment it can easily lead to misinterpretation. Research shows that even in highly elaborated environments programs today cannot automatically interpret all possible malfunctions. In some cases only a well-trained technician can analyse the data in order to find the exact reason of an error and to come up with a solution.The amount of sources and sensors that have to be watched over by a monitoring system is already extensive. Nevertheless there are still more inputs possible and sensible in order to enhance monitoring systems. One of these are the three pollution detection sensors that where introduced in this work. None of them has yet been put in a testing scenario but there is valid evidence that these sensors could play an important role in the future.

For communication purposes between the entities XML is the language of choice to enable a friction free and widely understood standard. It holds all possibilities to easily integrate new sensors and sensors from different vendors. But as most of the inverter producers provide monitoring systems for their own “landscape” in their own proprietary languages and XML is not the standard there it will take some time to either provide translation modules or demand XML interfaces from all partners. The idea to combine historical data with accurate weather forecasts to enable a reliable Yield forecasting turned out to be a very promising but in the end, as the calculation and comparison showed, not feasible idea. Nevertheless it is still valid to continue the research as for instance any operator of PV plants, which also owns storage plants, can even out fluctuations of the production. Furthermore in some world areas where the climatic situation is more stable than in middle Europe such a forecasting system could still be very valuable.

4.6 Outlook

The findings of this work will be implemented in a monitoring system that is currently under development. For a better and faster analysis an automated error detection, which will react on typical patterns would be very sensible. This error detection should in the future have the possibility to learn new malfunction states through the simple input of a technician in order to permanently enhance the system as a whole.

5 Literature

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6 Glossary

PV	Photovoltaic
kW	kilo Watt
MW	mega Watt
kWp	kilo Watt peek
Mwp	mega Watt peek
AC	alternating current
DC	direct current
A	Ampere
V	Volt
W	Watt
IR	infra red
CdTe	Cadmium Telluride
CSI	Copper Indium Selenid
CPV	concentrated Photovoltaic
EVA	ethylene-vinyl-acetate
TPU	thermoplastic polyurethane
PVB	polyvinyl butyral
MPP	maximum power point
MPPT	maximum power point tracking
PWM	pulse width modulation
W/m^2	Watt per square meter
kWh/kWp*y	kilo Watt hour per kilo Watt peek and year
kWh/m^2*day	kilo Watt hour per square meter and day
UV	Ultraviolet
AJB	array junction box
GJB	generator junction box
PT	positive temperature coefficient
P	power
U	voltage
I	electric current

STC	standard test conditions
PR	performance ratio
CCD	change coupled device
LED	light emitting diode
XML	extensible markup language
EEX	European Energy Exchange
ZAMG	Zentralanstalt für Meteorolgie und Geodynamik