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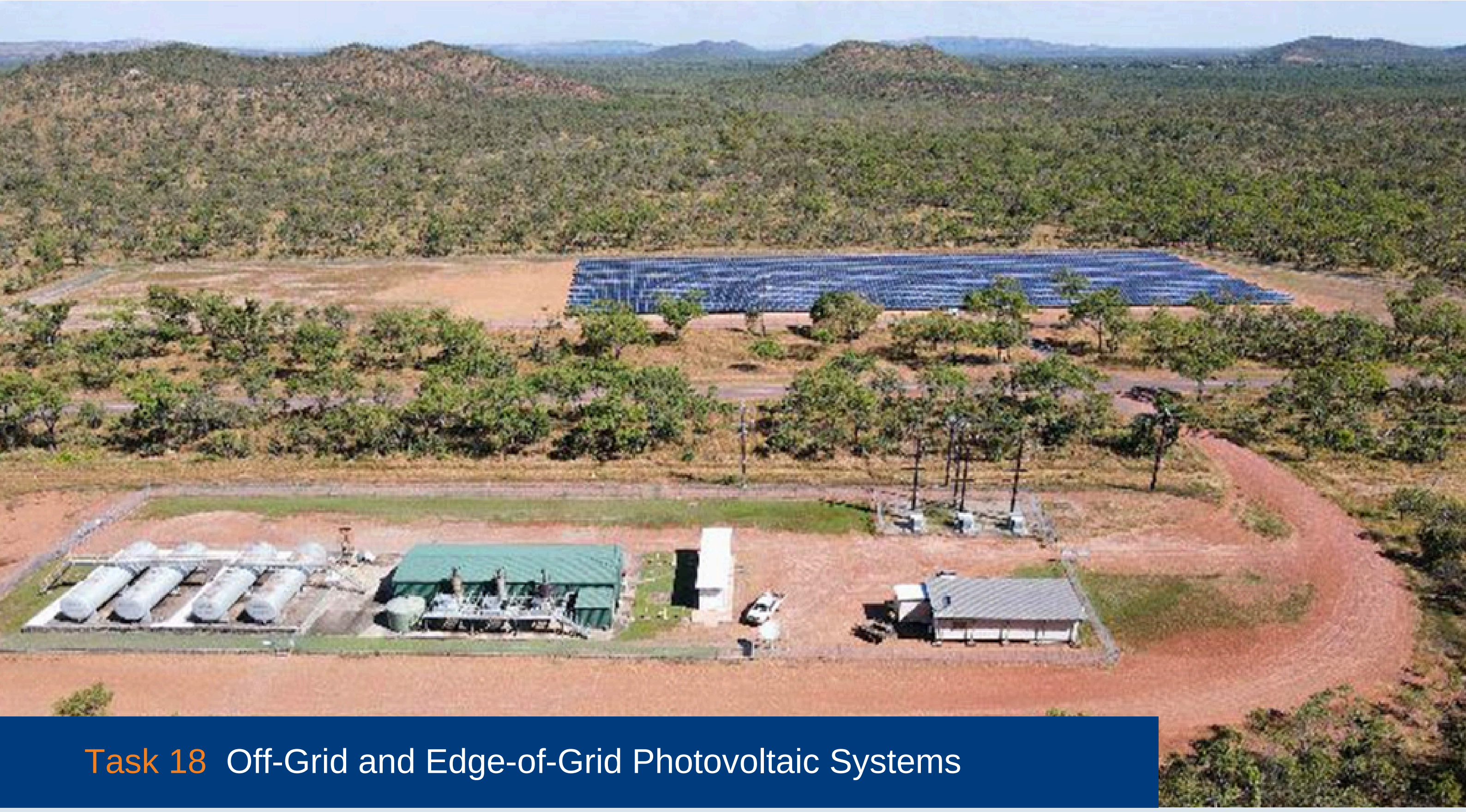
Photovoltaic Power Systems Programme



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

PVPS

Li-Ion Battery Systems in Off-Grid Applications

2025

Report IEA-PVPS T18-04:2025

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 27 IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkiye, the United Kingdom and the United States of America. The European Commission, Solar Power Europe and the Solar Energy Research Institute of Singapore are also members.

Visit us at: www.iea-pvps.org

What is IEA PVPS Task 18?

The objective of Task 18 of the IEA Photovoltaic Power Systems Programme is to find the 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 interference 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

Installation of the „Daly-River Mini-Grid“ in Northern Territory of Australia. Photo provided by Ekistika, Alice Springs.

INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Li-Ion Battery Systems in Off-Grid Applications

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

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AUTHORS

Main Content

Simon Rosenfeld, Rolls Royce Solutions, Germany
Jad Mhanna, Asantys, Germany
Georg Bopp, Fraunhofer ISE, Germany
Michael Müller, OFRES, Germany
Stefan Trittler, Asantys, Germany
Felix Stortz, Fraunhofer ISE, Germany
Nicolas Geze, Rolls Royce Solutions, Germany

Main Reviewers

Chris Martell, GSES, Australia
Jorge Ortiz, TTA, Spain
Paul Rodden, Ekistica, Australia
Flemming Vejby Kristensen, Denmark
Ömer Faruk Tuncbilek, Turkey
Yves Poissant, Canada
T. Paulin, Canada
Soukaina Boudoudouh, Morocco

Editor

Felix Stortz, Fraunhofer ISE, Germany

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ACKNOWLEDGEMENTS

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Georg Bopp, Felix Stortz: Fraunhofer ISE

