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International Energy Agency
Photovoltaic Power Systems Programme

Task 18 Off-Grid and Edge-of-Grid Photovoltaic Systems

PVPS

PV-Hybrid System Data Visualisation Recommendations

A handbook for operators of PV-Hybrid Systems and Mini-Grids

2022

Report IEA-PVPS T18-02:2022

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Mexico, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance (SEPA), the Solar Energy Industries Association (SEIA) and the Solar Energy Institute of Singapore are also members.

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What is IEA PVPS Task 18?

The objective of Task 18 of the IEA Photovoltaic Power Systems Programme is to find technical issues and barriers which affect the planning, financing, design, construction and operations and maintenance of off-grid and edge-of-grid systems, especially those which are common across nations, markets and system scale, and offer solutions, tools, guidelines and technical reports for free dissemination for those who might find benefit from them. The issues that will be focused on with regard to off-grid and edge-of-grid photovoltaic system will centre on:

- Reliability: A system that has the ability to generate and distribute energy to meet the demands of those connected with a high degree of confidence
- Resiliency: A system that can withstand or recover quickly from natural disasters, deliberate attacks or accidents
- Security: A system that is sustainability affordable and provides an uninterrupted supply of energy which adequately meets the associated demand.

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COVER PICTURE

PV Hybrid system at Brandeckturm, South Germany, Source : Elektro-Peter GmbH, Baden-Baden, Germany

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PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

PV-Hybrid System Data Visualisation Recommendations

IEA PVPS

Task 18

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LIST OF ABBREVIATIONS

IEA	International Energy Agency
PVPS	Photovoltaic Power System Program
NGO	Non-Governmental Organisation
SHS	Solar Home Systems
PV	Photovoltaic
SOC	State of Charge of the Battery
SOH	State of Health of the Battery
DC	Direct Current
AC	Alternating Current
MW	Megawatt
MWp	Megawattpeak
kW	Kilowatt
kWp	Kilowattpeak
kWh	Energy amount in Kilowatthours
V	Voltage
A	Current
°C	Temperature in Celsius
°F	Temperature in Fahrenheit
FC	Fuel Consumption
FG	Fossil Generation
RG	Renewable Generation
LC	Load Consumption
GFC	Genset Fuel Consumption
REC	Renewable Energy Contribution
HSEP	Photovoltaic Hybrid System Efficiency Performance
LPG	Liquid Petroleum Gas

EXECUTIVE SUMMARY

PV-Hybrid System Data Visualization Recommendations

A handbook for Operators of PV-Hybrid Systems and Mini-Grids

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PV off-grid systems play an important role in rural electrification, with the capacity to power up applications across a wide power range from several watts up to the megawatt range. The remoteness of off-grid system locations means maintenance is costly. Therefore, data logging is valuable to supervise the system and reduce operation and maintenance costs. Modern power electronic devices often offer a built-in data logging service which can reduce the costs to monitor the system significantly.

This work presents a standardised data visualisation form for battery based PV Hybrid off grid systems. It is applicable for lead-acid and lithium-ion battery based systems. The data visualisation displays the battery data and provides a fast and efficient overview on the system behaviour and battery condition. With the help of a standardised data format and visualisation, it is very easy to compare different systems. It is also possible to compare different years of operation of one system and to identify changes, increases in the load demand or loss of performance. This helps to improve the system, the energy management and to increase the lifetime of the battery. All these aspects can reduce the operating costs of the system. The visualisation summarizes the profile of the battery voltage, current and daily amp-hour usage and the corresponding minimum and maximum values as well as calculating mean values and standard deviations for lead-acid and lithium-ion based battery PV Hybrid off-grid systems.

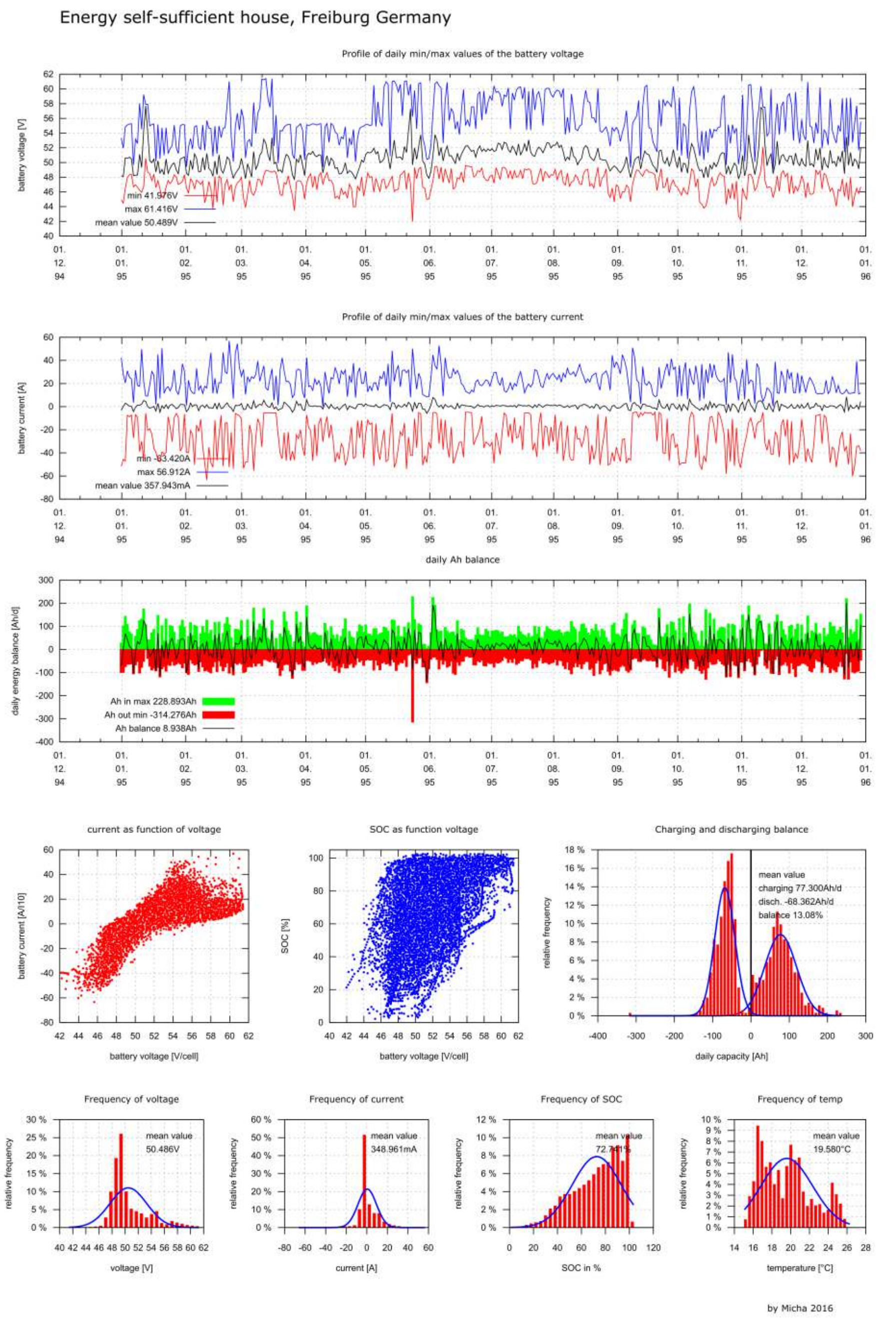
Battery usage diagrams picture the condition of the battery and provide an in-depth look at the functionality of the state of charge algorithm. All battery data are displayed as raw data so the visualisation can be used for lead-acid and lithium batteries. However it is more difficult to estimate the rest capacity of lithium-ion batteries based on the voltage behaviour compared to lead-acid batteries. Several statistically relevant histogram functions show a detailed picture of the usage of the system. This allows us to evaluate the system status.

Additionally, a detailed visualisation of the temperature data is provided. The temperature has a significant influence on the battery lifetime. In combination with the general data visualisation, a detailed look to the system is available. The standardised visualisation aims to fit on one page to make easy comparison possible.

Highlights

- Standardised data visualisation
- Easy to use
- Fast overview on many system
- Standardised comparison among different systems
- Comparison of different years in the same system

The following figures show an exemplary sample visualisation:



1 INTRODUCTION

1.1 General background

The first PV off-grid systems with diesel generators as backup power sources (PV Hybrid Systems) were built in the 1980s and the technology has now seen 30 years of technological development. Nonetheless not all technical issues are solved yet. Despite this, a stable market exists, and many PV Hybrid systems are installed world-wide supported by advanced products and trained installers. The long-term operation of the systems however, has proved to be especially difficult. Often the remoteness of the installations makes spare-part supply complicated and the maintenance costly. Furthermore, the involvement of many different institutions, companies and governmental agencies has resulted in complicated processes which need to be followed in order to make decisions. Hence we often see situations where the systems are running and supplying energy, while the information on the performance and efficiency of the operating systems is mostly unavailable.

World-wide, a lot of systems are installed year by year. Nevertheless, it is difficult to estimate the market size. This is particularly relevant in hot-spot markets, especially in cases where an electrification program establishes a market, which can break down right after the realisation of the program. The overall world-market is estimated to be between 200MWp and 2GWp per annum.

Nearly all PV off-grid systems are designed individually, resulting in a huge variety of different systems and system topologies. This document will provide a short overview on the dominant topologies which can be found in the market. It is important to emphasise that all topologies can provide good performance if they are applied under the correct circumstances.

The price reduction of solar modules within recent years has made them more economically feasible. Nevertheless, the range of published levelized cost of energy's (LCOE) is very wide (0.1 – 1.2 €/kWh). Of course, the real costs largely depend on the size and other boundary conditions of the system and location. Open and reliable calculations are extremely rare, but many economic simulations underline that realistic costs tend to be around 1€/kWh.

Maintaining low electricity demand in remote areas is often the most economical means of electrification. Electricity providers in industrialised countries also face the fact that it is cheaper to supply a city with a high population density than to supply a small village far away from the city.

PV hybrid systems can provide a reliable 24/7 power supply system for whole villages or industrial applications. Due to the availability of batteries and possible backup generators, the supply can be independent of the availability of solar and wind, even if those intermittent sources contribute a significant part to the supplied load.

The average system size of PV off-grid systems has risen significantly within recent years. This trend supports PV hybrid systems and makes the technology the lowest cost option in more and more locations where the distance to the nearest grid-access and the costs for grid extension, further improves the business case for any PV off-grid system.

Even though battery research has shown huge progress within recent years, new technologies have yet to significantly influence PV off-grid systems. Some PV off-grid systems have already been installed with Li-Ion batteries, but a market break through can only be seen for very small Pico-PV systems up to now.

Often PV off-grid systems are not maintained well, which results in early system failure and bad performance. Furthermore, such installations bring a bad reputation to PV and off-grid applications as users can then think that all such systems are not reliable.

System performance can suffer if the design and the operating strategy is not done properly and can results in high operating and maintenance costs. The powerful and easy to use data visualisation in this document is intended to help avoid this through supervision and comparison of the systems. It can really save costs for operators if they are aware of the performance and efficiency loss. Strategies to reduce the costs and to increase the efficiency can then be applied to the system.

The long-term objective is that decision makers and institutions initiating tenders do not only install PV hybrid systems but also make sure there is a suitable long-term operation and maintenance infrastructure available which can be foreseen in the financial plan. This includes data monitoring and data evaluation providing a continuous technical improvement to the systems.

1.2 What's this document about?

The key proposal of this document is to define an easy to use and standardised data visualisation for lead-acid based PV Hybrid systems. With the help of a suitable tool chain, big data sets of many PV Hybrid systems can be visualised and analysed within a short period of time. This permits a fast review of the performance of the systems and to compare different systems. This standardisation and the possibility to compare systems allows for the identification of weak points of the operating and management strategy of single systems. This again enables the operators to improve the efficiency of the systems. At the same time, fuel costs can be reduced.

The data visualisation focuses on the battery data as this is the most cost intensive component in any PV hybrid system. To optimize the use of the battery and to increase the lifetime of the battery is always key in order to reduce the overall operating costs of PV hybrid systems.

To realise the proposed data visualisation, it is necessary to monitor the most important battery data, like voltage, current and temperature.

The visualisation draws temperature heat maps, temperature profiles and daily energy profiles to analyse the load and the input sources. It draws many different types of histogram pictures which provide important information on the system statistics.

With the help of these figures, it is possible to adjust and adapt several charging and discharging set-points, scheduled generator start and stop points or any other applied management strategy to the real life operation of the specific system. This is often more valuable than pre-planned strategies as in many systems the reality of the usage differs heavily from the planned and scheduled operation.

By applying an optimised regulation strategy to the system based on real life monitoring data it is possible to reduce the operating costs of the system by increasing the efficiency of the system. Often a well-adapted operating strategy also increases the lifetime of the batteries.

2 REVIEW

PV Hybrid Systems have been used in off-grid power systems since the early 1980s and now form a well-established market offering. A professional supply chain is available for all the components needed to build PV Hybrid Systems. As such, these systems play an important role in rural electrification word-wide and it is becoming increasingly important to supervise and monitor the operation of PV off-grid systems in general but is especially relevant to PV Hybrid Systems. A good monitoring system enables operators to improve the maintenance schedule and organization and it ensures the systems are operating as expected. In case of a failure the operators can react much faster if a data logging infrastructure is implemented.

Typically, the data logging is different for each individual system. This makes it very difficult to compare the data of several different systems. Each data logging technology stores the data in a different format, and each uses differing types and numbers of parameters. Within the last decade it became more and more popular for power electronic components like MPP trackers or battery inverters to offer proprietary data logging on board. Using the same components increases the compatibility of the data logging.

This work proposes, explains and illustrates how to visualise data of lead-acid battery-based PV Hybrid systems. It aims to propose a standardised visualisation report which relies on easily measurable standard data that should be a gathered by most of the data logging offerings. It will be necessary to build a data conversion for each type of implemented data logging technology to the data format defined in this document. Based on that procedure, operators can reach an easy-to-use standardised data visualisation allowing for fast comparison of different systems. The point of comparison provides analysis of the performance of single systems.

The focus of this document is the lead-acid battery used in most existing PV off-grid systems as it has the highest components cost over the system lifetime. Therefore, it is important to optimize the battery lifetime. Battery data visualization and analyses are the first step towards an optimization of the battery management system and the battery condition. This is proposed and described here.

The described work focuses on data visualisation and does not intend to fully analyse battery data and performance data. However, the visualisation is an important first step and already implements aspects of the analyses. With the help of this standardised visualisation, it is easy to compare different systems. This enables optimisation of system weaknesses to improve further systems and also implement solutions in poorly performing systems.

The next scientific step is to develop a standardized data performance analyses based on the proposed work. This shall first be done with regard to PV Hybrid Systems, but can be extended to apply to any kind of PV off-grid system.

It is important to analyse and visualize a huge amount of different data of PV off-grid systems in order to provide general optimisation of the performance of such systems and to train decision makers, installers and operators to ensure high efficiency and performance of PV off-grid systems in general. The publication of the analysis and data visualization tools through the IEA PVPS program makes the information available to everybody and at no cost, so that they can visualize their own data based on the work proposed here. While the tool itself is not yet available, the visualization service is available free of charge. In order to use this service the data need to be converted into the format described in this report. To access the data visualisation, contact the author using the link provided at the end of this report.

Email for data visualisation service:
mm@ofres.org

3 CONSIDERED TYPE OF PV OFF-GRID SYSTEMS

3.1 General information

This chapter shall provide an overview on the most important PV off-grid systems. Not all types of systems will be equipped with data logging as this is not economically feasible (especially for very small systems). Nonetheless these systems will also be listed here in order to provide systematic overview. PV off-grid systems exist in a large power range. This can roughly be classified in the following type of systems:

- Pico PV applications for individual lighting systems in the single watt range. These systems are typically offered in the low-cost range and do not normally provide any data logging feature.
- Classic Solar Home Systems (SHS) show great performance for basic rural electrification world-wide in a power range from 50W to about 500W. Normally such systems do not offer data logging however there are significant projects in the last year combining SHS systems with a prepayment infrastructure and a data logging system to supervise a large number of systems.
- Inverter Systems perform well from 500W up to about 5kW and provide a 24/7 AC power supply to the application and the users. For such systems many data logging solutions are available. These types of systems are in the central scope of the proposed data visualisation.
- PV Hybrid Systems typically incorporate other power sources like diesel or gas driven generators or other turbines like wind and/or water turbines as backup power. Such systems can power up AC mini grids in remote areas or professional applications in the power range from 5kW up to 250kW. Data logging is typically included as these costs are low compared to the overall investment costs.
- Larger PV Systems are often Diesel-PV Systems with or without battery with power generators up to the megawatt range. Data logging is a must in these systems.

Smaller systems are typically pure DC-systems and come with a fixed layout of applications which is normally not changed during operation. Bigger systems contain battery inverters and supply AC power which is distributed through a mini grid which can be a single phase or three phase distribution grid to the users. Also, different grid types can be applied.

3.2 Pico PV-Systems

3.2.1 Description

Pico-PV Systems typically consist of a small solar module and a NiMh or Li-Ion battery, an LED light and optionally a USB plug to charge mobile devices and a DC output to supply small applications like a portable radio. The Pico-PV systems are typically portable devices containing all components within one easy to carry box, though devices with a separate solar module also exist. These devices are particularly useful sense once the size of the solar module rises.

Typical system components sizes are:

- Solar module 1-10Wp. In cases of bigger systems, the solar module is typically the only components which is not included in the whole package so that it can be mounted and easily separately to be permanently exposed to the sun.
- Battery 1,2V up to 12V with 2Ah up to 5Ah → about 10Wh to 30Wh
- LED 1-3W, typically between 100-500lm
- USB charging 4,95V @ 1A, also multiple charging plugs are available

The typical layout of a PicoPV system can be seen in Figure 1.

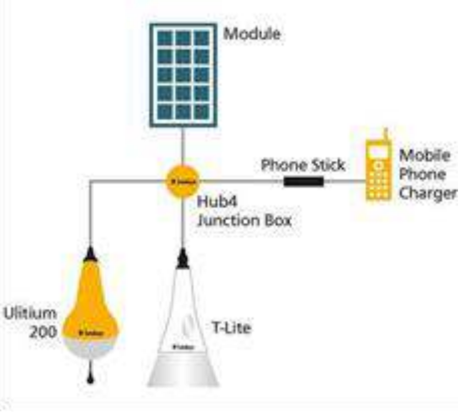


Figure 1: Examples of Pico-PV Systems (left) and schematic of such a system (right). Source of picture: Phaesun GmbH (https://www.phaesun.com)

3.2.2 Market situation

The idea of Pico-PV systems comes from the 1980s when solar cells were expensive and smaller solutions were more realistic. The technological innovations of the 21st century allowed for a market break-through for Pico-PV Systems. Most notably, innovations for Li-Ion and NiMh cells, but also the cost reduction for solar cells and the massive innovations for LED lights were the driving forces behind this. The mass market started in the 2010s. Now the world-wide market volume is estimated to be over two million devices per year. Price reduction is still ongoing and reasonable systems are available between $5 USD to $50 USD in 2022.