Michael Müller: OFRES

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Paul Rodden: Ekistica

Chris Martell: GSES

LIST OF ABBREVIATIONS

AC	Alternating current
aFRR	Automatic Frequency Restoration Reserve
AGM	Absorbed glass mate
BMS	Battery management system
BoL	Beginning of life
DC	Direct current
DOD	Depth of discharge
EoL	End of life
EPC	Engineering, procurement and construction
EMS	Energy management system
HVAC	Heating, ventilation and air conditioning
H&S	Health and safety
IEA	International Energy Agency
IEC	International Electrotechnical Commission
LCO	Lithium-cobalt-oxide
LCOE	Levelized cost of energy
LFP	Lithium-ferro-phosphate
Li-ion	Lithium-ion
LMO	Lithium-manganese-oxide
LTO	Lithium titanates
mFRR	Manual Frequency Restauration Response
NCA	Lithium-nickel-cobalt-aluminium-oxide
NMC	Nickel manganese cadmium
OPzS	Stationary tubular plate special
O&M	Operation and maintenance
Pb	Lead
PV	Photovoltaic
SDG	Sustainable development goals
SEI	Solid electrolyte interface
SHS	Solar home system
SOC	State of charge
SOH	State of health
STC	Standard test conditions
UL	Underwriters Laboratories
VRLA	Valve-regulated Lead-acid

EXECUTIVE SUMMARY

The standalone microgrid is getting attention and being adopted by energy communities due to several factors, such as increasing access to electrification, electrification of vehicles, and reducing greenhouse gas emissions with the help of renewable generation. Sizing and optimization are vital in deploying an efficient, reliable, and secure power supply at reasonable costs.

This report gives an overview of the current state of Lithium-ion (Li-ion) technologies in off-grid applications. One of the main contributions of the report is a classification table for off-grid systems. This provides recommendations of what battery system to use for different types of microgrids. Additionally, an overview of the Li-ion technology is gathered, and a comparison of Lead-acid off-grid battery systems and Li-ion off-grid battery systems is simulated. Furthermore, a case study with a real-world system is analysed and categorized into the classification table. Finally, operation and maintenance guidance are developed and presented.

Technology

The report summarizes the most common Li-ion cell chemistries. It describes the functionality of such battery cells and the possible applications.

Table 1: Overview of Li-ion chemistries and its properties [6].

Material	Capacity [Ah/kg]	Working Voltage [V]	Energy density [Wh/kg]
NCA ($LiNiCo_{0.85}Al_{0.15}$)	200	3.7	740
LCO ($LiCoO_2$)	160	3.9	624
NMC ($LiNiMnCoO_2$)	160	3.7	592
LMO ($LiMn_2O_4$)	100	4.1	410
LFP ($LiFePO_4$)	160	3.2 - 3.4	544

Categorization

The report provides an overview on the different system applications, the typical battery system size and categorizes 4 system classes

- Class 1: Battery size up to 0.5 kWh, portable loads and others
- Class 2: Battery size from 0.5 – 2 kWh/d, Solar Home Systems (SHS), Street lights
- Class 3: Battery size from 2 – 500 kWh, PV Hybrid Systems
- Class 4: Battery size from 500 – 5000 kWh, Industrial loads and grid supporting systems

The type of load is in general independent from the classification of the system as this mainly deals with the size. However typical types of applications were identified and can be classified according to the mentioned definition.

Li-ion battery systems can support all those kinds of systems while especially the very small Class1 and the big Class 4 are dominated by Li-Ion batteries independently from the type of application.

Case Study

In Haiti, a hospital system was built based on Li-ion systems and is under operation since 4 years. The system includes two PV fields with the power of 232 kWp and 210 kWp, respectively. These PV fields harness solar energy and convert it into electrical power to meet the energy requirements of the hospital. Each PV field is equipped with inverters that convert the direct current (DC) electricity generated by the PV panels into alternating current (AC) electricity. The inverters ensure compatibility with the hospital's electrical load and enable the utilization of solar-generated power. The system comprises of four gensets, two units rated at 200 kVA and two units rated power at 400 kVA.

The gensets serve as a backup power sources to supplement the electricity supply during periods of low solar irradiation or in the event of power outages. They provide additional power to meet the hospital's energy demands. The system can operate autonomously while the gensets are off, the inverters of the BESS operate in off-grid mode and form the grid. The system has two BESS that utilize Li-ion technology. The first BESS has 224 kWh, while the second has a capacity of 332kWh.

Simulations

Real system load data and site information have been used to develop a digital twin of these systems. After validating the model with the help of the monitoring data, system size parameter variations have been performed. With this simulation the load was scaled among all 4 defined system classes (see table Class1 to Class4). Optimal system sizes where calculated depending on the boundary conditions. This has been performed using Li-ion and Lead-acid batteries in order to investigate which technology performs better under which conditions.

Success Factors

In order to operate Li-ion battery systems in PV off-grid applications sustainably it is of crucial importance to maintain all relevant steps among the following aspects:

- **Design**: The systems needs to be designed taking into account the local boundary conditions not just from a technical point of view but also in regards to logistics human resources, communication infrastructure and the maintenance capabilities.

- **Implementation**: The installation phase shall be defined depending on the type of technology which will be installed and shall take all steps into account including adaption of the system and the Battery Management System (BMS) parameters according to the local conditions.

- **Operation**: The operation phase needs to be permanently supported by local maintenance staff to provide first level support. The supplier shall permanently monitor the system and receive status information online. With the help of data analyses, the performance of the system can be monitored

1 INTRODUCTION

Currently, 770 million people worldwide lack access to electricity. Sub-Saharan Africa, in particular, has the highest proportion of non-electrified communities, with 77% of its population without access to electric energy [1]. The United Nations Sustainable Development Goal 7 (SDG7) "Affordable and clean energy," aims to significantly decrease this elevated figure. Access to electricity affects health, living conditions, education, and economic growth of populations directly. On an economical perspective, it is often not feasible to extend the energy distribution grid in rural areas. Off-grid systems can be up to 30% cheaper than traditional grid expanding [2], offering opportunities for decentralized off-grid systems. As we shift towards a more sustainable and cost-effective energy supply, renewables have become the preferred choice. Their investment costs have steadily decreased over the years, and operational costs are relatively low because they don't rely on fuel, which can significantly drive up the operating expenses of traditional fuel-based engines, due to the high fuel price. Additionally, generators are highly dependent on fuel availability to provide energy. However, renewable energy sources exhibit fluctuations in their production as they depend on factors like available solar irradiance and wind energy. They often struggle to align with load patterns, which exhibit asynchronous behaviour. Addressing this issue requires the implementation of energy storage systems to stabilize the output of renewable sources. Typically any off-grid system consists of an energy production source, an energy storage system and the electric supply loads. Battery energy storage systems (BESS) show a wide span of flexible operation modes, providing not only an electric energy storage, but also function as part of a broader off-grid management strategy.

This report gives an overview of the current status of Li-ion technologies in off-grid applications. One of the main contributions of the report is a classification table for off-grid systems. Additionally, an overview of the Li-ion technology is gathered, and a simulation is done to compare Lead-acid off-grid battery systems and Li-ion off-grid battery systems. Furthermore, a case study with two real world systems is analysed and categorized into the classification table. Finally, operation and maintenance guidance are developed and presented.

2 APPLICATION AND CLASSIFICATION

In accordance with a German [3] and a European project [4] that investigated the extent to which the aging of Lead-acid batteries depends on the operating conditions in stand-alone PV system, this chapter examines the operating conditions for batteries in different stand-alone PV systems. The stand-alone PV systems are divided into the following four classes, as shown in Table 1:

Class 1: Year-round operation with 100% solar fraction, solar power between 5 and 100Wp for supplying technical devices, mainly in moderate climate zones, such as cigarette vending machines, parking meters, streetlights, etc.

Class 2: Year-round operation with 100% solar coverage, solar power between 1 and 1000 Wp mainly for supplying small houses in (sub)tropical areas, such as solar lamps, pico PV, solar home systems, garden houses, etc.

Class 3: Seasonal or year-round operation, usually with an additional generator in moderate zones and rarely in subtropical zones, 100% solar coverage is only possible in subtropical climates, solar power between 0.5 kWp and 1 MWp for supplying larger estates, such as alpine huts, hiking restaurants, schools, small villages, etc.

Class 4: Village or town supply with one or more large diesel generators, the PV system is used to reduce diesel consumption, the solar coverage rate ranges from 10% to a maximum of 30%, and the PV system size is between 0.2 and 10 MWp.

Additionally, a distinction is made between moderate climate zones, which have a pronounced difference in solar radiation between summer and winter (up to 1 to 6), and (sub)tropical climate zones, often called sunbelt regions, where the variation in solar radiation between the rainy season and the sunny months is at most 20% to 30%.

In table 2 the different classes with the essential technical data of the PV system and especially the battery system in terms of its operation and load is provided. The table includes the following data[1]:

- Typical application: Describe the four classes exemplary with different applications.
- Location: The climate zone in which the system is installed.
- Typical PV size: The typical installed capacity (rated power at STC) of the PV generator. The power range is very wide, because it depends on the load. As the subtropical climate zone receives approximately double the amount of solar energy per year compared to the moderate climate zone, the typical power range of the PV generator in the subtropical zone is half as large as in the moderate climate zone.
- Typical battery size: Nominal battery capacity multiplied by nominal voltage. The installed capacity range is very wide, because it depends on the load.
- Final yield: Daily solar energy consumption (for systems without an additional generator, this is the energy consumption; for systems with an additional generator, its coverage share must be subtracted) divided by the rated power of the PV generator.

[1] The exemplary figures for final yield, capacity ratio, solar fraction and autonomy time are mainly based on design calculations, realized systems and measurement results of a lot of off-grid PV systems of Fraunhofer ISE and Asantys. These exemplary figures can be used for dimensioning of off-grid PV systems and selection of a proper battery.

- Capacity ratio: Usable battery energy (usable capacity multiplied by nominal voltage) of the battery divided by the rated power of the PV generator. Usually the nominal battery energy (information on the name plate of the battery) is used, but in this case the usable battery energy is applied to get a better understanding of the real capacity because Lead-acid batteries should typically discharge to only about 50% of their nominal capacity to achieve good battery life, compared to 80% for Li-ion batteries. The number range of each class is quite broad for the following reasons: Li-ion systems tend to have smaller storage and larger PV generators than Lead-acid systems for cost reasons. If a backup generator is available in class 3, smaller storage units are also selected. Larger storage tends to be chosen in regions where there is a large variation in irradiation between days, and for solar lights and pico PV systems where the storage is to charge external devices such as a cell phone. Additionally, the significant decrease in PV module prices over the past 10 years has led to larger PV generators being more cost-effective than larger batteries.
- Solar fraction: The percentage of annual energy consumption covered by the PV generator. In classes 1 and 2 the total energy consumption is covered by solar energy only. In classes 3 and 4, peak load coverage and winter or rainy season operation are usually supported by a diesel generator, resulting in a solar coverage rate below 100%. In the subtropical climate zone, a big PV generator allows for 100% solar coverage even in class 3.
- Autonomy time: Usable battery energy divided by daily energy consumption. The wide range of numbers is described by the same reasons as in two sections before. The autonomy time drops from about 7 days in class 1 to 0,01 - 5 hours in class 4. This is due to the fact that, for example, the battery of a parking meter in the moderate climate zone has to bridge a week without sunshine during winter. In class 4, the battery is primarily used to cover short power peaks and bridge short solar dips caused by rapid cloud changes.
- Average discharge current based on nominal battery capacity: Mean discharge current over the discharge period (mostly during night). The provided values are for Lead-acid batteries and quite general, as they vary significantly throughout time and year and system sizing. For Li-ion batteries the values are about twice.
- Summarized equivalent full cycles per year based on nominal battery capacity: The cumulative number of equivalent full cycles during a year. The provided values are for Lead-acid batteries, for Li-ion batteries the values are about double. The numbers can be used to roughly estimate the battery life if no other aging effects are present. Lead-acid batteries primarily age due to incomplete charging, see SOC row, during months with low solar radiation in the moderate climate zone, particularly in classes 1 and 2 [3]. Li-ion batteries age quicker at very high or very low SOC [5].
- SOC: State of charge. The provided values are mainly for Lead-acid batteries, for Li-ion batteries the range is wider.
- Recommended Battery: The battery type, either Li-ion or Lead-acid, which is mainly used in the respective class.