3.2.3 References

Further information about Pico-PV Systems can be found in those reports:

- Gogla Pico-PV Report [1]
- IEA Pico-PV report [2]
- Pico-PV systems test report of Fraunhofer Institute for solar energy systems ISE (Freiburg Germany) [3]

3.3 Solar Home Systems (SHS)

3.3.1 Description

Solar Home Systems (SHS) are pure DC systems and consist of one or more solar modules, batteries (mainly lead acid, some systems with Li-Ion) and a charge controller with one or more DC outlets (to supply DC loads like DC (LED) Lamps, radio, fridge mobile charging and other devices). Typically, SHS are stationary power supply systems with a fixed DC wiring connecting the loads. The solar modules are usually securely mounted to maximize the energy yield.

Typical system component sizes can be summarized as follows:

- Solar module 50Wp up to about 500Wp
- Battery Typically 12V @ 20Ah up to about 250Ah
- Charge controller Shunt / Series / MPPT with 10A up to 30A
- Daily available energy 100Wh up to about 1kWh

Figure 2: Picture and schematic of a typical Solar Home System

A typical Solar Home System (SHS) can be seen in Figure 2. SHS provide a 24/7 power supply to supply DC-loads, mainly for lighting, refrigeration and other small DC applications like phone chargers, radio and others. The solar module charges the battery during the day whilst at the same time supplying the load directly. During the night the battery supplies the load without the support of solar modules. In order to achieve a managed energy flow, the charge controller is key in supervising the load and managing the battery. Figure 2. shows the charge controller as the central component which is connected to all other components. The charge controller controls the whole energy flow in the system. It also has to limit the charging current to the battery in order to prevent overcharging. In the case of a low battery, the controller has to disconnect the load to prevent damage to the battery due to deep discharge. Modern charge controllers offer a professional graphical display to inform the user on the status of the battery, as well as the whole system. USB-plugs to charge mobile devices are available directly at the charge controller. Nowadays, a professional algorithm exists to calculate the State of Charge (SOC) and State of Health (SOH) of the battery.

3.3.2 Market Situation

The first SHS have been installed in the early 1980s. Since then a stable world market for such systems has been established to electrify rural regions (typically with low population densities). The most important markets for SHS are South-East Asia and Sub-Sahara Africa. Some countries make intensive use of this technology in order to electrify rural areas. Today the world-market for SHS is above two million installations per annum. Even though the prices for such systems have fallen significantly due to lower solar module prices, there are still ongoing governmentally driven programs to subsidise the installation and rural electrification with SHS.

3.3.3 References

Further information about SHS can be found in the following documents.

- Gogla-report[4]
- IEA PVPS reports of Task2 [5]

3.4 Inverter Systems

3.4.1 Description

Inverter systems can reasonably cover a power range from 0.5kW up to about 5kW load demand. The system layout is similar to SHS. Solar modules are connected through one or more charge controllers to the central battery (mainly lead acid, some systems with Li-Ion batteries). The charge controller offers USB plugs and DC-outlets. One or more DC-AC inverters are connected directly to the battery and can offer a managed AC-grid. This can be a 120V/50-60Hz or 230V/50-60Hz output. Depending on the design architecture there can be more than one inverter installed in parallel. Typically, the inverter supplies the load independent from the charge controller.

Typical system component sizes can be summarized as follows:

- Solar module 200Wp up to about 5000Wp
- Battery Typically 24V @ 200Ah up to about 500Ah
- Charge controller Shunt / Series / MPPT with 10A up to 30A
- Battery inverter Typically 24V @ 0.5kW up to 5kW
- Daily available energy 1kWh up to about 25kWh

A typical schematic of an inverter system can be seen in Figure 3.

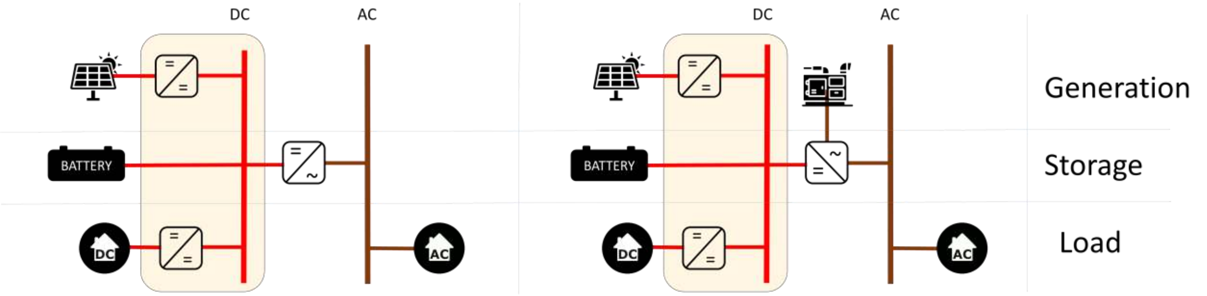


Figure 3: Schematic of an inverter system: left side is a pure inverter system and right side additionally with a backup generator

The solar modules (top, left) charge the battery (middle, left) through the charge controller (rectangle with round edges) during the day. The charge controller limits the charging once the battery is fully charged and manages the connected DC-loads. The inverter (between DC and AC) is connected directly to the battery and supplies the AC-loads. The inverter has its own input and output control and supplies the load independently from the charge controller. Once the battery voltage is below a certain set point the inverter automatically switches off and disconnects the loads in order to protect the battery from deep discharge. Usually, the charge controller and the inverter are separate devices and apply their control strategy independently from each other. More sophisticated devices combine the charge controller and inverter function within one device. This allows calculation of a battery algorithm like State of Charge (SOC) in one device and improved battery management can be applied. This can also be realized with the help of component-level communication between the different devices. Typically RS485 communication with a simple proprietary protocol is applied. The concept of separate devices brings more flexibility to the system in case of an increased load demand or if there is the need to extend the available power and energy. If designed well, if one component fails the rest of the system can still operate. Bigger systems offer an additional backup generator (right picture of figure 3) which is connected directly to the inverter and supplies the load from the inverter side. It can, in parallel, recharge the battery

3.4.2 Market situation

Pure stand-alone PV off-grid systems based on battery inverters are an important market segment for rural electrification. Due to the power range it applies to many application types. Semi-professional and professional systems are also realised with battery based inverter PV off-grid systems. Especially remote schools, clinics, also small hospitals, kiosks and other small business applications can be realized with sustainable and reliable inverter PV off-grid systems.

The market is world-wide and there are two segments which dominate.

1. A natural market has established in rural regions in both industrialised and emerging countries. The systems installed are owned and paid for by the users themselves. Service and maintenance is organized privately through the industry supply chain. The number of installed systems strongly depends on the population density and the electrification rate of the country.
2. A highly volatile project-based market exists. This project-based market is mainly driven by governmental or non-governmental electrification programs resulting in regularly opened tenders for rural electrification based on standalone PV off-grid inverter systems. The main market areas are South-East Asia including China and India and East- and South Africa.

The overall market size can be estimated to about 250MWp for 2021.

3.5 PV Hybrid Systems

3.5.1 Description

PV Hybrid Systems allow for a significant increase to the output power compared with the smaller Inverter, SHS and Pico Systems. In such PV Hybrid systems, one or more additional controllable power sources are added to the system. These controllable power sources can include other renewable sources like wind or water turbines. Often traditional diesel or gas generators are used in case the available renewable sources cannot provide enough electricity due to the intermittent character of their sources. Battery storage is also used as a controllable power source to manage intermittent generation and variable demand.

The main power source is still the PV module array to charge the battery and supply the load in parallel. While mainly lead acid batteries are used, a few systems with Li-Ion batteries have already been installed. PV Hybrid systems are designed to provide a reliable 24/7 power supply of the whole distribution grid.

Typical PV Hybrid system component sizes can be summarized as follows:

- Solar module 5kWp up to about 200kWp
- Wind turbines 5kW up to 50kWp
- Water turbines 3kW up to 50kWp
- Diesel/Gas generators 20kW up to 250kW
- Battery Typically 48V @ 500Ah up to about 10000Ah
- Charge controller Shunt / Series / MPPT with 10A up to 30A
- Battery inverter Typically 48V @ 5kW up to 10kW per phase stackable in parallel sometimes up to 9 inverters work in parallel
- Daily available energy 25kWh up to about 5000kWh

Small PV Hybrid Systems typically provide a single phase AC outlet which can be distributed through the connected distribution grid. A typical layout can be seen in Figure 4. Larger PV Hybrid systems incorporate several power sources. A distributed generation system can also be realized with this type of PV systems. In this case the power sources are no longer located in the same area but are installed at several locations throughout the distribution grid. The power output is typically more than one AC phase and potential offers a synchronized 3-phase grid. Such a diagram can be seen in Figure 4:

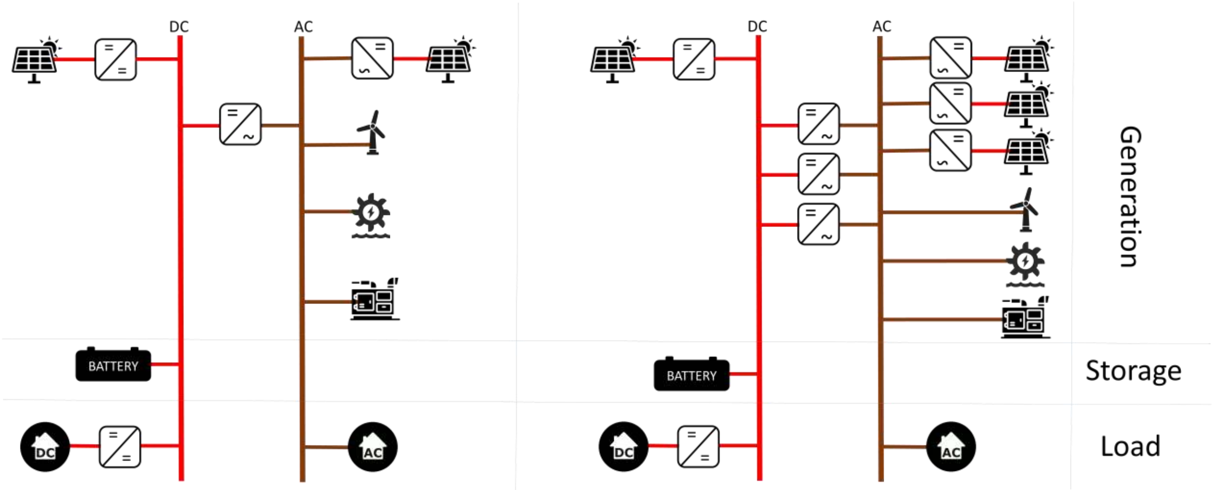


Figure 4: Single phase PV Hybrid System (left) and 3-phase PV Hybrid System (right)

PV Hybrid systems charge the battery from several sources. As well as the PV array, at least one more power source is added to the system. Often controllable generators like gas or diesel generators (gensets) are used. This allows for a significant increase to the output power and overall available energy. Typically, one component is designed to realise the overall energy management in the system. This can be the PV charge controller or the battery inverter. Bidirectional battery inverters are one of the key parts in such systems. They are responsible for supporting the supply grid and often control the whole system. The energy management has to calculate the State of Charge (SOC) of the battery and control the whole energy flow within the system. Part of the management strategy is to switch on and off all controllable generators like diesel or gas generators. Basically, all generators can charge the battery. The simplest control strategy is to switch controllable generators on once the voltage of the battery is low and to switch them off again once a reasonable SOC of the battery is reached. In bigger systems, more complex strategies are applied.

3.5.2 Market situation

PV-Hybrid Systems have a long tradition in rural electrification. The first systems were installed in the early 1980s. Those systems where often part of research and development projects and tested the functionality of the technology. At that time, the PV energy contribution was typically low when compared to the genset contribution as prices for solar modules where very high.

Beside the research purposes, NGOs developed the reputation of PV-Hybrid technologies by installing many systems for rural development and the supply of remote clinics or villages. As time went on, more governmentally driven electrification programs were developed to install PV Hybrid Systems for rural development and electrification. This process significantly increased the number of systems installed worldwide.

Nowadays there exists an established, international market for such systems. Beside rural electrification, commercial applications have gained an increasing share of the market. Applications like telecommunications repeater stations, mining supply stations and other industrial applications have built a well-established international market today. Additionally, there is growing demand for high quality PV Hybrid Systems technology for reliable power supply stations for private homes in remote areas of industrialised countries.

Today the PV-genset ratio has shifted more towards PV, due to the significant cost reduction for PV solar modules.

The international market for such systems can be estimated to be between 100MWp and 500MWp per annum. Global data is not available and most studies have been realized only for single markets. The uncertainty of the market size is notable. Apart from market considerations there exists several brand name manufacturers (especially for power electronics and battery inverters) who supply professional electronics to this market in reasonable quantity, indicating a stable and professional, well-established international market.

3.5.3 References

List of references

- IEA PVPS Task9 report club-er 2013 [6]
- IEA PVPS Task11 reports [7]

3.6 PV Mini-Grids

3.6.1 Description

PV Mini-Grids or PV-Diesel systems are a typically battery-less system with an available output power above 250kW. One or more central generators supply a distribution grid, which is typically a country specific standard grid designed and managed by the responsible utility. If the grid has to cover a specific distance, transformers may be applied to maintain the required voltage. Also, several sub-grids may be applied which are connected to the main grid with the help of a central transformer. The generation side consists of one or more central gensets which can be diesel or gas-based. Often, in order to increase their lifetime, the gensets do not run in parallel but share the operation time during the day. Typically, the bigger generator covers the hours with high power demand while the smaller devices share the low-load time. In addition to these controllable generators, a PV array is added to the system in order to reduce the fuel consumption of the generators. The size of the PV array can be chosen very flexibly. If the PV array is rather small relative to the size of the gensets there is typically no special additional control necessary. If the size of the PV array is chosen big enough in a way to cover the peak load demand an additional central energy and power control unit needs to regulate the power flow in the system. That allows to fully shutdown the gensets at least during the day as the central energy and power control unit will limit the PV inverter output power to the actual power flow. Excess energy from PV cannot be used in such a configuration.

Typical system component sizes can be summarized as follows:

- Solar module 5kWp up to about 5MWp
- Wind turbines 50kW up to 5MWp
- Water turbines 100kW up to 5MWp
- Diesel/Gas generators 250kW up to 25MW
- System components PV grid connected inverters, Genset control, power flow control, energy management unit, central control room, remote monitoring
- Daily available energy 1 MWh up to about 1000MWh

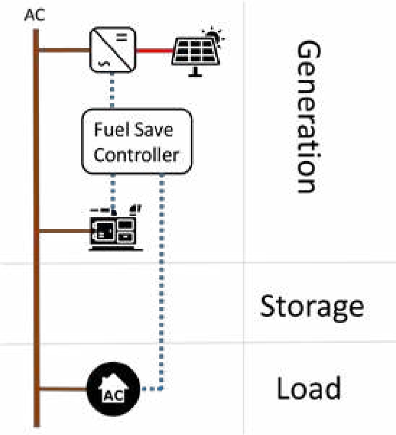


Figure 5: Picture and schematic of a PV-Diesel Mini-Grid

PV-Diesel Mini-grids are typically genset dominated generation systems. This means the connected grid is a genset-dominated grid. All operating gensets are grid-forming and control all relevant grid parameters like voltage and frequency with the help of its integrated control. All connected PV arrays, including geographically distributed PV arrays, are connected to the grid through grid feeding inverters which are typically not able to form a grid, but are allowed to follow the grid parameters given by the operating generators. In addition, an energy management unit controls the whole energy flow in the system and makes sure that the generation power is always equal to the load demand. This unit needs a fast communication interface to all grid feeding inverters and to all generators as well as information about the actual load demand. Depending on the management control strategy, it can regulate the feed-in inverter power. Notably, it is able to reduce the inverter power if this is necessary to stabilise the grid and to prevent the inverters from charging the generators even if this leads to the situation that not all available energy coming from the PV inverters can be used in the system. In the case, when more than one generator is available in the system, the energy management unit can also shut-down or start-up generators. If generators with different power ratings are installed the energy management unit can, for example, choose the active generator adequate to the load demand in order to optimize the generation efficiency and to increase the fuel efficiency. With the help of these strategies, it is possible to deliver significant fuel reduction. Due to low module prices this is an economically reasonable situation.

3.6.2 Outlook

Newly installed systems continue to integrate more advanced solutions which enable an increase in the PV energy share. Specially designed and adapted central PV inverters are not only able to feed into an existing grid but can also form and control the grid by themselves. A safe switching strategy is needed to allow switch switching over from one control strategy to the other. This allows the energy management unit to navigate between all available gensets. Depending on the location and size of the PV array this can allow pure PV power to drive the system during the whole day.

Due to the rapid development of Li-Ion batteries, an increasing numbers of mini-grids are equipped with an additional Li-Ion storage in the MWh range. This also allows the gensets to switch off during low load demand in the night. The energy management unit has to apply a different control strategy, more similar to PV-Hybrid Systems described above.

Both aspects provide an increase to the PV energy share of the whole energy demand significantly. Also, PV dominated systems can be realized with the help of these new technologies.

3.6.3 Market Situation

World-wide, many PV mini grids have been installed. Even though the market potential is huge, the number of operating systems is limited. Many of the early installed systems are donated systems which were installed within the frame of either research or demonstration projects. As a result, there is limited information about realistic installation costs and operating costs. The upcoming decades will show how falling costs and competitive markets will deliver an increase in installed systems per year.

Installed and running systems can be observed in Panama, Brazil, Nigeria, Sub-Sahara, India and other East-Asian Countries and Australia.

In early years the market size was limited to several single systems per year but growing interest in resilience and efforts to reduce energy poverty mean that 100's of systems are now installed all over the world.

3.6.4 Reference

- IEA PVPS Task9 report on PV diesel Systems [8]

4 SCOPE OF ANALYSES

The scope of this work is to visualise the monitoring data of any PV off-grid system with batteries. As the most important cost driver is the battery this document focuses on the visualisation of the battery data.

The proposed standardised data visualisation is a pure technical data visualisation and does not take into account any other data. It is based on the monitoring of the battery data and simply visualises the content of the measured data.

Three different type of data visualisations are proposed here:

- Visualisation of energy (generation and consumption) data

  A simple energy analyses of the overall input and output energy sum in order to provide an overview on the whole system efficiency and the share of the different generators supplying the load. This already can help to optimise the usage of controllable generators like diesel generators.

- Temperature data visualisation

  A detailed visualisation of the battery temperature shall bring important information about the environmental boundary conditions under which the battery is treated within the systems. Especially a visualisation over a long period of time, like several years, can show the additional aging of the battery due to the average ambient temperature influencing the battery.

- Battery data visualisation

  The daily and yearly input- and output analyses including the statistical information on the system usage is the main data visualisation proposed here in this document. It is a powerful standardized tool and provides important system information within several graphs fitting to a one page visualisation of the system.

The proposed visualisation is capable of processing big data sets of many PV off-grid systems within a short time in order to overview the systems and to compare them.

5 REQUIRED DATA

In order to realise the proposed PV Hybrid system battery-data visualisation, a minimum data set is required. Typically, all necessary data collection is within the standard scope of commercially available data loggers. Nevertheless, the required data shall be listed here with a short comment.

5.1 Energy analyses

To perform the (annual) energy analyses, the following data is required. All data shall be the sum of all input and output sources (in cases of more than one source) and shall be measured in kWh. To perform the analyses a measurement period needs to be defined, e.g. one year. All data needs to reflect the sum over this period.

- Fuel consumption, to be measured in litres. This shall be the overall fuel input into the system. In the case of more than one generator, the consumption of all generators shall simply be added. Also, if different types of generators are used, like one diesel generator and one LPG generator, the consumption of each generator shall be added, even if this leads to a mixture of different types of fuel. This can be done, as the main interest of the analyses is to analyse the share between fossil and renewable sources.
- Fossil generation, to be measured in kWh. This shall be the overall energy sum of all fossil generators over the measurement period. It shall reflect the overall energy contribution to the system coming from the fossil side.
- Renewable generation, to be measured in kWh. This shall reflect the overall renewable energy contribution. It shall be the overall energy sum of all generators like photovoltaic, wind or water turbines.
- Load consumption, to be measured in kWh. This shall be the overall load consumption of the applications. The measurement point shall be the output of the power source. The distribution line losses are included into the consumption side which is justifiable as it is not possible to supply the load without transmission losses.

5.2 Single parameter analyses

To perform the single parameter analyses, which is especially used to analyse the battery temperature, the following parameters need to be recorded by a data logger. The measurement step can be defined according to the local and technical conditions but a minimum period of one recorded measurement per minute is recommended. The defined measurement step shall remain the same throughout the analysis.

- Time stamp. This shall contain year, date and time in a suitable accuracy.
- The parameter itself such as:
  - Battery temperature in °C or °F
  - Battery voltage in V
  - Battery current in A

- Output power in W
- State of charge of the battery (SOC)
- State of Health of the battery (SOH)
- Or any other parameter can by visualized

5.3 Energy balance

To analyse the energy balance and the performance of the system the following data is necessary:

- Time stamp. This shall contain year, date and time in a suitable accuracy.
- The batteries voltage in V. If there is more than one battery installed in the system, the analyses can be done separately for each battery. The voltage shall be the overall voltage of the whole battery pack which can consist of many battery cells in series and in parallel.
- The battery current in A. This shall be the overall battery current to be measured directly at the pole of the battery. It shall be the overall sum of all power devices charging or discharging the battery. It shall be negative while the battery is discharged and positive for a charging situation.
- The state of charge (SOC) of the battery. This reflects the actual charging status of the battery. This value has to be calculated at any central point in the system by one of the components. It will not be calculated within this analysis and has to be provided by the system as a separate parameter. The proposed analyses will then validate the plausibility of the SOC.

6 ANNUAL ENERGY ANALYSES

The energy analyses of the PV-Hybrid System provides interesting information on the system efficiency. At the same time, very little data is required to be recorded permanently to perform this type of analyses.

6.1 Scope of energy analyses

The scope of the energy analyses proposed in this chapter is to provide key figures describing the performance of the system. It is possible to perform the analyses with the help of pure in-out energy data which can be easily gained with the help of simple AC kWh counters. No detailed battery data or profile data will be required. No Ah-counting and no energy throughput data for the battery will be taken into account at this stage. The central aspect remains to characterise the system with the help of extremely little input data.

6.2 Required data

Figure 6 shows the schematic of the overall PV Hybrid plus battery system. The diagram does not specify the detailed system layout of the specific system. In fact, it does not influence the definition of the performance parameters whether a DC-coupled, AC-coupled or any other type of mixed systems is analysed. The idea of the annual energy analysis which is presented here is to obtain a system performance overview with the help of very few input parameters. Therefore, it is necessary to quantify the following parameters which are described in Figure 6: Schematic of measurement points for data analyses.

- FC : Fuel Consumption. The measurement unit typically is in litre [l]. This parameter describes the overall amount of all types of fossil fuels which had to be put into the system within the analysing period. Typically, this is diesel-fuel. Depending on the type of generators used this can also be natural gas, LPG or any other type of petroleum. If more than one generator is used in the system, the parameter FC shall be the sum of the fuel consumption of all generators.
- FG : Fossil Generation. This parameter measures the overall energy contribution from the generation side of all controllable fossil generators in the system. It is measured in [kWh] and should be the output energy coming from the generators. It will reflect the AC output side. For this counter it does not matter whether the generators supply load directly or provide an input to the PV-Hybrid System power converters.
- RG : Renewable Generation. The energy contribution of all different renewable power sources used in the system is counted here. The parameter reflects the energy sum of all power generators. In the case of mixed generators the individual energy contribution is summed up. This overall sum can consist of Photovoltaic generators, wind generators, water turbines or other renewable power sources used in the system. The unit of the parameter is [kWh].
- LC : Load Consumption. There is a need to count the overall energy consumption of the system. This is a pure load counter which does not take into account whether the power comes from power inverters, generators or others. It simply counts the overall energy consumption of all loads. The unit is [kWh].

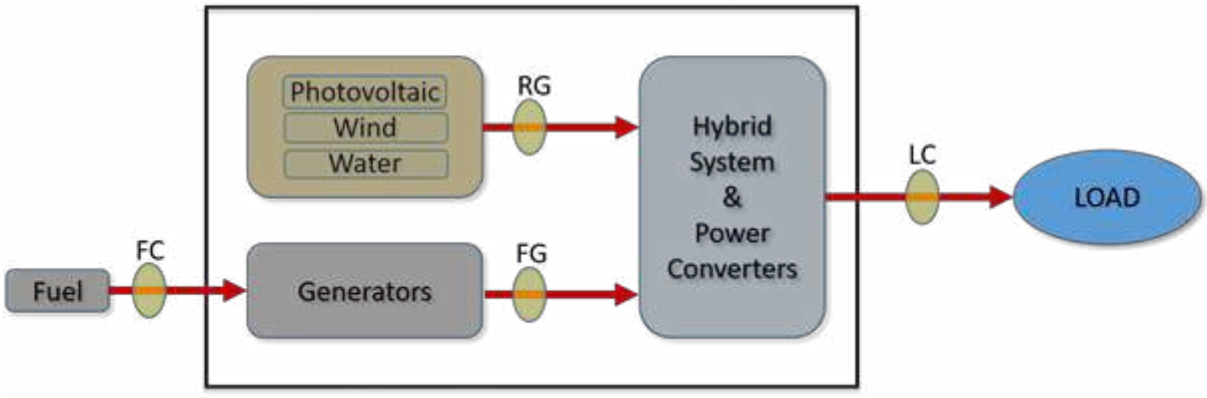


Figure 6: Schematic of measurement points for data analyses

6.3 Energy analyses key factors

This data needs to be available for the whole measurement period in order to calculate the overall PV Hybrid System energy efficiency. The following key figures can be easily calculated:

- GFC : Genset Fuel Consumption. It is measured in [l/kWh] and calculated by :

  GFC[l/kWh] = FC[l] / FG[kWh]

  Input parameters are the Fuel Consumption in litres and the overall amount of Fossil Generation in [kWh]. The key figure Genset Fuel Consumption shall be as low as possible and not only depends on the used type of generators but also on the control strategy of the whole system. Many generators show relatively high consumption at low loads while the efficiency at high loads is rather good. To optimise the system, it is recommended to supervise the GFC key figure and eventually to change the genset control strategy according to the consumption profile of the specific genset. The genset shall only run at times in which it can operate in a high fuel efficiency operating point.

- REC : Renewable Energy Contribution. This is measured in [%] and calculated to

  REC[%] = RG[kWh] / (RG[kWh] + FG[kWh])

  The REC key figure is an important and easy to calculate figure. It shows the fraction of renewable energy sources in the system. It shows which are the main sources to supply the load. This figure can also be used to optimise the energy management strategy of the system to increase renewable energy contribution and to reduce the fuel consumption. The REC figure shall always be as high as possible. In systems without a fossil genset it is 100%.

- HSEP : PV Hybrid System Efficiency Performance. The figure is measured in [%] and calculated by :

  HSEP[%] = LC[kWh] / (RG[kWh] + FG[kWh])

This key figure shows the efficiency of the whole system and reflects the losses during energy storage within the battery. Clearly this parameter shall be as high as possible but cannot exceed 100%. The overall system efficiency can be optimised by reducing the load during night time and by increasing the renewable energy contribution. Also, the applied energy management strategy of the fossil generators has significant influence on this parameter. The efficiency of the generator depends on the load consumption. This means it is possible to increase the efficiency of the whole system if the type of generator is adapted to the load and managed according to efficiency rules. The aging of the battery also has a negative effect to the overall system efficiency as the battery losses increase by the number of used cycles.

6.4 Energy analyses examples

The proposed energy analyses can easily be performed and needs little data. Some examples can be seen in Figure 7: Example data energy analyses. Three different systems are listed and compared. Example 1 is a small pure PV system without any additional generators. The load is a 120W AC-load which is running 24/7 and is connected directly to the inverter supplied by the battery. The PV array is a 1kWp array connected to a 30A charge controller which charges the 24V@400Ah lead acid battery. Due to the lack of additional generators all key figures are zero, just the Hybrid System Efficiency Performance (

HSEP) provides information of the efficiency of the system. The value is 87.5% which is a very high efficiency value. This indicates that a significant part of the load is supplied directly by the PV array during the day. It also shows that the battery is still quite new and very efficient.

The 2nd example in Figure 7: Example data energy analyses is a small PV-Hybrid System to supply a little village. The design is a 12kWp PV array supported by a 20kW generator which is not only operating as a backup generator but contributing significantly to the permanent load supply. The village is divided into three sections. Each section is supplied by one single phase. The consumption of phase two is significantly higher compared to the other phases. This is due to the longer distance of the houses in one line. The HSEP is already quite low with at 73.1%. This includes the losses inside the battery, the power electronics, and the power distribution. The Renewable Energy Contribution is quite low with REC = 36.3%. Already this analysis provides an optimisation proposal for the given system. If about 9850l diesel must be purchased at around 1USD/l this ends up in 9850USD/a fuel costs. The fuel transportation costs shall be included in the fuel costs meaning the price for diesel shall be 0.5USD/l while fuel transportation also costs 0.5USD/l to the remote site. Fuel prices vary a lot from country to country. The given numbers mean typical numbers and are from 2019. The assumption is a ratio 1:1 for fuel costs and fuel transportation costs. In remote areas this can easily be 1:3 or more. 1kWp PV can be purchased at about 1500USD including installation. This means an additional 6kWp PV array can be paid back within one year resulting in about 7000kWh PV contribution more per year. This can be saved at the diesel fuel contribution resulting in 25% reduction of fuel costs. This is 2500USD/annum additional savings just from increasing the PV contribution from 36.3% to about 70%.

			Example 1	Example 2	Example 3
			Pure PV	**PV-Diesel**	**Hybrid**
G1	LPG Genset	[l]			111953
G2	Diesel Genset	[l]		9850	56523
FC	Fuel Consumption	[l]	0	9850	168476
G1	LPG Genset	[kWh/a]			198632
G2	Diesel Genset	[kWh/a]		25600	156852
FG	Fossil Generation	[kWh/a]	0	25600	355484
PV	Photovoltaic	[kWh/a]	1536	14589	46539
Wind	Wind Power	[kWh/a]			59623
Water	Water turbine	[kWh/a]			35601
RG	Renewable Generation	[kWh/a]	1536	14589	141763
L1	Load L1	[kWh/a]	1345	5120	125600
L2	Load L2	[kWh/a]		15600	135680
L3	Load L3	[kWh/a]		8659	117895
LC	Load Consumption	[kWh/a]	1345	29379	379175
Key Figures					
GFC	GensetFuelConsumption	[l/kWh]	0,00	0,38	0,47
REC	RenewableEnergyContribution	[%]	100,0%	36,3%	28,5%
HSEP	HybridSystemEfiiciencyPerformance	[%]	87,6%	73,1%	76,3%

Figure 7: Example data energy analyses

The last example in Figure 7 is a PV Hybrid System with 35kWp PV, a 60kW wind turbine and a 10kW water turbine. These renewable sources are supported by two controllable generators, a 30kW diesel generator and a 100kW liquid gas (LPG). Those generators never run at the same time and share their availability. The system can seldom run without a generator however the power electronics are capable of doing so. The overall energy contribution of the renewable sources is already less than half of the overall energy demand. Also, the Hybrid System Efficiency Performance provides a reasonable key figure and offers room for optimization. This can be done by changing the power of the sources and by adapting the control strategy.

7 SINGLE PARAMETER ANALYSES

7.1 Introduction

This chapter shall introduce a one-page visualisation of one single parameter. Different graphs shall provide a fast overview on the whole data set. The profile of the parameter is displayed as well as histogram information and a characterisation of the fluctuations within the parameter. It shall be a visualisation and not a full data analysis. However, already the one-page visualisation allows for the drawing of valuable conclusions.

The proposed visualisation can be applied to any kind of parameter. To create a picture of a PV Hybrid Systems it makes sense to apply this to the following set of parameters:

- Battery voltage [V]
- Battery current [A]
- Battery Temperature [°C]
- Battery State of Charge – SOC [%]

All these parameters provide significant information about the condition of the battery and may provide necessary conclusions. The output of this visualisation is four pages of standardised graphs to display the most important battery parameter.

The following sections shall describe the single parameter visualisation in more detail. As an example, the temperature was chosen to describe the visualisation however the same procedure can be applied to any kind of other parameter. In Appendix A, five examples of PV Hybrid Systems are given for which the battery voltage, current, temperature and SOC have been analysed.

7.2 Description

Temperature data is generally key data in the analysis of the performance of any battery system. This data has an especially significant influence on the lifetime of the system. This can be further applied to any kind of battery. As the battery is the most cost intensive part of many PV off-grid systems analysing the temperature data is important. In particular, the temperature range that the battery is operating in is of great importance (especially for lead-acid batteries). According to [9]/[10], the life-time decreases linearly with rising ambient temperature. If the same type of battery pack is treated with exactly the same irradiation and load profile but under different ambient temperature conditions the life cycle can see notable change, for example a system with lower average ambient temperature sees significantly longer life cycles. To know the battery operating temperature means to already know one important parameter which largely influences the life-time of the battery and with this the overall costs of the PV hybrid system.

This chapter shall propose a method to visualise the battery temperature data and to estimate the lifetime of the battery according to these ambient conditions in the usage of the specific system.

To perform the visualisation, it is recommended to always group the available data to a set of data of one year. If one measurement point per minute is recorded this leads to 525 600 measurement point/year which still can be handled quite easily. At the same time this allows an effective comparison of different years and their deviations (mainly caused by weather conditions).

7.3 Measurement recommendations

To analyse the performance of any kind of PV off-grid system it is essential to measure the battery temperature as accurately as possible. It is recommended to measure the temperature close to the battery using sensors which can be mounted in the middle of the battery pack, directly in between two battery blocks. This allows for the detection of the maximum temperature within the battery pack.

For bigger battery systems it is recommended to define several points to measure the temperature at different locations within the battery. Typically, one measuring point in the middle of the battery is applied and another one at the front end of the battery.

Generally, it is recommended to apply another sensor to measure the ambient temperature within the powerhouse where the battery and the power electronics is located. In addition to this it makes sense to also measure the outside air ambient temperature.

Temperature data is typically available from many devices. Power electronics devices in particular, measure and record internal temperature data to supervise the electronics. This information is valuable to record and to analyse in order to have a look to the overall performance.

Depending on the type of data logger attached to the system, the temperature measurement capabilities can be very different. External data loggers allow a good flexibility to apply more than one sensor. If the internal data logger of the inverter/charger or another power electronics device is used, often there is no user configurable interface to the temperature measurement.

Temperature measurement is always aligned to the thermal capacity and it is therefore not critical in terms of the applied measurement interval. Typically, minute-data (one value recorded every minute) are fully sufficient for analyses. Ideally the recorded values are an integral value or an average value over several measurement points in a raster of one measurement per second. This leads to accurate and stable measurements. If this is not possible it is also sufficient to apply one single shot measurement per minute and store this single value. The temperature change of the whole battery back is limited to the typically very high thermal capacity of the massive material and this leads to the situation that the temperature difference within one minute is quite low and limited.

The applied measurement accuracy also strongly depends on the capability of the used data logger. Generally, it is recommended to design the whole temperature measurement circuit to ensure an accuracy of +/- 1% while the resolution of the measurement shall be at least 1°K increment.

An example of a minimum requirement to a possible data-set is described here:

dd.mm.yyyy hh.mm; T[°C]

23.04.2008 10:23; 20

23.04.2008 10:24; 21

23.04.2008 10:25; 22

23.04.2008 10:26; 23

23.04.2008 10:27; 24

23.04.2008 10:28; 25

7.4 Data visualisation

Temperature data can be visualised very effectively and visualisation can enable a quick and effective analysis of the system in order to have a look at the possible performance and life-time issues.

7.4.1 Parameter profile

The first step to visualise the temperature data is to draw the temperature profile over time. A picture of such a profile can be seen in Figure 8

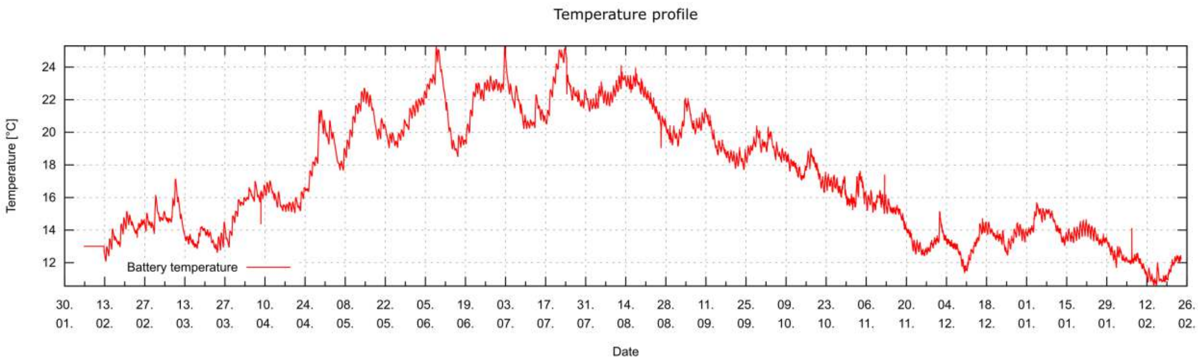


Figure 8: Parameter profile of sample data set

This profile shows a good overview of the data, the maximum and minimum temperature during the measurement period and provides a view into the usage conditions of the applied system. The given example shows the battery temperature of a typical summer-winter scheme in the northern hemisphere. The layout of this profile indicates a strong link between the measured battery temperature and the ambient temperature, while the short-cycle deviations of the ambient temperature should be typically higher than the deviations within the battery temperature.