The table clearly shows that the stress on the battery varies greatly among the different classes. For example, the number of full cycles ranges from around 10 per year to 500 per year. Until 10 years ago, the dominant battery in stand-alone PV systems was the Lead-acid battery. However, to achieve a lifespan of 6-8 (max 10) years for the different classes, various types of Lead-acid batteries need to be chosen /3/. The most suitable Lead-acid battery for the classes 2 and 3 is the OPzS (stationary tubular plate special) battery. Due to cost considerations, modified starter batteries (reinforced grid plate) can also be used in class 1 and in the moderate climate zone in class 2. Partial cycling often leads to acid stratification, which can be prevented or eliminated by regular full charging (at least every 14 days) or the use of a gel battery. In a gel battery, the electrolyte (sulfuric acid) is immobilized in a gel, and to maintain a recombination process, it needs to be tightly sealed with the help of a valve, hence the name valve-regulated Lead-acid (VRLA). Gel batteries are maintenance-free since no acid needs to be replenished, but overcharging must be avoided. Due to cost considerations, absorbed glass mate (AGM) instead of gel can also be used in class 1 but be aware standard AGM do not prevent for acid stratification which do not occur in class 1.

Due to the technical advantages of Li-ion batteries over Lead-acid batteries described in Chapter 3, Li-ion batteries are widely used in many systems today. Especially in class 2, for example for solar lamps and pico PV systems, only Li-ion batteries are used, as well in class 4. In the other classes the approximately double investment cost of a Li-ion battery system compared to a Lead-acid battery system remains a hindrance for a general replacement of Lead-acid batteries with Li-ion batteries. However, Li-ion batteries allow for almost twice the depth of discharge, although this is often not taken into account in the design and economic calculations. This is understandable considering limited initial investment funds.

In moderate climate zones, it should be noted that most Li-ion technologies should be charged with significantly reduced current at temperatures below zero degrees Celsius (see Chapter 3). This is not the case for Lead-acid batterie but be aware if the SOC is very low the electrolyte froze below zero degrees Celsius. Li-ion technologies are often classified into energy types (currents < 1C) and power types (currents > 1C), with power types usually being necessary only in class 4.

Table 2: Classification table of battery off-grid systems

	class 1		class 2		class 3		class 4
Typical application	Parking meter, streetlamp, cigarette automat		solar lantern, Pico PV, SHS, garden shed		Hybrid system mountain hut or village supply		PV – diesel big village supply
location	Moderate zone	(Sub-) tropical zone	Moderate zone	(Sub-) tropical zone	Moderate zone	(Sub-)tropical zone	worldwide
Typical PVp size	10- 100 Wp	5 - 50 Wp	1 - 500 Wp	1 - 250 Wp	1 kWp – 1 MWp	0,5 kWp - 0,5 MWp	0,2 -10 MWp
Typical battery size	20 – 500 Wh	15 – 250 Wh	10 – 2000 Wh	5 -1000 Wh	20 – 200 kWh	10 – 500 kWh	0,1 - 5 MWh
Final yield = Daily solar consumption/ PVp	0,25 – 0,75	0,5 – 1,5	1 - 2	2 – 4	1 - 2	1,5 – 4	1,5 – 4
Capacity ratio: Usable battery energy/PVp	2 - 4	4 – 7	3 - 6	3 – 12	2,5 – 4	5 – 8	0,1 – 2
solar fraction	100 %	100 %	100 %	100 %	30 - 80 %	80 - 100 %	< 40 %
Autonomy time	5 - 7 days	3,5 – 7 days	1 – 2 days	1,5 – 3 days	0,5 – 2 days	1 – 2 days	0,01 - 5 hours
average discharge current	small currents ~ I_{150}	medium currents ~ I_{75}	medium currents ~ I_{75}	medium currents ~ I_{50}	medium currents ~ I_{25}	medium currents ~ I_{25}	high currents ~ I_{1} - I_{10}
Average cycle	a lot of small daily cycles	a lot of medium daily cycles	each day ~ 10% cycle each weekend ~ 60% cycle	each day quarter or half cycle	each day quarter or half cycle	each day quarter or half cycle	deep cycles ~ 0.5 cycle/h – 1 cycle per day
Summarized equivalent full cycles per year	few cycles per year ~ 10/year	~ 100/year	~ 75/year	~ 150/year	~ 75/year	~ 150/year	~ 500/year
SOC	Winter: low SOC Summer: high SOC	Every day ~ 50-100%	Winter: low SOC Summer: high SOC	Every day ~ 50-100%	Winter: ~ 40-90% Summer: ~ 50-100%	rainy season: ~ 40-90% Summer: ~ 50-100%	~ 10-90%
Recommended battery	Lead-acid, Li-ion	Li-ion, Lead-acid	Lead-acid, Li-ion	Li-ion, Lead-acid	Li-ion, Lead-aid	Li-ion, Lead-acid	Li-ion

3 REVIEW OF LI-ION BATTERY SYSTEMS

In this chapter, the Li-ion technology is described. Furthermore, it contains an overview of future battery technologies. Additionally, the chapter describes the safety of Li-ion batteries and operation strategies of BESS.