7.4.2 Parameter heat map

In addition to the temperature profile, the temperature heat map allows a more detailed view to the recorded data. An example of the heat map drawn from the sample data can be seen in Figure 9:

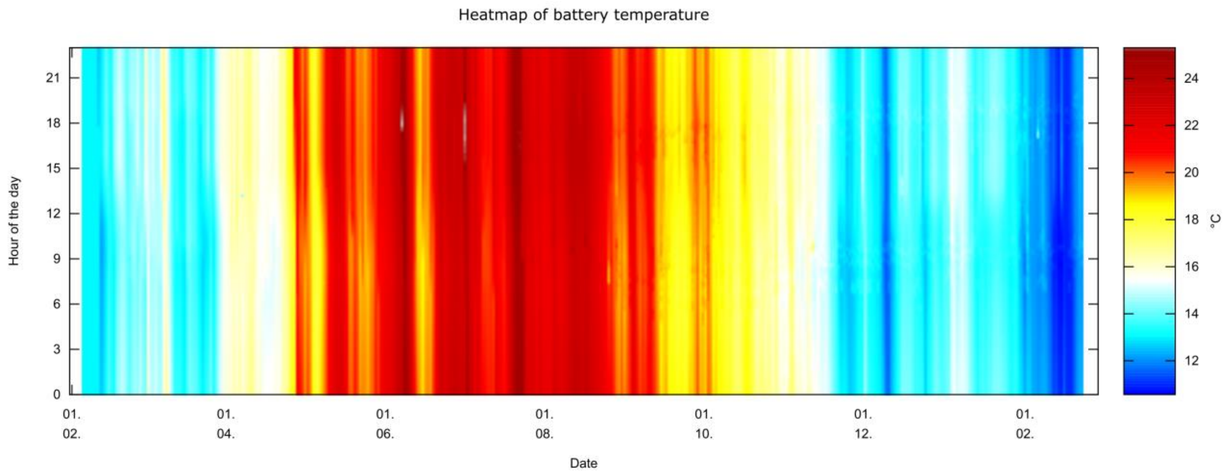


Figure 9: Heat map of sample data set

The heat map is drawn in a way that each measurement point is displayed with one dot. The colour of the dot reflects the temperature. The colour scale right beside the heat map indicates the assignment of the colours to the temperature values.

The X-axis displays the time stamp while all values of one single day are displayed as ascending minute-values starting from mid-night to build a vertical line above the specific date. This means the Y-axis shows the time as hours of the day from 0-24. If such a visualisation is done for all days in a year, graphs like in Figures 9 and 10 will be generated.

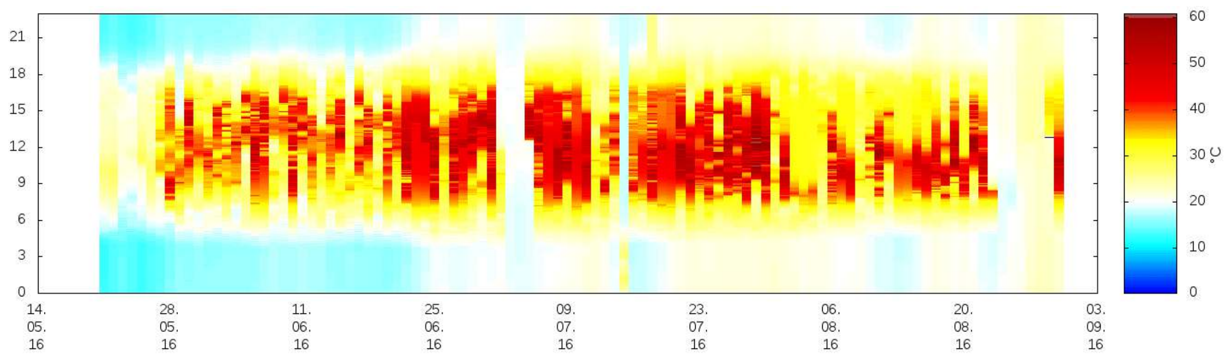


Figure 10: Heat map of a battery temperature data set

The advantage of the heat map is the capability to clearly display differences in the annual profile as well as in the daily profile. The example of Figure 10 shows significant temperature deviations of about 30K within each single day, while the overall temperature behaviour is quite similar for each day within the whole measurement period from May to September. In contrast, the profile from Figure 9 shows a rather stable temperature over the course of one day, while the average daily temperature changes significantly through the measurement period.

This means the heat map is a powerful tool to visualize the temperature profile in a 2-dimensional graph. Hot spots can be identified as well as extreme weather-based conditions can be seen. The heat map of the battery temperature also indicates the share of time in which the battery operates at high temperatures which has a significant influence on the lifetime of the battery.

7.4.3 Frequency distribution of temperature

In order to configure the frequency distribution diagram, the number of bars needs to be defined and a bar width should be calculated.

A reasonable value for the number of bars to define the graphic can be n = 25. The width of the bars can be calculated by

$$w_U = (U_{Batt\_max} - U_{Batt\_min})/n \qquad w_I = (I_{Batt\_max} - I_{Batt\_min})/n$$

To calculate the diagram the number of values within each bar is summed up. All absolute values are normalized by the number of values (sum of numbers not values). Furthermore, a Gauss fit is calculated and displayed over both frequency distributions. The temperature distribution does not have to follow the Gauss curve as the temperature is influenced by many factors such as user behaviour, the power electronics, as well as some influence of the ambient temperature and other factors. The Gauss fit shall be implemented here into the graph in order to compare the temperature behaviour with normalised Gauss behaviour.

$$f(x, \mu, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

While μ is the mean value of all temperature data and σ is the standard deviation from the mean value. Another key piece of information that can be drawn from the temperature data is the histogram. Figure 11 shows an example of a histogram of the sample data set according to the temperature profile of Figure 8. This provides information on the frequency of occurrence of a specific temperature range. Therefore, the whole temperature range needs to be grouped into bins. In the example in Figure 11 it has been decided to use 45 bins to display the temperature range from 10°C to 25°C. To receive a stable and comparable diagram it is recommended to use not more than N = 50 bins. The width of each single bar can then be calculated by:

$$bar_{width} = (T_{max} - T_{min}) / N$$

Where barwidth is the width of each single bar in [°K], Tmax is the maximum temperature within the data set and Tmin is the minimum temperature. In the given case we receive barwidth = 0.333°K.

With the help of this definition, we can calculate the number of temperature values within each bar and divide this by the overall number of data points to receive the frequency of occurrence of this temperature bin. In the given example the number of temperature values between 10°C and 10.333°C is 5.430. The whole data consists of 530.987 data. This means 1.02% of all values belong to this bin. By performing this calculation through the whole set of bin results in the graph of Figure 11

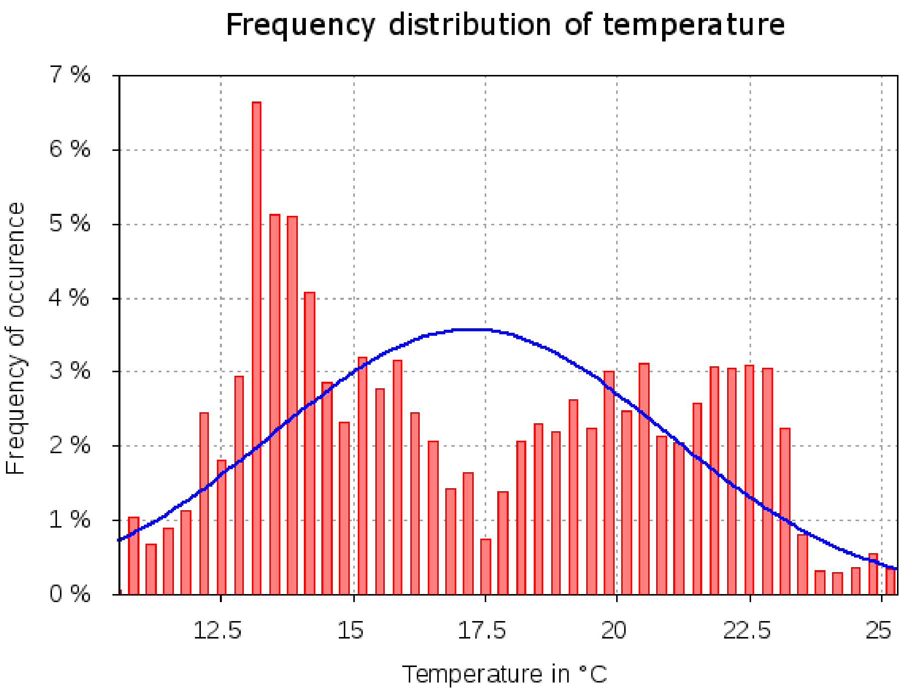


Figure 11: Frequency distribution of temperature

In addition to the histogram, it makes sense to add a Gauss curve to the frequency of occurrence of the temperature. The Gauss fit is calculated by:

$$f(x, \mu, \sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

While μ is the mean value of all temperature data and σ is the standard deviation from the mean value. The blue line in Figure 11 reflects the Gauss fit for the given set of temperature data.

This visualisation allows a detailed view of the operating temperature of the battery. Figure 11 shows a relatively equal distribution of the temperature through the whole temperature range while there is a significant peak at about 13°C. Nevertheless, the mean value is at about 17.5°C even though this exact value does not appear often.

7.4.4 Profile of parameter value difference

Another interesting piece of information to be gained is the profile of the parameter fluctuations. This can be calculated on the basis of the parameter changes. An analysis of the differential changes of the parameter over time can provide this information. Here it is calculated on the basis of the temperature data. A possible snapshot of a temperature profile can be seen in Figure 12. The temperature difference profile shows the value of the rising temperature from any lower turning point up to the next top turning point. The graph is divided into 7 rectangles which wrap the profile up to the next turning point at which the slope of the curve is again zero.

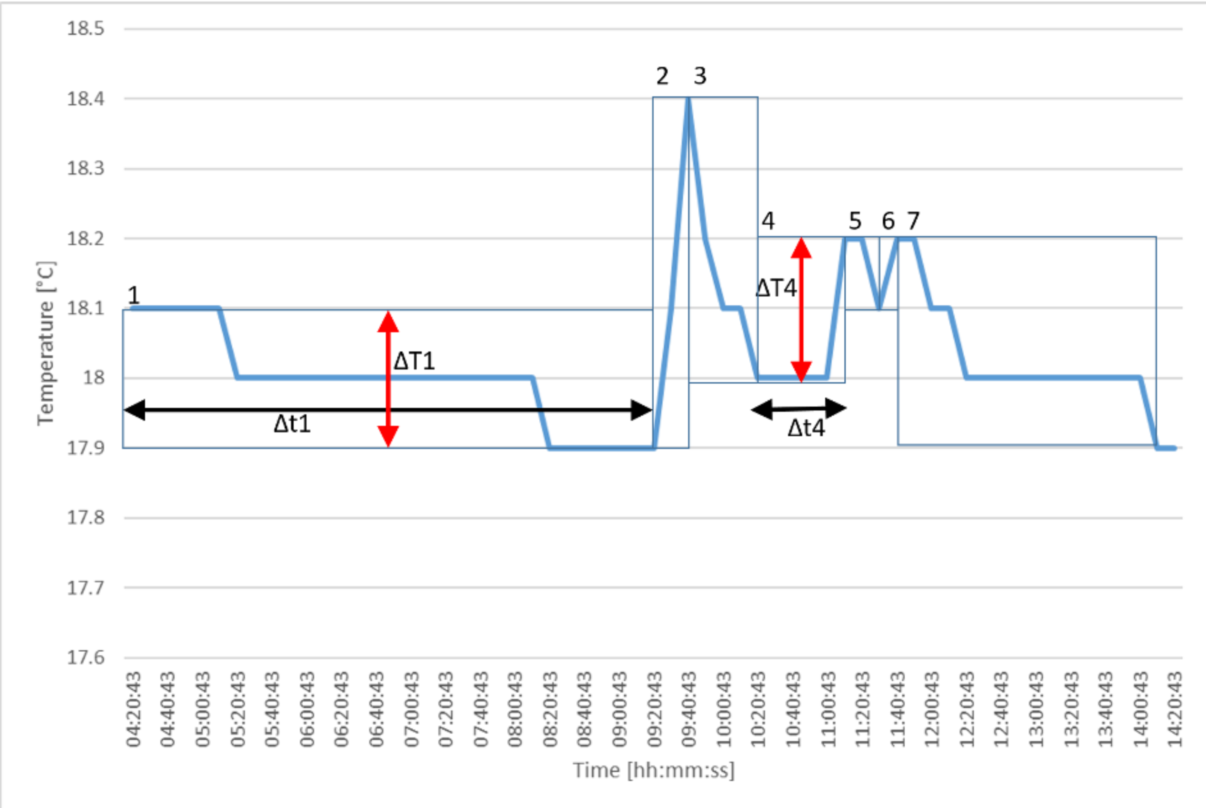


Figure 12: Calculating the parameter delta profile

For rectangle 1 the temperature difference is ΔT1 = 17.9°C – 18.1°C = - 0.2°C, for rectangle 2 it is ΔT2 = 18.4°C – 17.9°C = 0.5°C. By definition, a falling temperature follows a rising temperature and the visa versa. For each calculated temperature difference (ΔTn), the specific time stamp indicating the end value of the time of the specific rectangle is recorded into the data set. The sample date set from Figure 12 generates the data set described in Table 1.

Number of rectangle	Generated time stamp	Temperature difference [°C]
1	25.3.2008 09:20:43	- 0.2 °C
2	25.3.2008 09:40:43	+ 0.5 °C
3	25.3.2008 10:20:43	- 0.4 °C
4	25.3.2008 11:20:43	+0.2 °C
5	25.3.2008 11:30:43	- 0.1 °C
6	25.3.2008 11:50:43	+0.1 °C
7	25.3.2008 14:00:43	- 0.3 °C

Table 1: Data set for calculating temperature differences

This list shows the temperature gradients which the battery is exposed to and provides valuable information about the battery condition. This data can be brought into a profile graph which can be seen in Figure 13 on the basis of the sample data set. In this case all gradients are displayed in a positive curve regardless of whether it is a rising or falling gradient. That makes it easier to compare the rising and falling gradients.

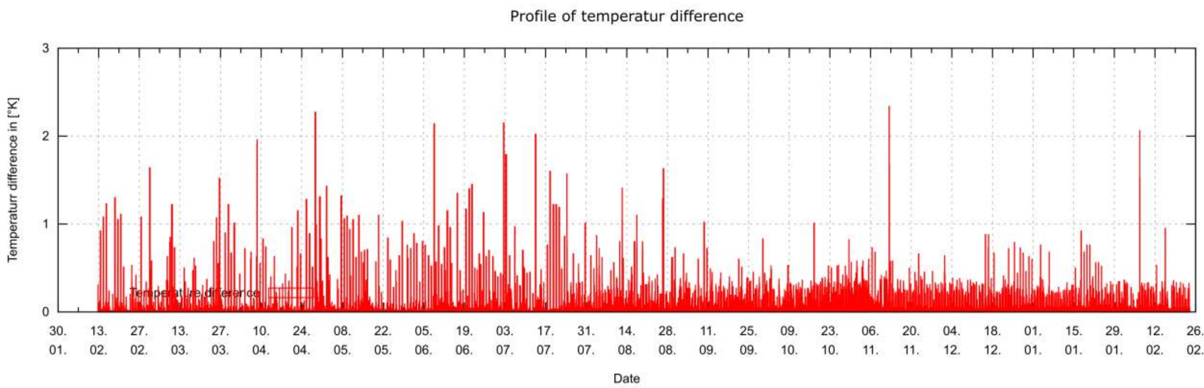


Figure 13: Profile of temperature gradients

The example data set from Figure 13 shows the profile of the temperature rising and falling gradients. This shows a rather small average gradient around 1°K while few exceptions show a rising or falling gradient of about 3°K. Over the course of the reporting period the temperature change is limited and reflects only small changes. This is reasonable and the figure also provides further valuable information on the battery temperature behaviour. The battery treated in such a way should survive and perform well under these circumstances.

7.4.5 Frequency of occurrence of the parameters value difference

Based on the calculated rising and falling temperature difference data as listed in the example of 'Table 1: Data set for calculating temperature differences' it is also possible to draw a histogram. Such a graph shows the frequency of occurrence of the temperature difference inside the system. This is especially insightful into the battery performance. Figure 14 shows such a diagram for the sample data set. As in figure 11 not only the histogram but also the Gauss fit can be calculated here.

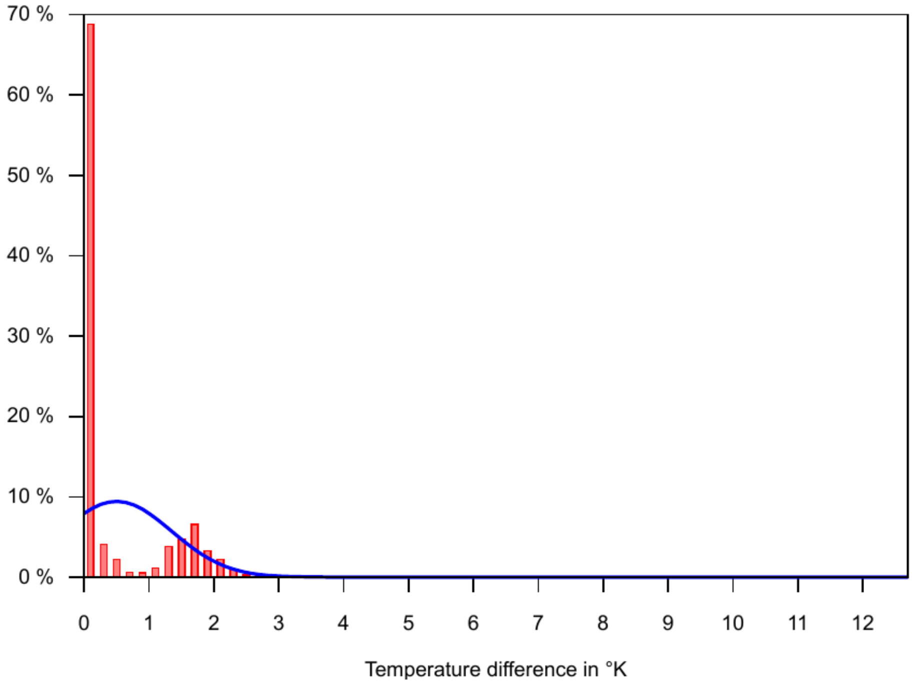


Figure 14: Histogram of temperature difference

The given example from Figure 14 shows here a clear maximum at nearly zero which indicates a slow temperature rising and falling gradient. Another peak can be seen at around 1.2°K. Higher temperature differences normally do not occur. This characteristic allows for the analysis of the battery condition inside the system due to user and load behaviour. A case where there is a high load compared to the battery capacity and the load is applied for a rather long period of time would result in a high temperature difference gradient as all components (including the battery) would run under a sudden start of full load creating a steep temperature rise for the whole system. If this happens regularly it is an indication that the whole system is operating under an accelerated aging condition.

If the figure of the temperature difference histogram looks similar to the given example it is an indication of a reasonable system design in which the normal load is rather low compared to the nominal power of the power electronics and the capacity of the battery.

7.5 Summary

The key to a good evaluation of an off-grid photovoltaic system is a good battery temperature measurement. The sensor located in the centre between two battery cells should have a good thermal conductivity to the case of the battery cells. Normally it is sufficient to install a single temperature sensor as the thermal capacity of the battery is relatively high. Typically, the temperature throughout all of the battery is the same. Both main materials, the electrolyte and lead have a high thermal capacity and which will maintain a similar temperature through the whole battery pack.

The battery temperature is a key figure to the whole system, and also a good indication of the whole system maintenance costs. Due to the fact that any battery replacement is the biggest maintenance cost share, ensuring a reasonable battery condition throughout its lifetime is a considerable cost saving issue. Analysis of the battery temperature provides important information about this and provides an overview of the ageing and expectable lifetime of the battery. If the average battery temperature rises by about 10°K the lifetime of the battery can be reduced by about 50%. The closer the average temperature of the battery to 20°C the higher the lifetime of the battery. This not only applies to lead-acid batteries, but also to lithium-ion batteries.

This chapter proposed a graphic visualisation of any single parameter where the battery temperature was used as an example to describe the different graphs. These graphs are simple to generate and fit on one page. On the basis of this information, it is possible to evaluate the system condition of the battery and to obtain a rough prediction of the overall lifetime of the battery. Of course, many other parameters influence the battery lifetime. Hence this estimation is just a snapshot from the battery temperature data. But due to the fact that the temperature is one of the most important lifetime influencing parameters at least this influence can be checked with the help of the proposed graphical data visualisation.

The generated graphs allow a more detailed look into the system where, in particular, the battery voltage, battery current, the temperature and the SOC are important parameters to characterise the system behaviour. For each parameter a one-page data visualisation provides relevant information.

8 BATTERY PARAMETER ANALYSES

8.1 Introduction

Most PV off-grid system types described in chapter 3 guarantee a 24/7 supply of the loads with the help of a battery. Therefore, reliable supply is a key part of the system. The most important step in the analysis of system performance it is the analysis of the battery usage during operation of the system. This chapter will look further look into the battery data. First of all, it is important to visualise the recorded data. Therefore, the focus shall be to group and visualise the data.

8.2 Measurement recommendations

To be able to have a look to the whole picture of the system it is essential to measure all values. Regarding the battery the following parameters are most important:

- Time stamp [dd.mm.yyyy hh:mm]
- Overall battery voltage [V]
- Overall battery current [A]
- Battery temperature [°C] (see chapter 7)
- Battery state of charge (SOC) [%]
- Additional error parameter

It is important to measure the values with reasonable increments. It is recommended to measure at least one value per minute. All values must be either a mean value over the measurement period of one minute with sampling rates of some milliseconds, or alternatively, it is possible to measure the integral value over the whole measurement interval.

In terms of measurement accuracy, it is important to measure the voltage of the battery directly at the battery poles with the help of a separate measurement cable (sense line). It is important not to use the power line cable to the power electronics for the measurement as this cable must carry high currents which will lead to a voltage drop within the cable. The result is a systematic error for the voltage measurement. For the current measurement it is recommended to use a separate mechanical shunt to ensure sufficient measurement accuracy. The internal current measurement of charge controllers or battery inverters is often not precise enough.

Many charge controllers and battery inverters offer a value for the state of charge. The accuracy of most of these algorithms is low, nevertheless it is possible to use these values for the recording as an independent calculation of the state of charge is often not possible.

8.3 Data visualisation

This chapter aims to explain the proposed data visualisation of the battery data in order to be able to get a fast overview of the system operation and the system battery management. In combination with the temperature information and visualisation it is possible to provide a good overview of the performance of the battery and also of the performance of the whole system.

Generally, it is recommended to display all values as normalised values. All given examples are visualised as normalised data. The voltage of the battery is normalised by the number of cells. In the case of a nominal 48V battery this is 24cells. If this battery has 50.4V the normalised voltage is 2.1V = 50.4V/24. The overall battery current is normalised by the nominal capacity of the battery. If 15A flow into a 100Ah battery this will be displayed as a charging current of 15A/100Ah = 0.15h-1. A Current of 1C will then be displayed as 1 h-1. This normalisation reflects related current values of a 1Ah battery. All displayed energy counting balances are normalised by the capacity of the battery. If a 100Ah battery is discharged by 50% within one day the value to be display is 0.5 = 50Ah/100Ah. For all currents and energy counting it shall be defined that charging currents are always positive, while discharging currents shall be negative currents. This is a reasonable perspective from a battery point of view.

8.3.1 Profile of battery voltage

The battery voltage is the central parameter of the battery even though it does not reflect the state of charge sufficiently. The first step is to visualise the battery voltage.

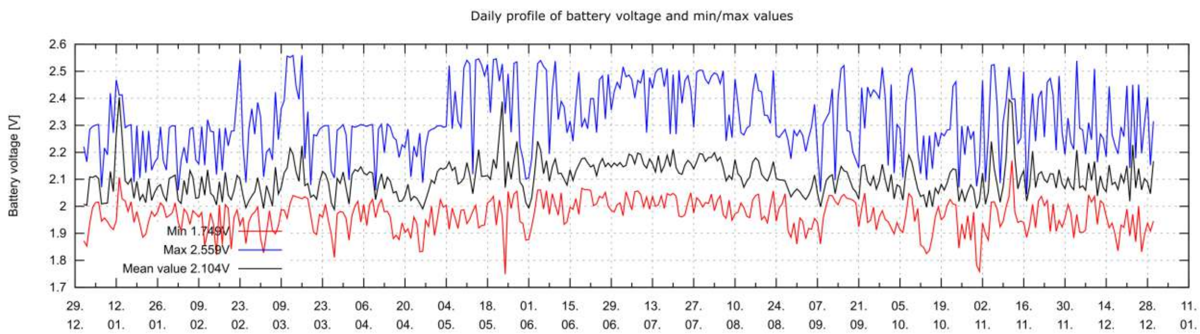


Figure 15: Profile of normalized battery voltage

The battery voltage profile shown in Figure 15 shows the normalised battery voltage over the whole recording period. The black line shows the mean value of the battery voltage. A mean value of all voltage data within one day is calculated and displayed as the mean value for that day. The curve reflects all daily mean values through the whole measurement period of one year in this example. In addition to this is makes sense to calculate the overall mean value of the battery voltage through the whole data set. In the given example this is 2.104V. The blue line visualises the maximum battery voltage calculated as an absolute maximum value within each day. In addition to this the absolute maximum within the whole data set is calculated. The given example shows here Umax = 2.559V. In the same way the minimum line is calculated as absolute daily minimum values and an absolute annual value of Umin = 1.749V.

Already this visualisation allows insight into the performance of the system. In Figure 15 it can be seen that the absolute mean value of the battery voltage is rather high with 2.104V which indicates a reasonable battery management. Also, the absolute minimum and maximum values show that the battery was always operating within the specifications of the battery manufacturer between 1.75V < Ubat < 2.6V. In case a charge controller fails the battery voltage could rise above these values or could also be discharged deeply below 1.75V. This can be detected with the help of the proposed battery voltage profile of Figure 15. The profile also shows a relatively equal distribution of the maximum daily battery voltage values and it can be seen that the battery is charged fully in a regular scheme throughout the year. The red minimum line also shows a generally low discharge during the summer as the whole period is displayed with about Umin = 2.0V rate. During winter there is no period in which the battery remains at a deep discharge value for a long time. From this point it can be seen in the given example that the battery should maintain a healthy life-time due to reasonable energy management. Furthermore, the graph provides information on the setpoints of the charge controller. During February and April, a reasonable threshold of Umax = 2.3V/cell can be seen. This indicates the float charge voltage and shows that the battery is not deeply discharged through this period. During summer we can see a regularly reached end of charge voltage of Umax = 2.5V/cell which shows that there is a higher energy throughput during summer making a regularly applied boost charge voltage necessary. This example shows that already this graph provides a lot of information on the battery management and the functionality of the applied charge controllers and battery inverters.

8.3.2 Profile of battery current

Similar to the battery voltage profile an overall battery current profile can be drawn. The corresponding example can be seen in Figure 16

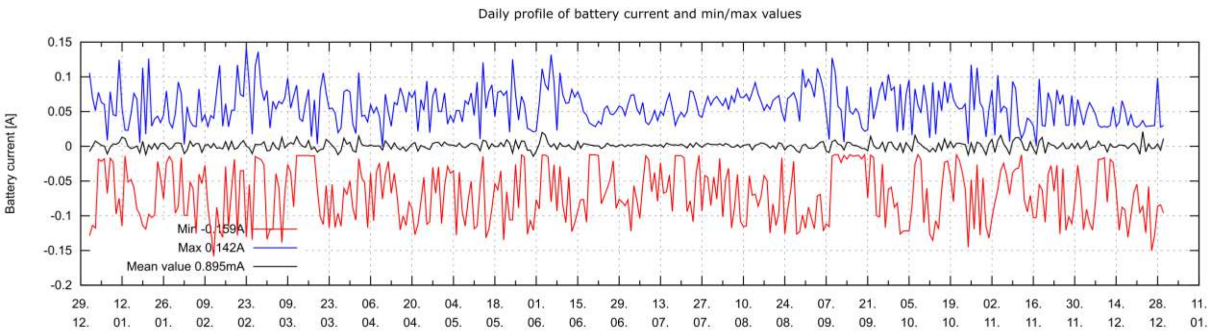


Figure 16: Profile of normalized battery current

The battery current profile shows a black line indicating daily mean values calculated by all available data points of one day. The blue line shows the absolute maximum current (charging current) per day. The red line shows the absolute minimum current (discharge current) within the specific day. The same calculation has been done for the whole recording period resulting in an absolute mean value of the current, an absolute maximum charge current and an absolute minimum current which is then the maximum discharge current.

Out of this diagram several conclusions can provide more information of the performance of the system. It can be seen that the daily mean value is through all the year very stable and close to zero. This means nearly every day the energy balance is equalized, and the amount of discharge can be recharged by the solar module arrays. An important note is the overall mean value of the battery current Imean_total = 0.895mA. This value is a positive value which means the overall charging to the battery is higher than the overall discharging. The value finally reflects the self-discharge rate of the battery. Here the value is in the range of about 0.1% of the nominal capacity. This is a reasonable value. A significant rise to this value during operation indicates advanced battery aging. This value being small signifies a well performing battery. If this value is negative the battery will not survive under the given management strategy as it means the applied generators are not able to charge the battery sufficiently. The diagram also shows similar absolute minimum and maximum values of the battery current. This indicates a reasonable system design and layout where charging and discharging of the battery are weighted equally. An absolute minimum battery current (discharge) that is significantly higher than the charging current shows that the loads can discharge the battery quite quickly, while the charging process to cover this load demand might take a rather long time. Such a situation could lead to a permanently deep discharged battery. The graph also shows usage profile information. It can be seen that during March and September the discharge current is very stable over a 2-week period while the charging currents show typical behaviour. This indicates that the system was not fully utilised during this time as is typically the case if the users are, for example, on holidays.

8.3.3 Energy balance Profile of the system

A key assessment of PV off-grid systems is to look at the Ah-balance. A reasonable approach is to analyse this on a daily basis as this provides valuable information on the degree of autarky which the battery is still able to realize. Furthermore, it provides information on the design of the system and shows whether the system was sized properly according to the load profile.

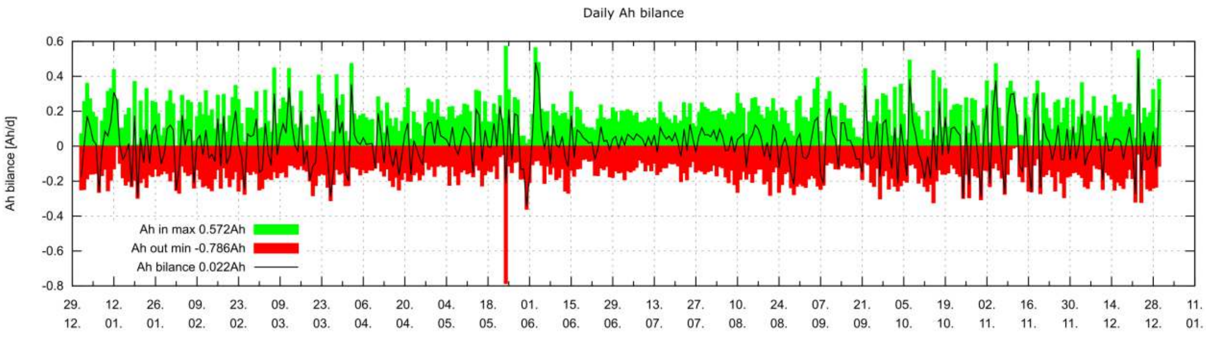


Figure 17: Daily Energy balance

The applied analyses can be seen in the example of Figure 17. For each day the integral of all charging currents over time is calculated. This energy sum is calculated regardless of whether the charging is interrupted by a period of discharging or not. All positive currents are multiplied by the time increment during this day to form the energy sum which is displayed by the green bar in Figure 17. The same calculation can be done with the discharge currents resulting in the red bars of Figure 17. The black line shows the subtraction of the discharge energy sum (red line) from the charging energy sum (green line). If the black line is within the green bar graph the energy balance is positive for this day. In cases where it is within the red graph the day results in a negative energy balance. Furthermore, the day with the highest energy yield is calculated. The same is calculated for the day which shows the highest load demand within the reporting period. An important number is the mean value of the black line which shows the overall average value of the daily energy balance:

$$Ah_{average} = \sum A_{hin} - \sum Ah_{out}$$

This energy sum is calculated over the whole reporting period. This value is displayed in Figure 17 next to the indication of the black line.

The analyses of Figure 17 shows first of all the distribution of the load through the whole year. No clear seasonal differences can be seen. During summer (particularly during June and July) the load demand is lower and more stable than during the rest of the year. It can also be seen that the applied PV generators are always able to recharge the battery within a reasonable time period. There exists just one single day during the year which shows a significantly higher load demand (about 3 time higher than the average daily load demand). The energy sum of all connected generators is able to cover about 2/3 of this load demand. When comparing with the energy yield of the rest of the year, it can be seen that there is additional energy available which could cover a potential increase of the load demand. Overall, the energy balance is typically positive indicating reasonable battery management. The day providing the maximum energy yield contributes Ahin_max = 0.572Ah/day. In the case where the battery management strategy allows the battery to discharge until the state of charge reaches SOC = 30% the figure shows that all connected generators are able to recharge the applied battery up to SOC = 87.2% = 30% + 57.2%. This indicates a reasonable system sizing as the generators are able to nearly fully recharge the battery within one day if necessary. It can also be seen that the maximum load demand reaches AhLoad_max = 0.786Ah. In a potential case of no energy contribution from the generation side, the battery could be discharged by about 78% of the nominal battery capacity. Due to the fact that the given example is just a single day through the year it can be stated that the average load demand is in the region of about 25% of the nominal battery capacity. This also indicates a reasonable sizing of the connected generators in the provided example. If the overall energy balance is negative or remains negative for a significant part of the reporting period this indicates a difficult system sizing situation which will not be able to cover the load demand in a sustainable way.

8.3.4 Battery state diagram

To have a closer look at the operating strategy of the energy management unit, it is reasonable to visualise the behaviour of the battery current and SOC depending on the voltage of the battery. To do so, a diagram can be drawn as shown in Figure 18. The x-axes are the normalised battery voltage, while the battery current or SOC is placed on the y-axes. Each single data line of the monitoring data will then be displayed as a single dot. Displaying all data sets results in a dot-cloud shown in Figure 18.

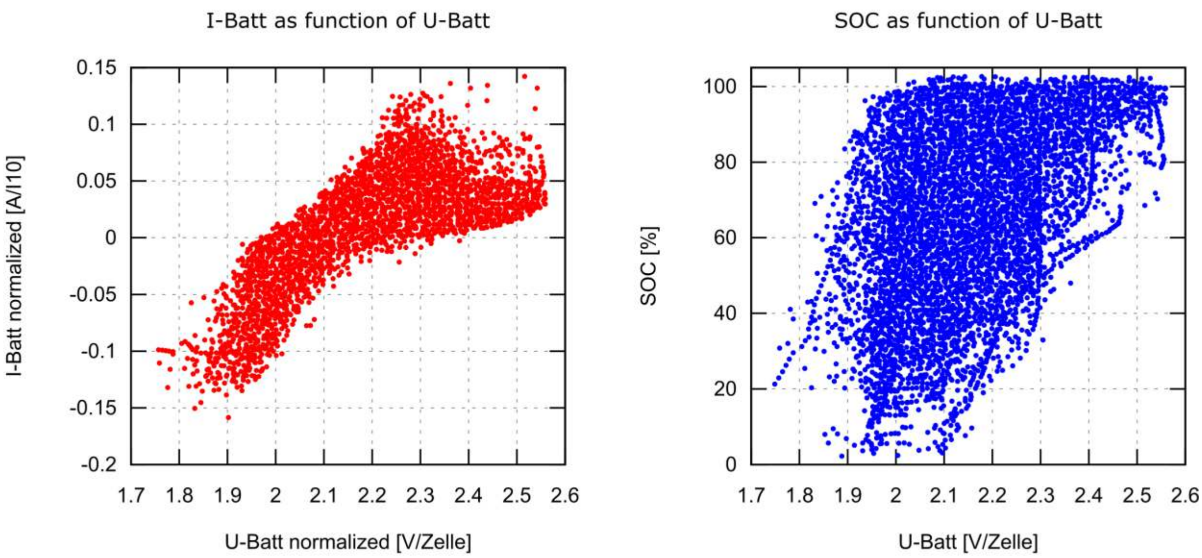


Figure 18: Battery current and SOC over normalized battery voltage

The voltage is displayed as the normalized battery voltage in [V/cell] and can be seen as x-axes in both diagrams. The current is normalised by the capacity of the battery in [A/Ah] and reflects the y-axes in the left diagram. In case of a 100Ah battery the rating means that a current of 10A is displayed as 10A/100Ah = 0.1A/Ah in the given example. 5A/100Ah = 0.05A/Ah. Positive values are charging currents, negative values discharge the battery.

- In case of the given example in the left side of Figure 18 it can be seen:
- The absolute values of the maximum charge and discharge currents are similar. For the charging side it is about 0.14A/Ah and -0.16A/Ah for the discharging. This indicates a reasonable system sizing as the applied generators including PV can recharge in about the same time in which it was discharged.
- The highest charging and discharging currents can be seen at very low and very high voltages. First of all, this is related to the properties of a lead acid battery for a standard situation. Furthermore, the given example shows that charging and discharging currents which discharge the battery within about 5 hours occur quite often.

These results reflect quite a short battery autonomy time. In the given example, no more than one day of battery autonomy time is realistic. For systems to survive in locations with strong summer/winter behaviour this type of sizing is not recommended unless it is possible to have a significant energy contribution from additional generators.