3.1 Technology

Since the introduction of the Li-ion battery by Sony in 1991, a lot of research has been made. State of the art Li-ion batteries show a wide spectrum of different designs and materials, but the underlaying working principle hasn't changed since 1991. One Li-ion cell consists of two electrodes. Each of the electrodes has an electrochemical potential, measured against a standard reference electrode. Together, they constitute a cathode and anode pair. The difference between the potential of both defines the electromotive force between them and equals to the open circuit voltage of the battery cell. Both electrodes are electrically isolated by a porous membrane, the so-called separator. The battery cell contains an ion-conductive electrolyte, enabling the movement of lithium-ions between electrodes through the separator and their integration into the active materials of the electrodes during the charging and discharging process. The current collectors connect the electrodes to an external circuit, serving as an electrical pathway to ensure a uniform distribution of electrons across the electrodes, allowing for the transfer of electrical energy to and from the battery cell. When the external circuit is closed, electrons migrate from the negative electrode to the positive electrode, balancing the potential difference between the electrodes. Positive lithium-ions are also migrating through the electrolyte in a similar direction. In that way the chemical energy, stored in the cell, is converted to electricity in the external circuit.

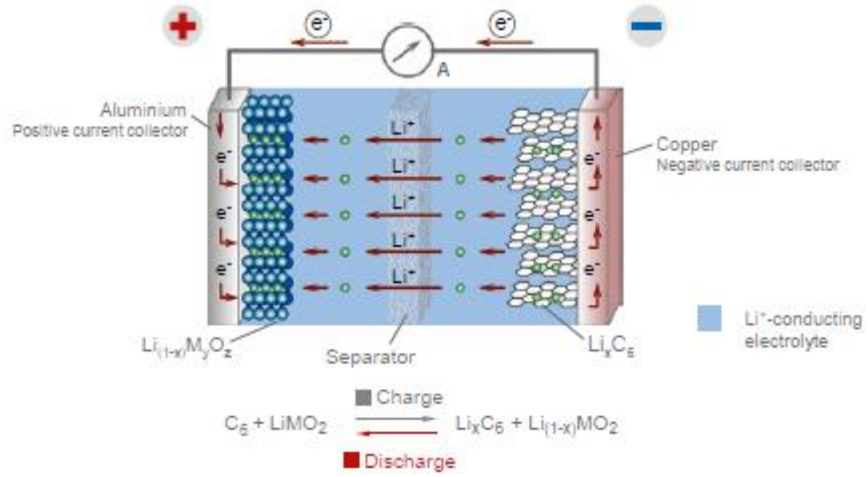


Figure 1: Set-up of a Li-ion battery (shown in the discharging process) [6].

3.1.1 Cathode

The electrochemical characteristics of a Li-ion cell are defined by its components. The behavior of the battery is significantly impacted by the interactions among its constituent elements: cathode, anode, separator, and electrolyte, which comprise a lithium salt and solvent. The traditionally used active material for the cathode is lithiated cobalt oxide ($LiCoO_2$). To overcome issues regarding safety, size and cost, research led to the development of other cathode materials. Nowadays, there is a broad spectrum of materials already available with further research being made. In general, cathode materials can by classified in three categories based on their crystal structure: oxides, spinel oxides and phosphates.

Oxides

Oxides form a layered crystal structure with alternating metal, oxygen, and lithium-ion. The metal component can consist of one or a combination of the following elements: nickel, manganese, cobalt, and aluminum. Lithium cobalt oxide, also known as LCO is probably the most used cathode material. The cobalt redox pair creates a potential of around 4.0 V against the lithium pair. When extracting all lithium-ions from the LCO-cathode, it shows a theoretical capacity of 274 mAh/g. When it comes to rechargeability, this number can't be reached, as some lithium needs to remain in the cathode for stability reasons to ensure the structure remains steady and intact. Therefore, the maximum reversible capacity is 140 to 150 mAh/g. The energy density of LCO could hardly be matched by other materials as it shows a high working voltage, high relative density, and bulk density. However, issues regarding stability and safety pushed the market to focus on other materials. It should also be mentioned that cobalt mining is frequently associated with adverse working conditions. The Democratic Republic of Congo holds a significant share of global cobalt reserves and continues to confront challenges related to modern slavery and child labor in the industry. Additionally, cobalt is relatively expensive.

By far the most famous of oxide-cathode combinations is the multi-metal phase consisting of nickel, manganese, and cobalt ($LiNiMnCoO_2$), also known as NMC. The exact concentration of each element can vary, due to a specific use case, combining advantages of the three boundary phases LCO, LMnO and LNiO, resulting in a higher reversible capacity and a better cycling stability. It shows a higher energy density, due to the use of cobalt, a higher stability, thanks to the manganese and a higher capacity with the nickel. Similar to LCO, NMC can only use a share of around 66 % of a theoretical capacity of 274 mAh/g for maintaining its structure, resulting in a capacity of up to 160 mAh/g.

Spinel Oxides

Oxides that adopt a spinel structure, defined by a cubic symmetric crystal lattice structure, are represented as LiM_2O_4. In this scenario, the metals occupying the "M" position can be either manganese or nickel. The most widely recognized commercial variant is $LiMn_2O_4$, commonly referred to as LMO. The three-dimensional spinel structure provides a well-connected framework for the storing of Li-ions in the cathode structure, known as intercalation and dissolving Li-ions, known as deintercalation, as Li-ions can access the cathode easier than two-dimensional frameworks such as Oxides, resulting in a higher rate-capability. Therefore, LMO spinels can be charged with up to five times higher currents. On the other hand, LMO shows poor cycling stability, resulting in a continuous decline of its reversible capacity. The cathode surface degrades when the average oxidation state of manganese drops below a certain level. Substitution manganese atoms with non-manganese atoms or injecting dopant atoms into the lattice structure of the cathode helps increase its stability.

Phosphates

Another category of cathode materials is comprised of phosphates. The fundamental formula for this class can be denoted as $LiMPO_4$, with "M" representing elements such as iron (Fe), manganese (Mn), cobalt (Co), or nickel (Ni). The most famous variant of that class is lithium ferrous phosphate ($LiFePO_4$, known as LFP). Iron being the most common element in the earth's crust, it is cheaper than other materials, especially cobalt. The bonds of the oxygen in the phosphate are much stronger than the ones in the metal oxides. This means metal oxides are at a high risk of releasing oxygen, and since oxygen cannot escape the isolated cell, it is prone to react with the organic electrolyte, potentially triggering an exothermic reaction. Also, the difference in size and density of the charged and the discharged state, when compared to other cathode materials, is very low, resulting in less tensions, avoiding structural damages to the cathode. Therefore, cycling stability is much higher and LFP cells can be operated at a wider temperature span.

In order to compare the most commonly used cathode materials commercially, they are presented in the following table:

Table 3: Different Li-ion technologies in electrical comparison [6].

Material	Capacity [Ah/kg]	Working Voltage [V]	Energy density [Wh/kg]
NCA ($LiNiCo_{0.85}Al_{0.15}$)	200	3.7	740
LCO ($LiCoO_2$)	160	3.9	624
NMC ($LiNiMnCoO_2$)	160	3.7	592
LMO ($LiMn_2O_4$)	100	4.1	410
LFP ($LiFePO_4$)	160	3.2 - 3.3	544

The selection of cathode materials involves careful consideration of specific application requirements. For smaller devices like smartphones and laptops, size and weight are key factors. Electric vehicles prioritize high power, energy density, and lightweight design. Stationary systems prioritize cycling stability over energy density due to less space constraints. Also, safety concerns increase with size as more energy is centralized. A burning smartphone can be handled far easier than a burning car, which can generate a lot higher amount of heat, as more energy will be released.

High energy density applications, such as electric vehicles, commonly opt for layered oxides like LCO or NMC. However, these materials are relatively scarce and more costly compared to iron-based alternatives like LFP. Metal oxides, though, carry safety risks due to their potential for oxygen release and exothermic effects. In contrast, LFP has lower energy and power densities but is well-suited for stationary systems, offering safety and extended operational lifespans when properly installed.

3.1.2 Anode

The variety of anode materials is relatively limited in comparison to cathode materials. Graphite, initially employed, remains in use today and is currently the most economically viable option due to its balanced performance characteristics. It is lightweight, cheap and offers a quite high intercalation potential of storing one Li-ion in every six carbon atoms. On the other hand, the use of carbon is also not free of risks. The intercalation potential for graphite is only 80 mV higher than the lithium metal plating potential. Only small overcharging errors can cause deposition of metallic lithium. As plating grows, they can form dendrites, which are able to cause damage to the cell. An occurring effect that prevents such failures is solid electrolyte interface (SEI) formation. During charging of the batteries within the first cycles the electrolyte reacts with the graphite anode, arising to a decomposition of the reductive electrolyte and a consumption of the Li-ion. The product is deposited onto the electrode surface as a passivation layer, the SEI. This layer stops further decomposition of the electrolyte and protects the negative electrode. This effect has some great impacts on the overall battery performance such as power, safety, cycling stability and service life of a Li-ion battery cell.

Other anode materials are soft or hard carbons, which limits the potential of the deposition of metal at the anode but also lower the energy density and so far, couldn't prevail themselves over dominating graphite electrodes, due to its low price and higher energy density.

In the future, lithium titanates (LTO) could become of major interest for stationary batteries. Even if they can only provide a low cell voltage and capacity (lower limit of 1.4 V, resulting in max. 2.3 V cell voltage), they are superior in case of safety and lifetime. LTOs do not need to form a solid electrolyte interphase and has a larger surface than carbon anodes. Those two characteristics are the reason why they can be recharged faster and can provide higher currents. If space is not limited, stationary applications with cells consisting of LFP and LTO electrodes could play a serious role for large scale systems with up to 5-times more cycles than commercialized batteries.

3.2 Future perspective on Lithium batteries

Li-ion battery technology has been pushed to the limits of gravimetric and volumetric energy density since 1991. Although research is ongoing, it is approaching natural limitations imposed by the electrode materials and electrolyte. Therefore, interest is growing in other battery technologies based on different cell chemistries, especially with the increasing demand for energy storage. Since space is often not a critical factor for off-grid systems, factors like safety, aging, and performance become more relevant. Consequently, alternative solutions are gaining traction, moving away from the primary driving force of electric vehicle technology improvements.

There are various approaches to enhancing battery cells. The use of metallic lithium instead of lithium-ion components as electrodes could theoretically result in higher energy densities. However, this is not feasible with current state-of-the-art batteries. Other technical developments are overcoming this limitation by adopting alternative battery technologies.

Solid-state batteries, which incorporate a solid electrolyte, aim to overcome the limitations associated with liquid electrolytes, such as flammability, limited voltage, poor cycling performance, and stability issues.

Lithium-sulfur batteries, consisting of a metallic lithium electrode and a sulfur electrode, exhibit the highest theoretical energy density based on their chemistry. However, they currently face challenges related to cycle life and are far from achieving their theoretical energy density value.

Lithium-air batteries also promise an extremely high theoretical energy density by using atmospheric oxygen and also metallic lithium as active materials, but show issues in the case of stability, cycle life and efficiency.

Given that price and safety are key market drivers, technologies using non-rare raw materials are also being explored. In sodium-ion batteries, sodium replaces lithium in the cathode. While this technology may not achieve the energy densities of existing Li-ion batteries, it could become attractive on a megawatt (MW) scale due to its cost-efficiency, stemming from the abundant and inexpensive availability of sodium worldwide.

Another approach is redox-flow batteries. This technology utilizes reduction and oxidation reactions of two separate liquid electrolytes flowing through a cell to exchange ions. The chemical components are stored in two distinct tanks, allowing for a scalable solution since the tank size is independent of the cell size. Although redox-flow batteries offer long cycle and calendar lives, they cannot compete with the round-trip efficiency of some other battery technologies.