- The charging strategies can also be seen in the picture. For the low voltage disconnection rule an absolute value of U_{lvd}=1.75V/cell can be identified in the diagram. This is a quite low but is still reasonable value and indicates a battery discharge from battery inverters.
- The maximum charge values can be seen U_{float}=2.3V/cell, U_{boost}=2.4V/cell, U_{equal}=2.55V/cell. This indicates a reasonable and well managed charging process done by the applied charge controllers. In case of a failure of the charge controller these values are no longer visible in the given diagram.
- The overall characteristics of the diagram show a typically lower charging current for high battery voltages and indicates the typical battery hysteresis. The current behaviour within the range of 2.2V/cell > U_{batt} > 2.5V/cell provides valuable information of the remaining capacity of the battery. The less dots in this area and the higher the currents in this area, the older the battery.

In case of the given example in the right-hand side of Figure 18 it can be seen:

- The SOC distribution is relatively equally weighted over a cloud within a high voltage and SOC window. The typical battery hysteresis can be seen as the vertical ends of the blue dot cloud. In comparison to a good battery SOC situation the area between these two “lines” is relative wide which provides information about the accuracy of the SOC calculation in the system. In this case the performance is low.
- It can also be seen that often low battery voltages appear in combination with very high SOC ratings. This indicates that high discharge currents appear in the system. This means the chosen battery capacity was rather small in comparison to the applied inverters and results in a short battery autonomy time.
- This type of diagram also allows insight into the remaining battery capacity and its age. If a good SOC algorithm is applied the width of the SOC window will be small. Within the aging process of the battery the SOC window will be widen increasingly. Also, the density of dots with high SOC rating and low battery voltage increases. At the same time the number of dots with low SOC values and high battery voltages increases.

8.3.5 Frequency distribution diagram

For the most important parameters like the voltage, current, state of charge, temperature, and the energy balance of the battery it is recommended to have a look to the frequency distribution and the statistical scattering around the mean value.

One example of the frequency distribution of the daily energy balance can be seen in Figure 19. The left-hand side shows the daily discharge rate while the right-hand side shows the daily charging rate of the system. The values are calculated according to the graph in Figure 18 and are displayed to provide an easy comparison with other systems. The normalization factor is the battery capacity in Ah.

The written numbers in Figure 19 display the mean values. The given example shows an average charging rate of 19,3% of the nominal battery capacity per day. The average discharging rate per day is 17,1%. It is important to see a lower value for the average discharging rate, otherwise the energy balance is negative over the reporting period which is an indication that the system will fail soon. The average balance rate is here +13,08%. This means the average daily charging rate is about 13% higher than the discharging rate. This number reflects the energy efficiency of the battery, this value will increase as the battery ages. Throughout the ageing process it becomes interesting to divide the analysing periods in single years to determine a rising factor of this value. A significant increase in the rising factor indicates that the battery needs to be changed soon.

In addition to the mean value a Gauss fit is put into the graph which graphically shows the deviation from the expected distribution. In the given example it can be seen that the fit is very close to the expectation indicating reasonable system behaviour. This further applies in Figure 19 for the charging and discharging frequency distribution.

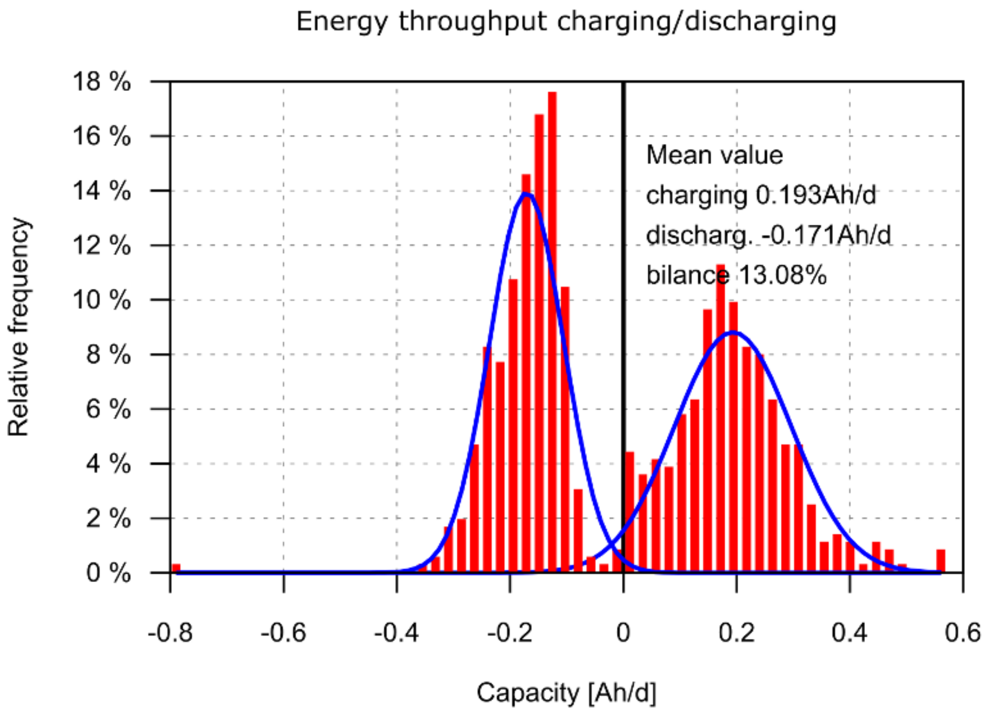


Figure 19: Frequency distribution of energy balance

Figure 19 shows the frequency distribution of the energy balance. The X-axis displays the charged/discharged capacity per day [Ah/d] normalised to the battery capacity. 0.5 means that 50% of the battery capacity was used on that day. The Y-axis reflects the frequency of occurrence of the specific value.

Valuable statistical information can also be found in Figure 20. It shows the frequency distribution of the battery voltage (left side) and the battery current (right side). How to create a frequency distribution diagram is described in chapter 7.4 Data visualisation.

For the given example the overall average voltage is 2,104V which is a reasonably high voltage for a lead acid battery. Most probably the Gauss fit will look more or less similar to what we find in Figure 20. As long as the system is able to recharge the battery fully regularly. More interesting it is to have a look to the bars with the highest relative frequency of occurrence in the voltage frequency distribution diagram. The given example shows a clear dominance of the discharging side. This means the battery is typically a longer period of time operating in lower battery voltages. Concerning the battery current it can be seen the given example provides 0.872mA. It is important to see positive values here as this underlines an average positive energy balance. Here we can see a high bar with very low discharge currents and rather equally distributed charging bars. This provides valuable information on the discharge behaviour of the system. Generally smaller discharging currents lead to longer battery lifetime and it is important to see good and stable charging bars reflecting a solid charging characteristics and enough energy resource to recharge the battery.

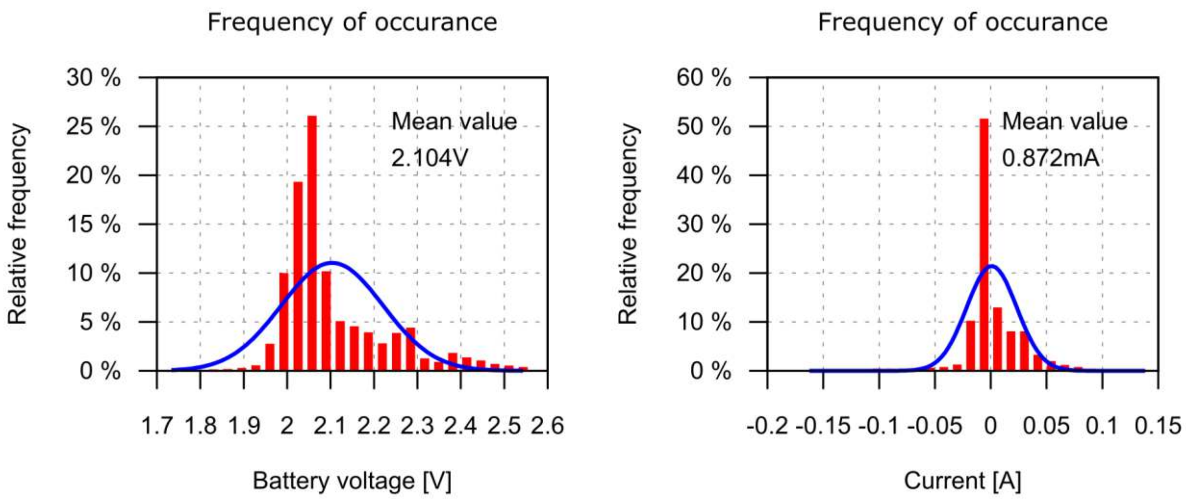
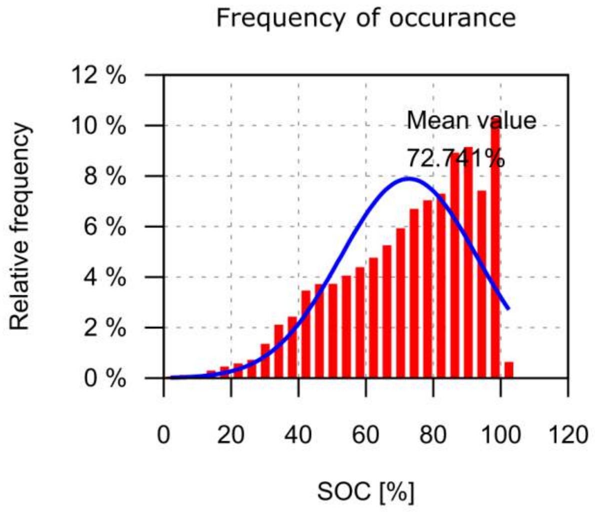


Figure 20: Frequency distribution of battery voltage and current

Figure 20, the X-axis shows the battery voltage [V/cell] and the battery current normalised by the battery capacity.

The state of charge (SOC) and the temperature of the battery bring interesting information if the data are converted to a frequency distribution diagram. Figure 21 shows the frequency distribution of the SOC and the battery temperature.

The sample data show here a quite high average value of SOC = 72,74% and the highest relative frequency of occurrence at high SOC levels. This is a good behaviour of the system and indicates a reasonable system management. The lower the average SOC value and the lower the bars with highest frequency of occurrence are the higher the probability for the battery to be damaged early.



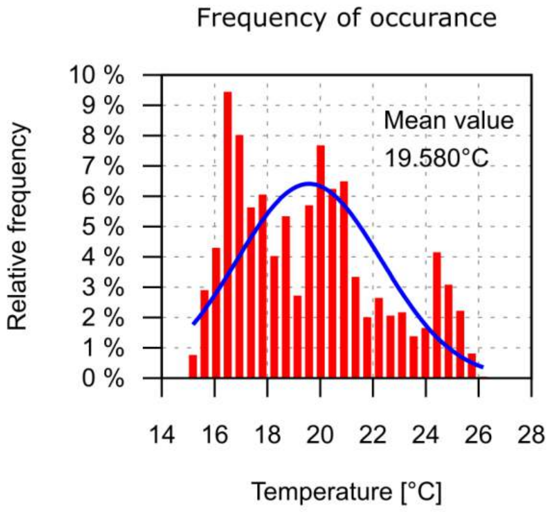


Figure 21: Frequency distribution of SOC and temperature

The temperature distribution contains a lot of information on the battery history and can provide insight into the remaining lifetime of the battery. In the given example we can see a nearly ideal average temperature and a very reasonable distribution. The higher the average temperature and the wider the range, the shorter the lifetime of the battery. It has to be taken into account that if the average operating temperature is increasing by about 10°K, then the battery lifetime is reduced by 50%. Therefore it is recommended to record and control the battery temperature carefully.

8.4 Summary

The lead-acid battery is a key part of many small and medium sized systems and is the focus of the data visualisation. Therefore, it is essential to have all relevant battery data available. The battery voltage data is critical, as well as the sum of all battery currents from charging and discharging devices is necessary. Charging currents are defined to be positive whilst a discharging current is negative.

The approach described is designed to deliver a visualisation of the battery data however some graphs require a background calculation which could already be defined to be more than a simple data visualisation. The overall characteristics of the graphs aims to provide a fast and standardised overview of the lead-acid battery condition and does not claim to analyse the battery data in a systematic way. The whole analysis is conducted in a rapid and simple way without detailed knowledge.

The graphs are divided into three sections. Several profile pictures aim to provide an overview of the whole data set. This allows a good estimation of the consistency of the data and brings plausibility to the visualisation as seldom occurring extreme values can be identified. That being said, potentially single days show a fully different behaviour compared to the rest of the data set. This can also be identified very quickly with the help of the given visualisation.

The second part consists of special graphs concentrating on the battery properties and the applied state of charge algorithm. As a lot of information is concentrated in these diagrams battery experts will find interesting diagnoses possibilities on the basis of this visualisation.

Finally, several graphs provide an overview on the system based on different histogram visualisations. Each single histogram displays exact mean values and automatically adds a Gauss-Fit to the given data. This allows for the categorisation and characterisation of the user behaviour and the battery condition.

With the help of the given battery data visualisation it is possible to estimate the battery condition and the system behaviour very quickly and efficiently. Also, the realised charging and discharging characteristics can be seen directly in a statistically relevant way. The data visualisation proposed here is very powerful.

It is recommended to perform the data visualisation regularly on the basis of a fixed time period. A reasonable period can be one year. If the proposed data visualisation is done with the same system once a year it is easy to compare the graphs of several years. This allows tracking of the changes in the user behaviour and the consequences to the system. At the same time, it allows for comparison of the battery behaviour which can ideally end up in a situation that can predict how long the specific battery can still survive under the given circumstances in order to schedule a battery replacement early enough before the system breaks down.

If all data are normalised on the basis of the cells and the capacity of the lead-acid batteries, as proposed, it is also easy to compare different systems. Also, a variety of system sizes can be compared on the same basis. In case an operator of PV-Hybrid Systems operates several systems in different locations under different circumstances this visualisation can bring a fast and important comparison of all systems which allows the identification of weak points of the operating strategy in order to improve the system performance. It also allows to adapt the systems operating strategy to the different user behaviour as specific circumstances can be identified quickly with the help of a comparison with other systems.

Furthermore, the battery diagnoses diagrams allow for a detailed look at the functionality of the applied state of charge algorithm of the system electronics. This can bring interesting information to improve the state of charge algorithm itself or to identify its capability to act in an adequate way under the given system properties and the environmental circumstances of the specific system.

9 CONCLUSION

There exist many different types of PV off-grid systems. The most suitable system design depends on the size of the system, the location, and the load profile. The first section of this document listed the most important types of systems like Pico-PV, Solar Home Systems, Inverter Systems, PV Hybrid Systems (DC coupled and AC coupled systems) and PV Mini-Grids. Each of these systems show a good performance if the design is chosen according to the requirements and the local boundary conditions. It is essential to choose the applied system carefully based on all available information. Particularly, in regards to PV Hybrid Systems it is important to say that both DC coupled and AC coupled systems are independent topologies which show a great performance if the location and the power range is chosen carefully. DC coupled systems tend to be more efficient in smaller applications while AC coupled systems are typically chosen for system sizes above 50kW output power. The description of the different systems in Chapter 3 shall provide a rough overview on the most important systems and guide the user according to the output power requested by the load. Nevertheless, other systems could be preferred depending on the local circumstances.

The main goal of this document is to provide a proposal for a fast, easy to use and standardised monitoring data visualisation of PV hybrid systems within an extreme wide power range. Small systems with several watt output power as well as systems in the mega-watt power range can be analysed with the help of the given visualisation. The ability to compare different types of systems makes the analyses usable for a huge variety of systems. Therefore, all parameters are normalised and categorised accordingly.

The approach focusses on visualisation of the lead-acid battery performance as the most costly component of existing PV Hybrid systems and cannot be applied to battery-less systems. The goal is to optimize the battery set points on the basis of the results of the visualization, in order to increase the battery life times and to optimize the usage of the battery.

The analysis is divided into three sections:

- To analyse the energy flow and the efficiency of the system based on energy counting information (chapter 6)
- To analyse any single parameter like the temperature profile of the battery (chapter 7)
- To analyse the real-life data of the battery including the daily energy profile and important statistical data of the charging and discharging process (chapter 8)

The proposed approach does not reflect all possible analyses. Depending on the topology of the system, a much more detailed analysis may be needed to provide further information. The idea of the general visualisation is to have a good overview on the performance of the system and to visualise the systems data in order to have a fast impression of the usage and the efficiency of the systems. Comparability and standardisation with the help of normalised data are important aspects and provide the foundation of this data visualisation.

The proposed data visualisation provides insight into the system usage and the way the battery is treated under the given local circumstances and boundary conditions. It is especially suited to help analyse the systems data according to the following aspects:

Each analysis is one selection of several graphs which fits to a one-page information sheet of the system. This allows for a fast overview of the system and the load usage.

If the visualisation is done over a long term, divided into several time slots like, e.g. 5 years, data is divided into 5 sections, each containing a one year data set the whole analysis can run 5 times and produce 5 sheets while each page is reflecting a one year data analysis. With the help of such a method, a single system can easily be analysed, which can be particularly helpful in identifying the aging effects of the lead-acid battery. According to this information the battery set point parameters can be improved and adapted to the age of the battery in order to optimise the battery condition.

Finally, it is easy to compare different types of systems and different sizes of systems as all data is normalised data. With the help of this feature, it is possible to get an overview on the systems efficiency in different locations, with different topologies over a variety of different system ages. The standardisation of the data visualisation makes the whole definition applicable to many systems. This is particularly relevant for operators who have to supervise many different systems in a multitude of locations and provides a key to maintain a good overview on the health of each single system.

The proposed key figures help to understand the functionality of the systems and to analyse their real-life performances based on just select data coming from the systems data loggers.

A precondition to perform the proposed analyses is to have a suitable tool chain which accepts many different data formats in order to allow a fast data visualisation. The realised data visualisation is based on a tool chain which uses ANSI C written small programs running under Linux console which uses different libraries to process the data. The graphs are drawn automatically with the help of the Gnuplot environment. The following steps are implemented:

- An input data converter starts a data plausibility test and converts the user defined data format into a standardised data format which is fixed and can be used by all following jobs
- A central data processor which calculates several functions and performs basic data analyses.
- Several Gnuplot scripts which finally draw the graphs
- A wrapping bash script which summarises and organizes the whole information and all graphs.
- A converter which finally generates either high resolution graphics or easy to use pdf files

It is also possible to generate the given visualisation in other ways. The described tool chain exists and was the basis for this document. Anyone who is interested in performing the analyses can contact the author. It is possible to analyse and visualise data at no cost with this existing tool chain. While the tool is not yet available for public download, the visualization service is available free of charge. In order to use this service the data need to be converted into the described data format. For more information contact the author under mm@ofres.org.