3.3 From cell to system

The cell packaging design can be quite different, in regard of the application. Metal-based housing is part of all state-of-the-art housing materials and required because it is the only solution that can fully prevent the entry of moisture into the cell and diffusion of solvent out of the cell. Cells can be either in a soft pack or in a hardcase and further characterized into a round, prismatic or pouch cell geometry. The layered inner structure of the foils can be of a cylindrical roll, flat jelly roll or stacked. For bigger battery storage systems (> 200 kW) in grid-connected or off-grid applications, in he most cases prismatic hard-cases are used as they allow an easy modular setup and allow better cooling conditions because of a higher volume to surface ratio, compared to rolled-up cylindrical battery cells.

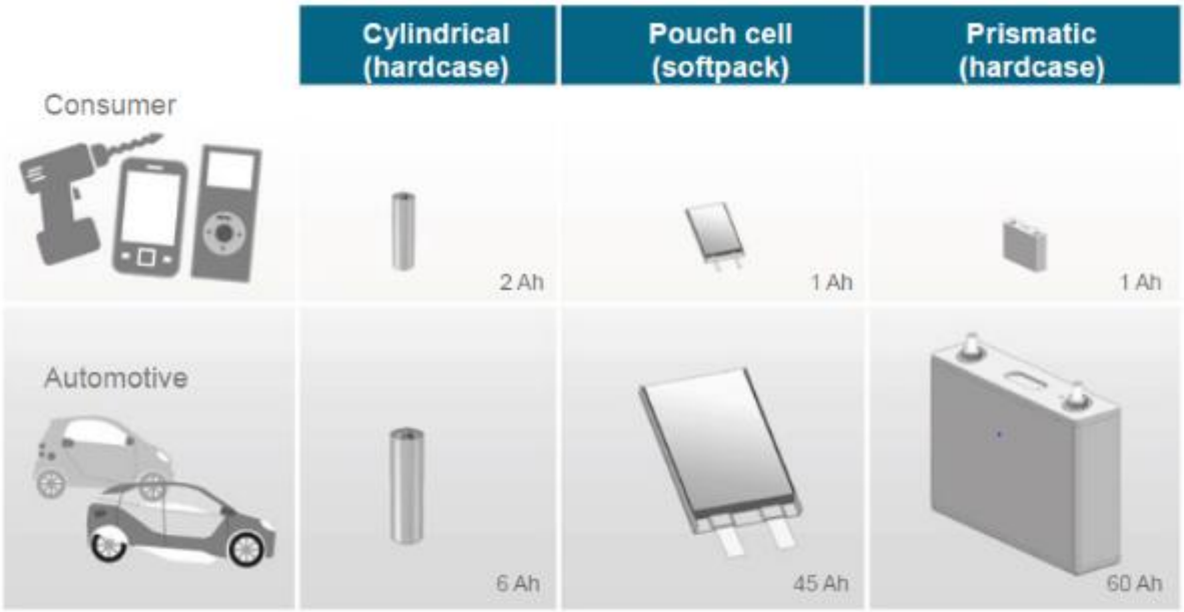


Figure 2: Commonly Li-ion cell housing and packaging types [6].

The maximal voltage cell is defined by its cathode and anode material and ranges between 2.2 V and 4.2 V per cell. In various applications, it is necessary to connect multiple cells to fit the required power output, which is the product of voltage and current.

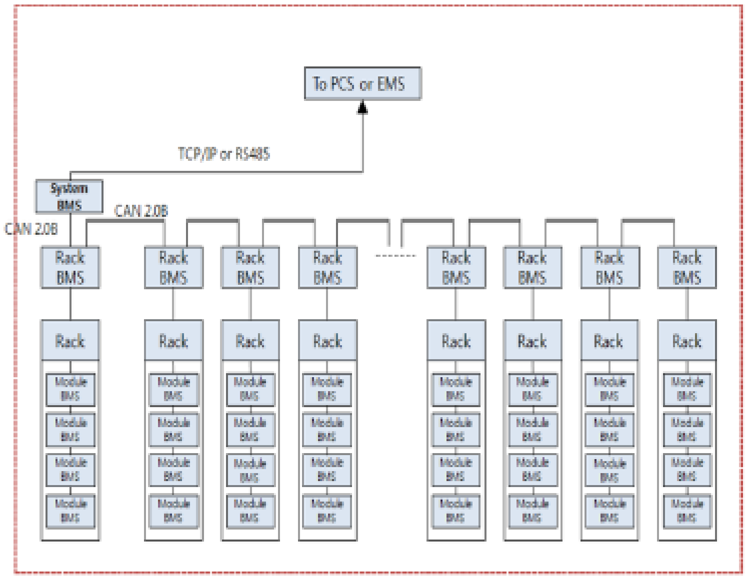


Figure 3: Overview of a BMS for a BESS [7].

Serial connections of cells sum up the voltage of the individual battery cells and a parallel connection of cells increases the usable current of the battery storage. For small mobile applications, batteries are assembled as a block of cells in serial and parallel connections. In the context of large-scale batteries, modular designs for BESS are favored. They rely on a defined number of cells that are connected in series groups to add up the voltage to a specific value. Those modules are further connected in serial to form a battery rack. Several packs can be interconnected in parallel to increase the capacity. Often bigger BESS are available as a containerized option, in which the HVAC system and the additional electronics, like the battery inverter are located. The battery modules are connected to a bi-directional inverter: when discharging, the inverter converts the direct current (DC) from the battery into alternating current to feed the distribution network. Vice versa, alternating current (AC) from energy sources is converted to direct current to recharge the battery. In small, simplified, renewable-only solutions the distribution grid may operate on direct current. However, this is a less common scenario, as most household appliances and electronics are designed to operate on AC power. To ensure compatibility between the inverter's AC output and the off-grid's requirements in the most cases a transformer is employed. The transformer adjusts the voltage level of the inverter's AC output to match that of the distribution grid, ensuring a seamless integration of the BESS into the off-grid system.