Figure 22: QR code for data analysing service

10 REFERENCES

For further information about the IEA – Photovoltaic Power Systems Programme and Task publications, please visit www.iea-pvps.org

The following references have been used within this document

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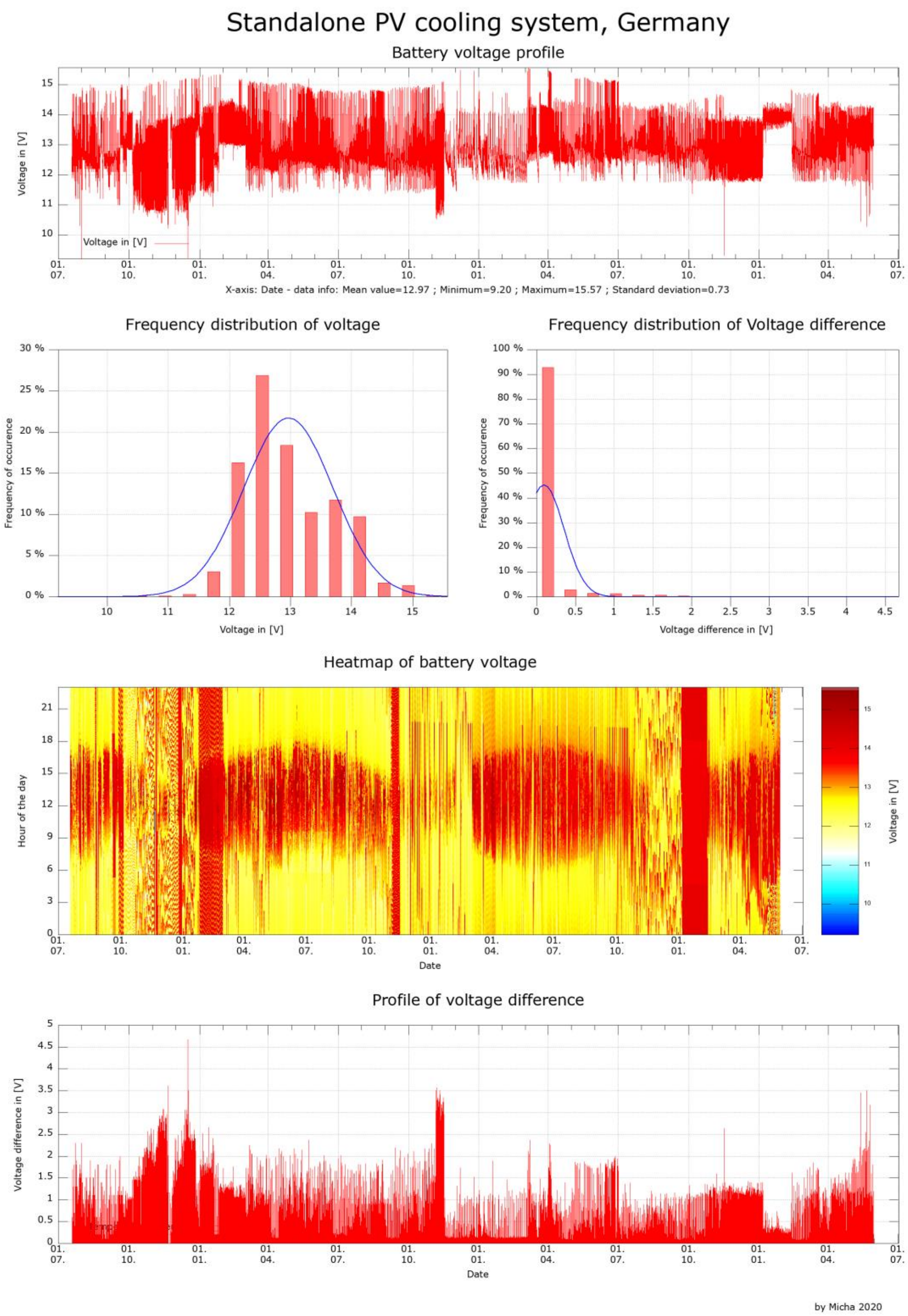
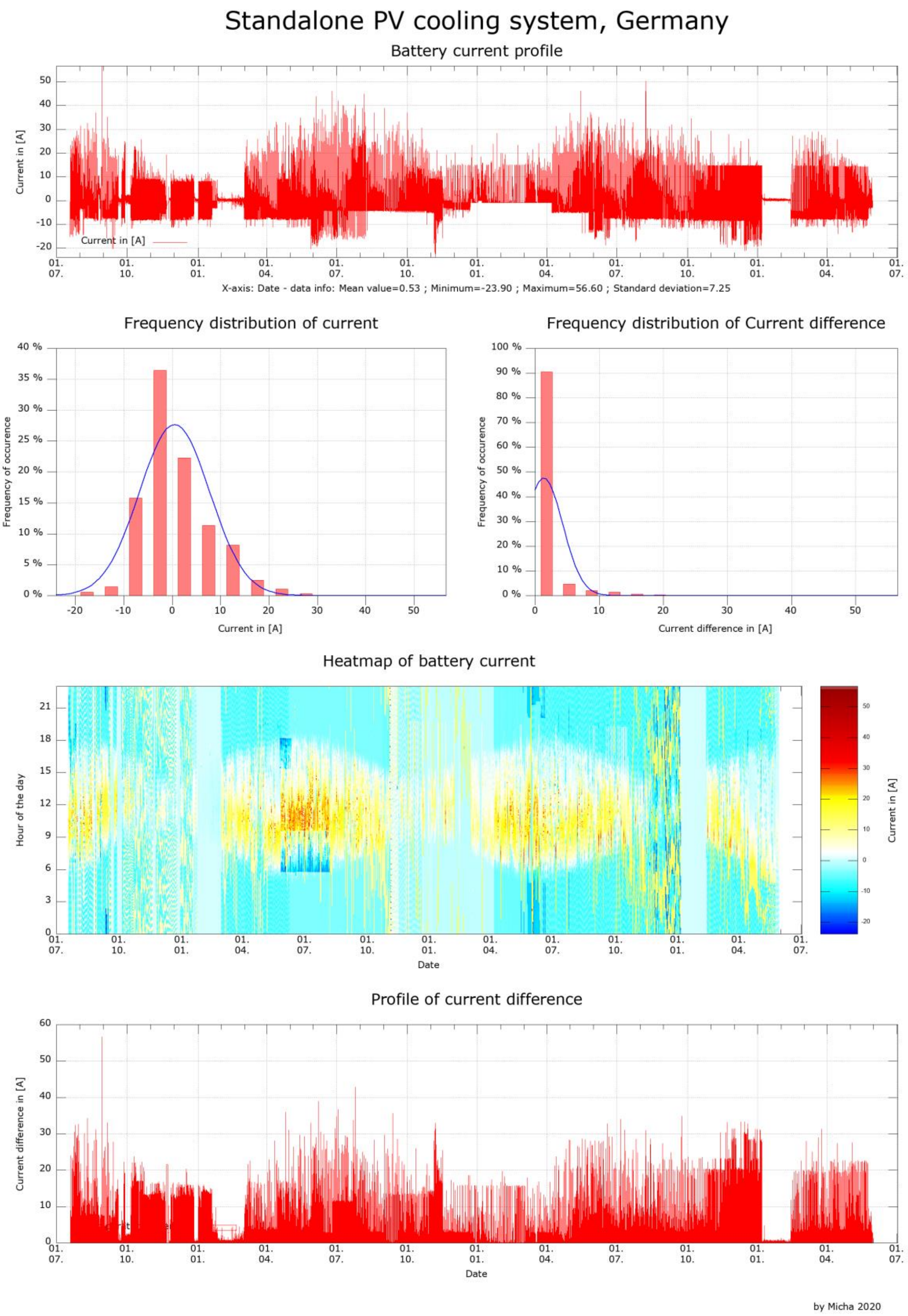
[10] The Battery Manual, 38,1 (1996), Page 12, Fetherolf, D.J.

11 APPENDIX AND EXAMPLE VISUALISATIONS

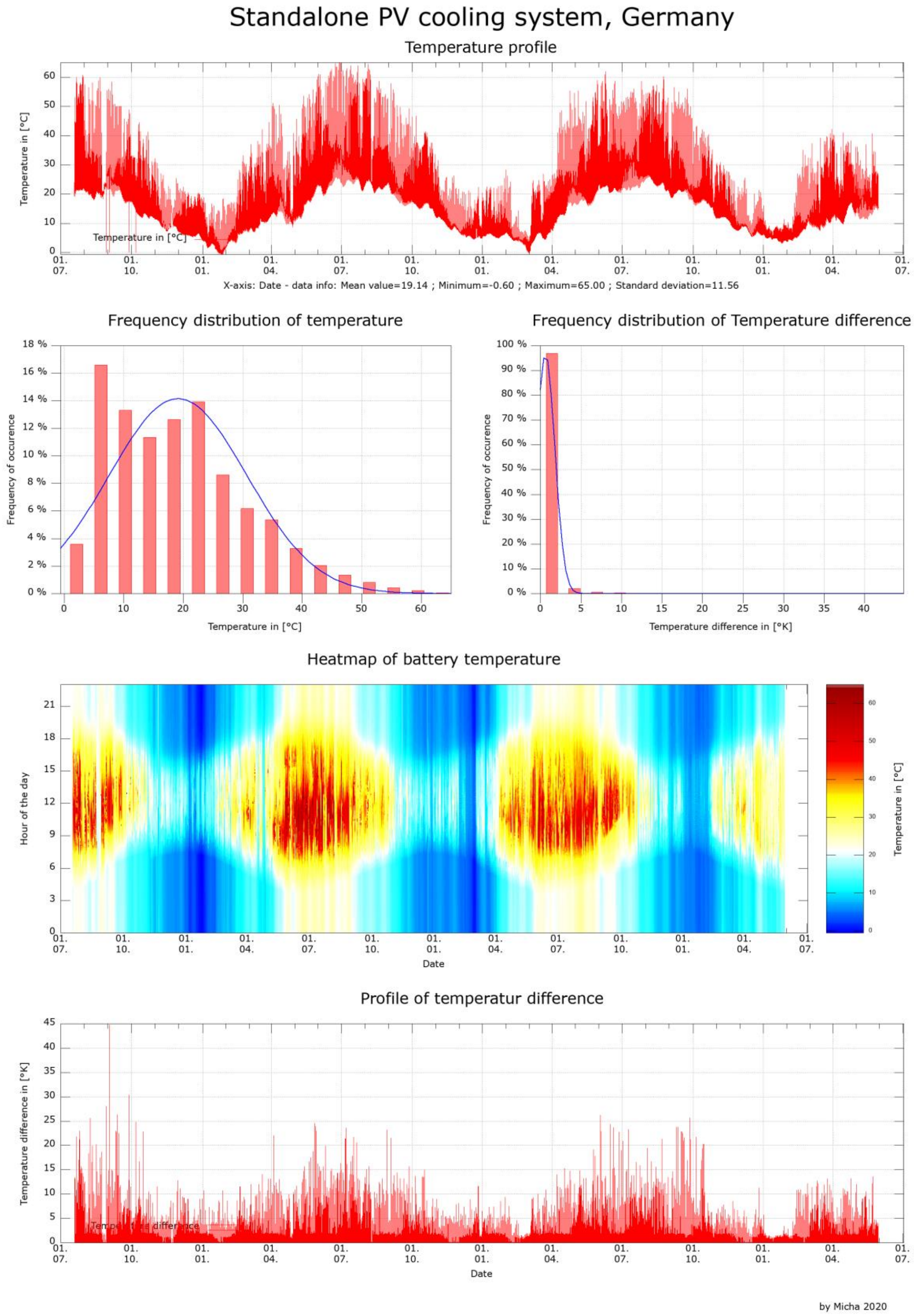
11.1 Cooling System – Voltage



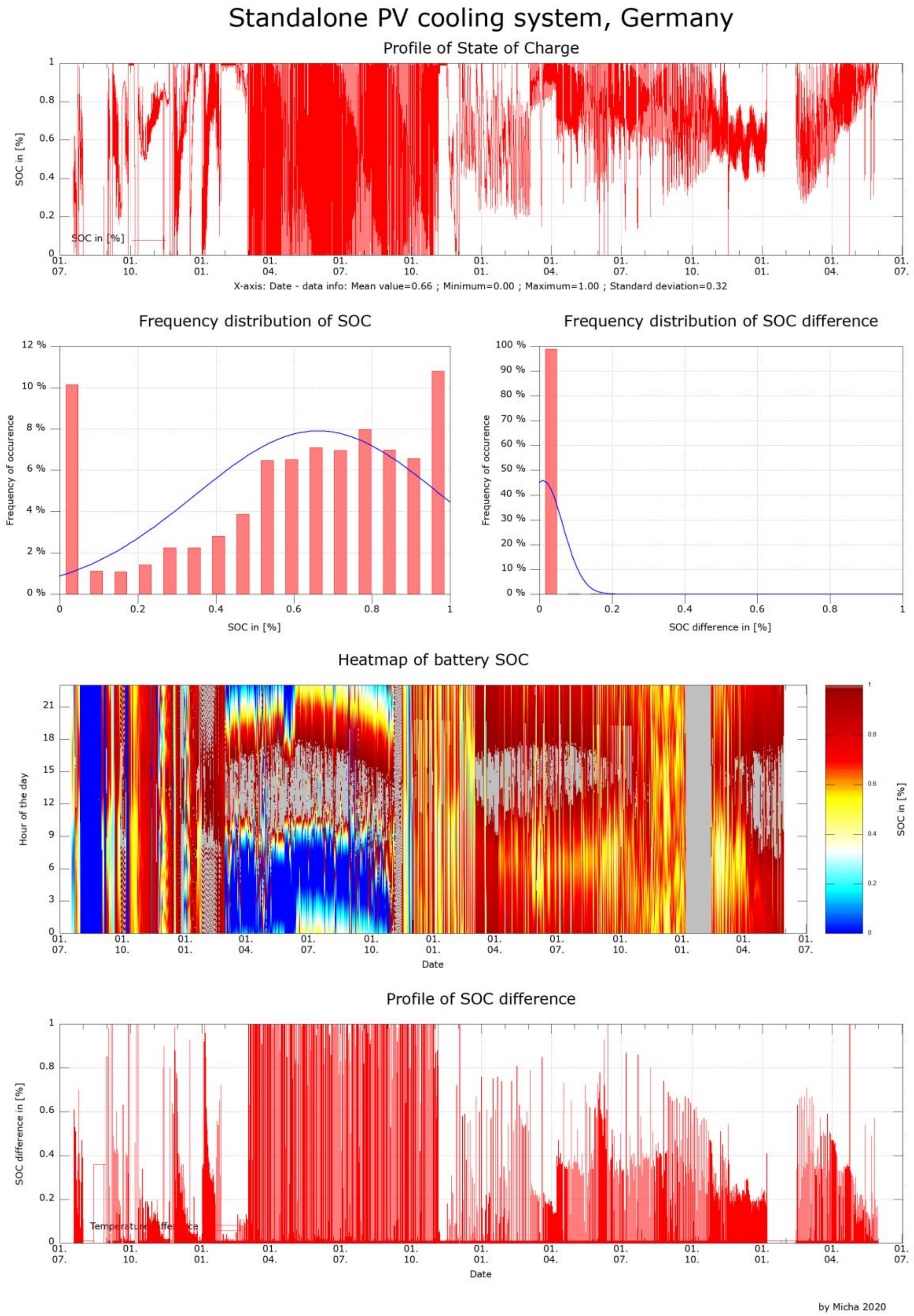
11.2 Cooling System – Current



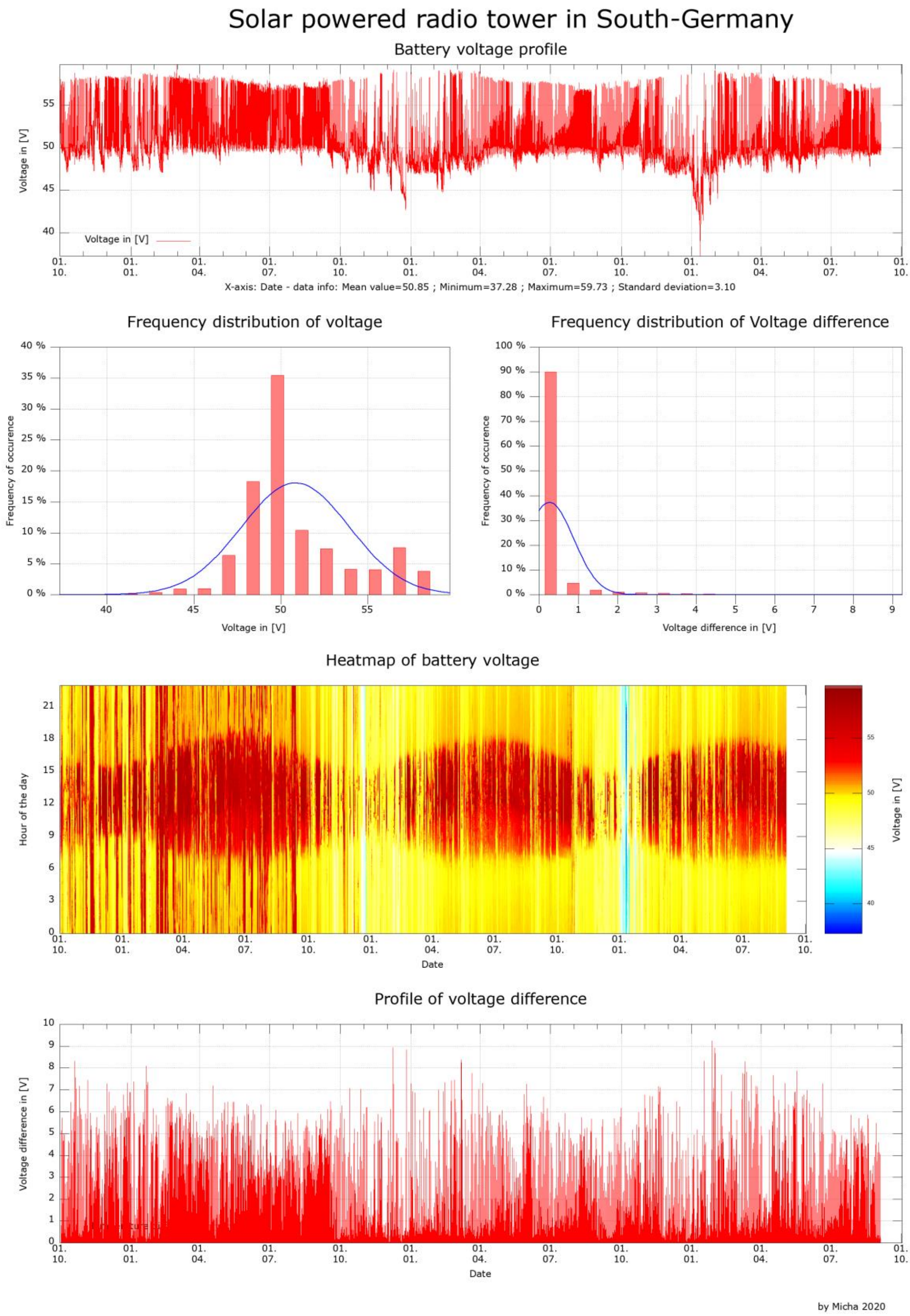
11.3 Cooling System – Temperature



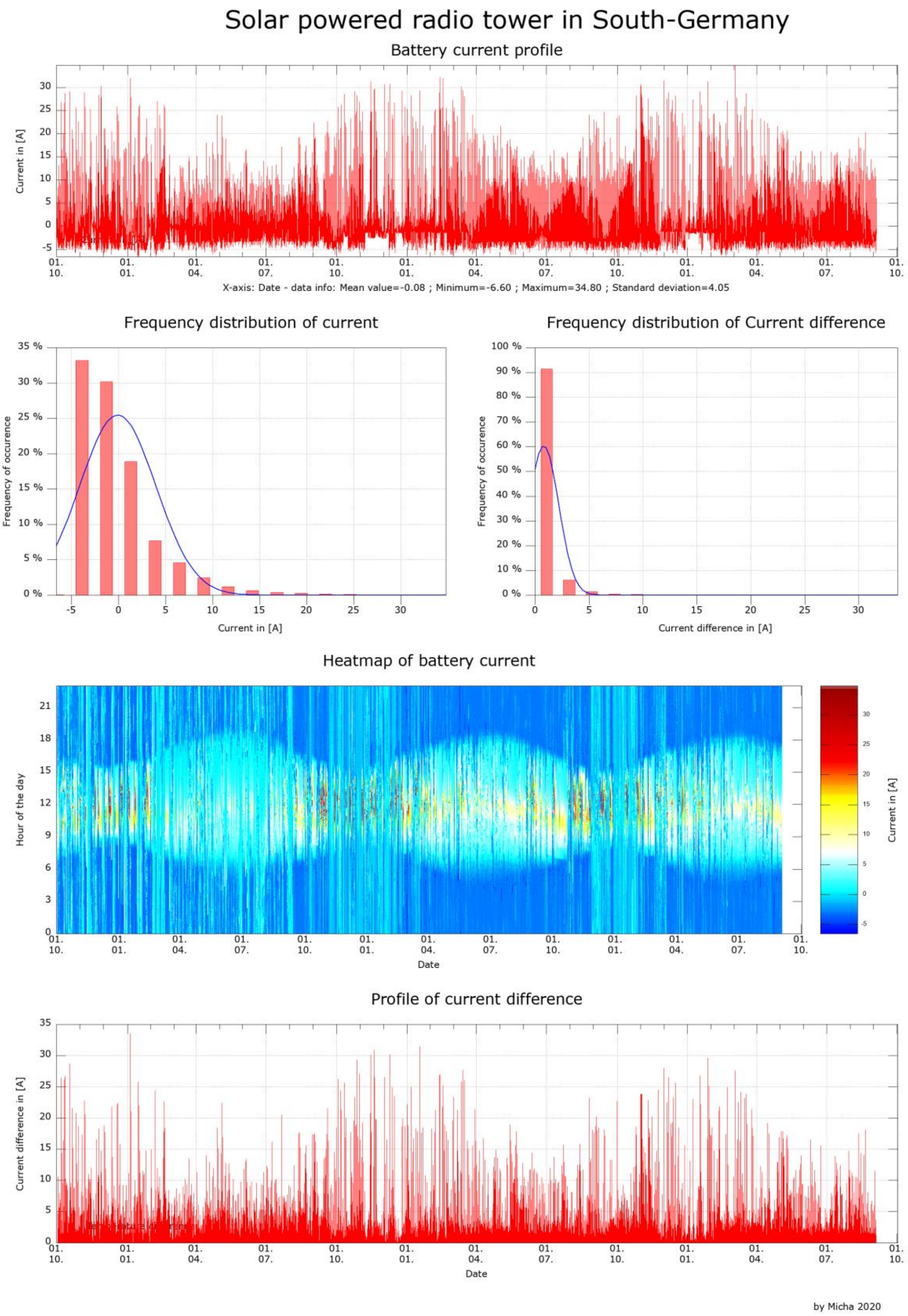
11.4 Cooling System – State of Charge



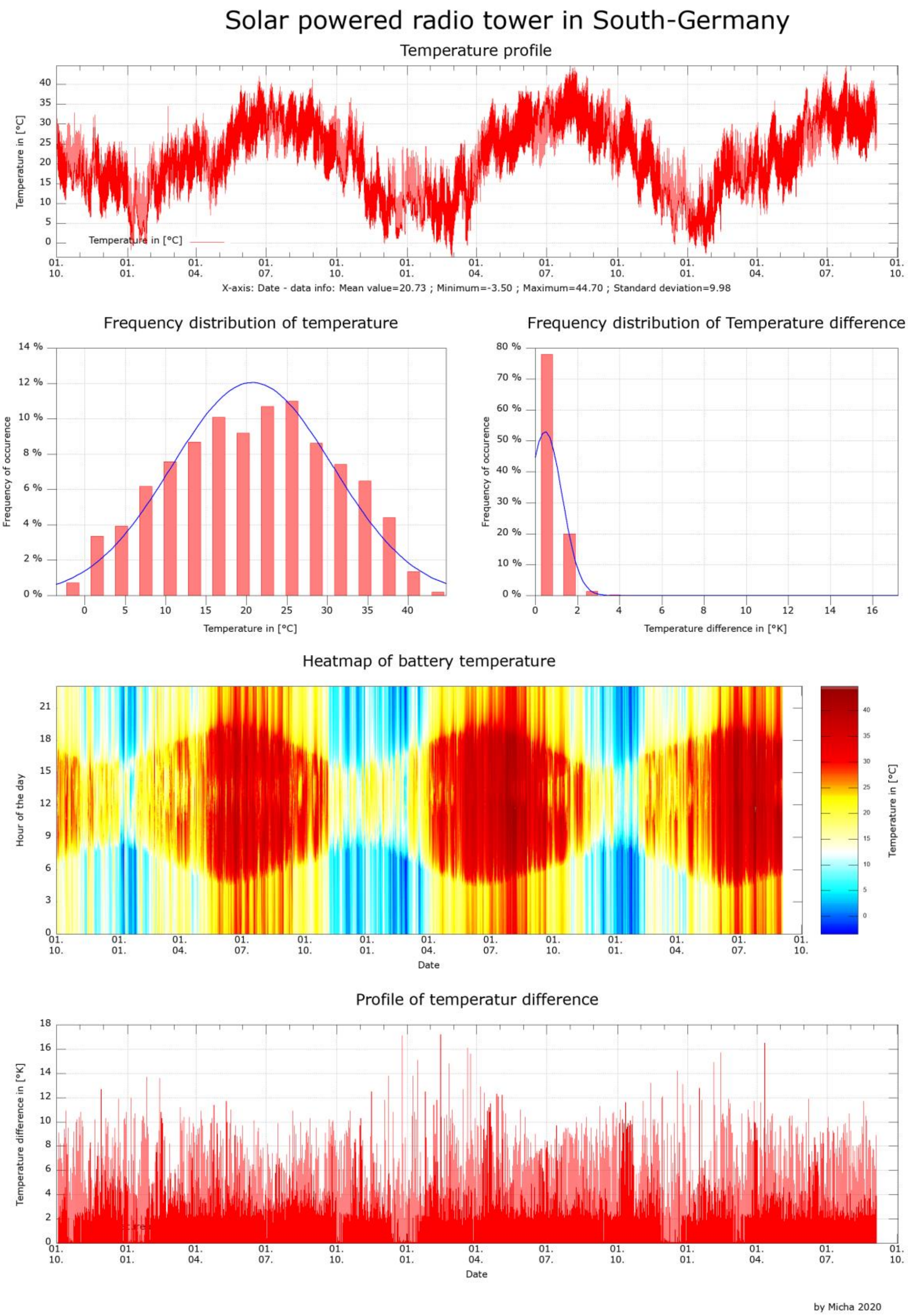
11.5 Radio Tower – Voltage



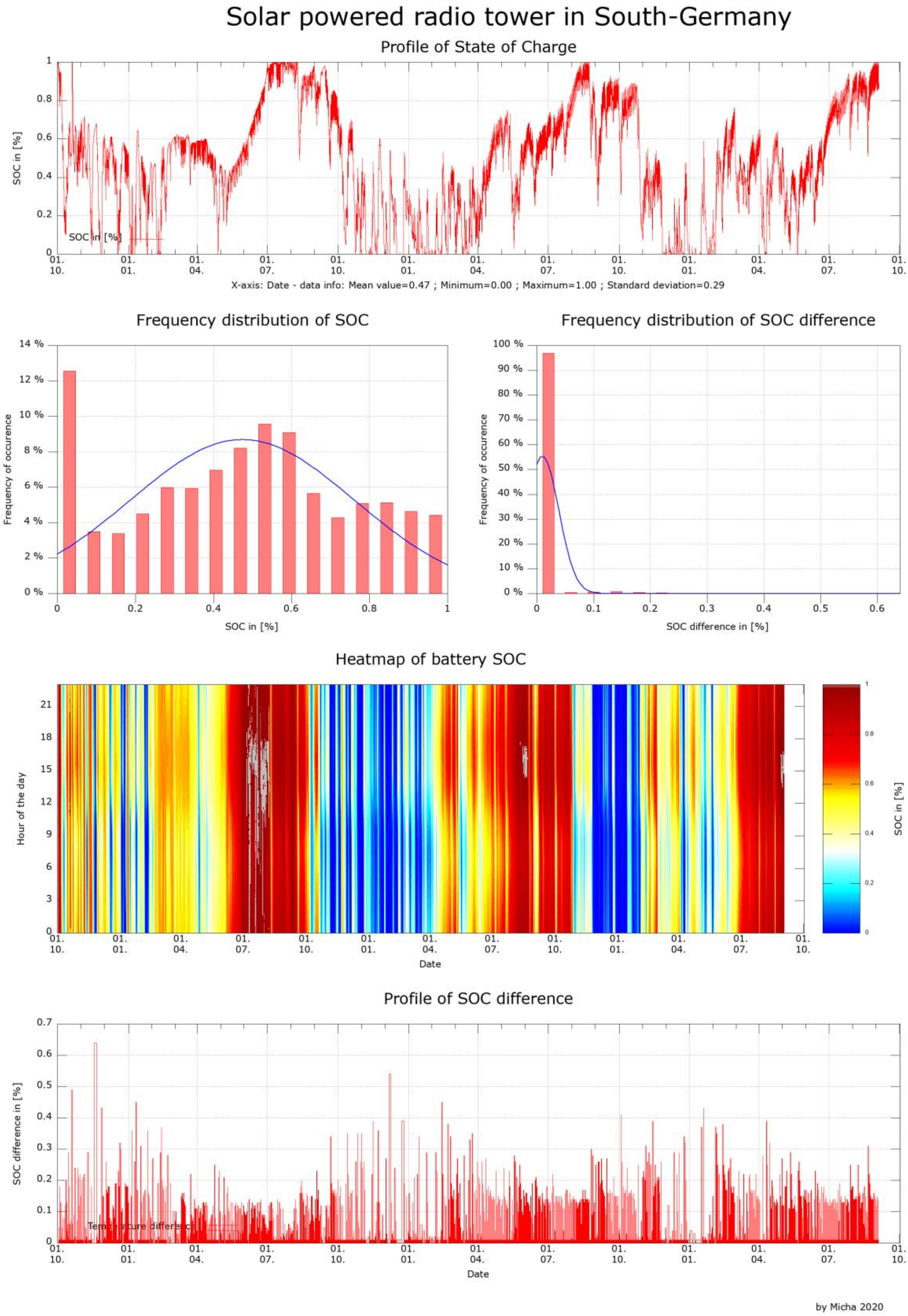
11.6 Radio Tower – Current



11.7 Radio Tower – Temperature

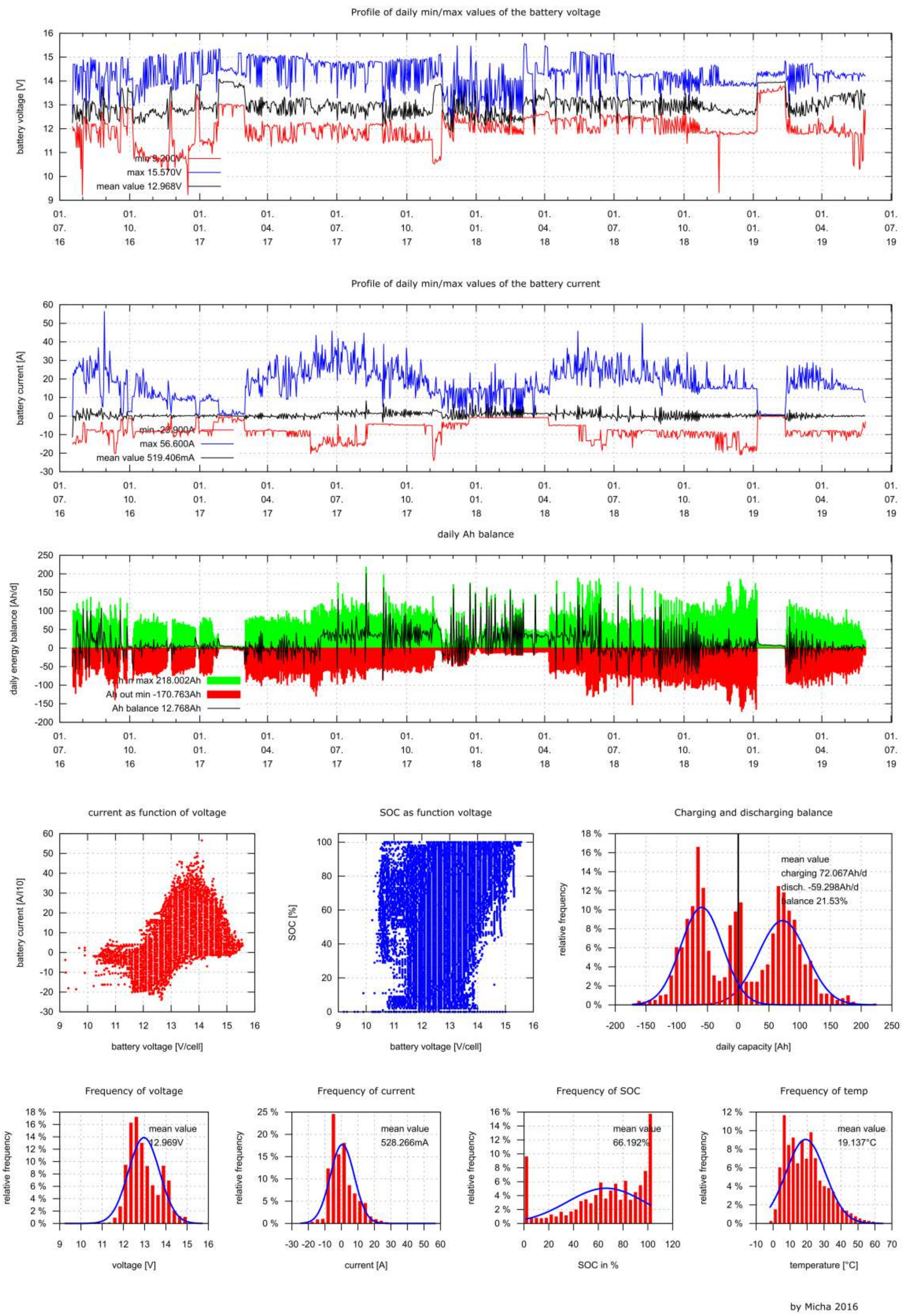


11.8 Radio Tower – State of Charge

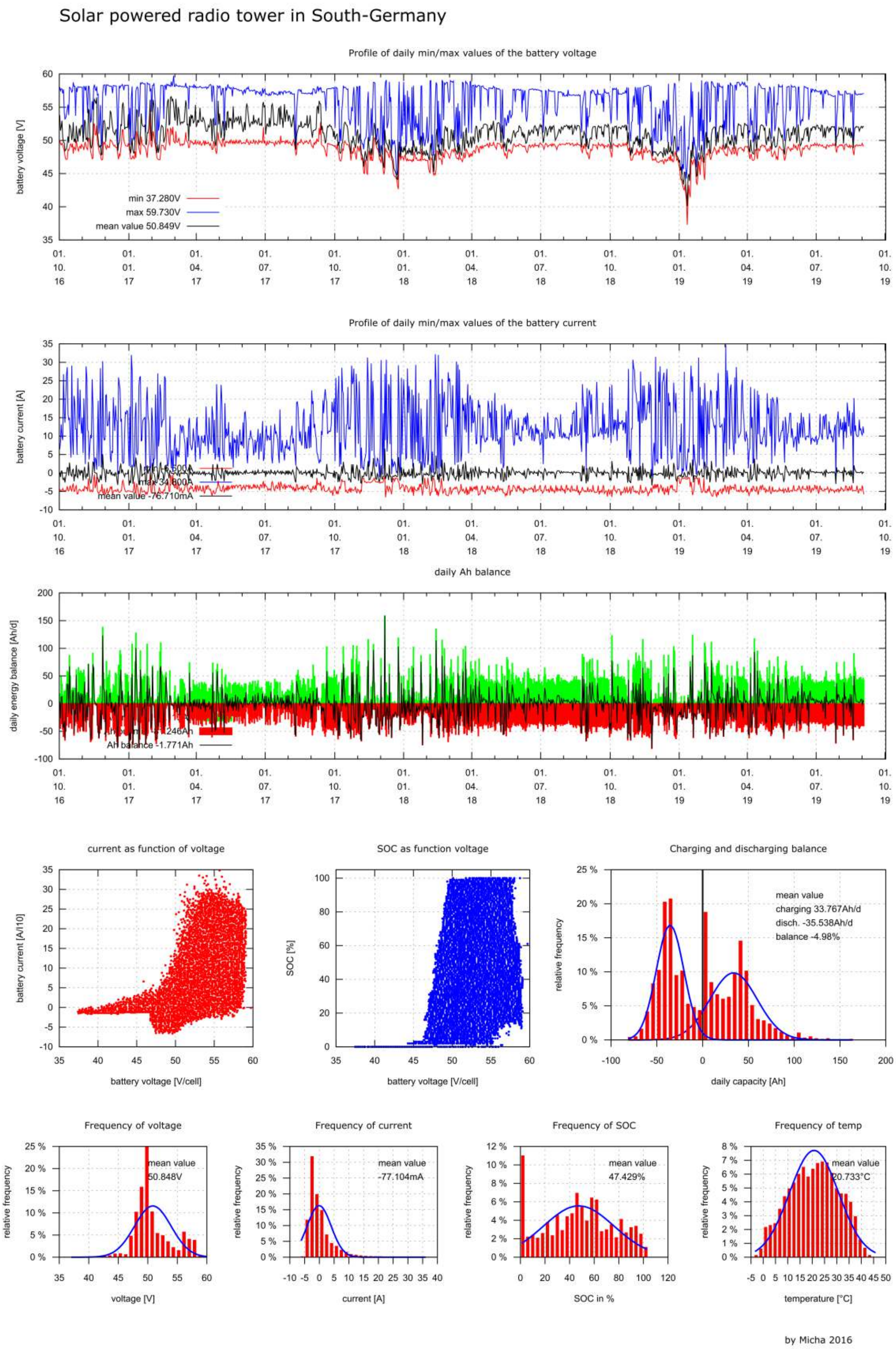


11.9 System Data – Cooling System

Standalone PV cooling System, Germany



11.10 System Data – Radio Tower



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