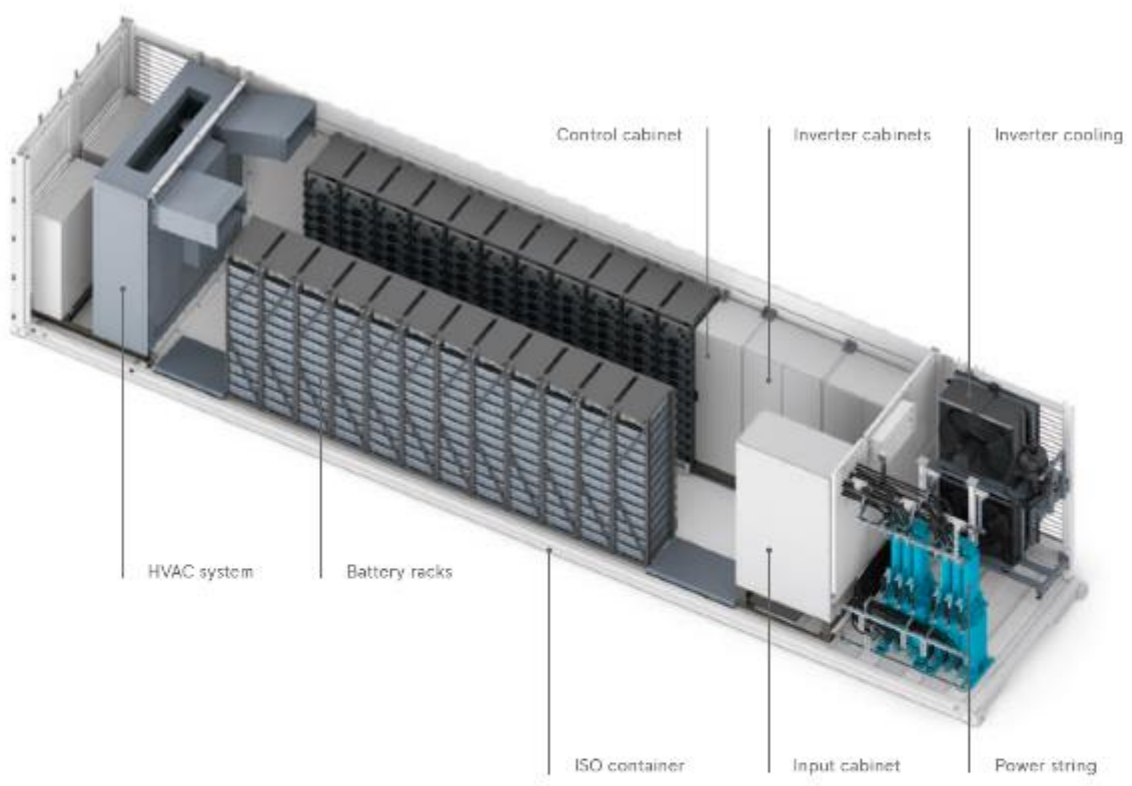


Figure 4: Overview of a container BESS solution with the main components [7].

3.4 Aging

One of the most significant challenges to address when optimizing Li-ion batteries pertains to the phenomenon of aging.

Aging refers to the progressive degradation in the performance and capacity of Li-ion batteries over time due to the repeated charge-discharge cycles. This natural process results in reduced battery life and overall efficiency.

Degradation is often determined by a state of health (SOH) of the battery, which displays the percentage of currently available capacity compared to the nominal capacity at beginning of life (BOL). The major effects are an increasing consumption of lithium-ions resulting in a capacity fade over time and an increasing internal resistance resulting in a reduced available power provided by the cell.

Today, degradation phenomena aren't completely understood yet, due to their high complexity and simultaneity. Nevertheless, the main effects and the reactions inside the cell are identified and can be attributed. Aging processes are often characterized by calendric and cycling aging.

Calendric aging addresses the degradation process that happens over time, starting from the moment the cell is produced, even if the system is not installed yet. Calendric aging can't be reduced by an operation strategy of the battery system. Mostly it is affected by the core temperature of a battery, which is highly dependent on the ambient temperature and humidity. An increment of the temperature kinetically promotes the unwanted chemical side-reactions, such as decomposition of the electrodes, interactions between the electrolyte and released oxygen, resulting in faster degradation.

Cyclic aging effects are driven by the number of cycles as well as the rate the battery is being charged and discharged. The battery cell degrades slightly with every cycle. The already mentioned SEI formation is a necessary effect for safety reasons of cells containing graphene electrodes. In fact, the formation of the passivation layer doesn't stop after the first cycles. It is way slower than in the beginning, but the SEI is constantly growing. This causes an ongoing fade of capacity as lithium-ions are consumed and a reduction of available power, as the resistance rises, because lithium-ion need to migrate through the passivation layer to intercalate.

3.4.1 Factors Affecting Battery Lifespan

Li-ion batteries undergo aging processes that affect their performance and longevity. Several factors contribute to this phenomenon, including:

Temperature: The operating temperature of a battery is a critical factor. Low temperatures (e.g. <10 °C) can limit degradation but may hinder intercalation processes, while high temperatures (e.g. > 40 °C) accelerate unwanted chemical reactions, leading to faster degradation. The optimum temperature for battery performance may differ between resting and charging/discharging states.

Depth of Discharge (DoD): The extent to which a battery is discharged during each cycle can have a significant impact on its longevity. While Li-Ion batteries offer a relatively high DoD capability, reaching up to 95 % compared to other battery technologies, it is noteworthy that employing shallow discharges, wherein only a small fraction of the battery's capacity is utilized, can enhance the battery's operational life compared to frequent deep discharges and high charging cycles."

C-Rate: The rate at which a battery is charged or discharged, known as the C-rate, affects its aging. There are several definitions to calculate the C-rate but is mostly given by the ratio between the charging or discharging current against its Ah capacity. At 1 C the battery can be completely discharged with a constant current in one hour. Faster charging or discharging rates can lead to stresses and tensions within the electrodes, potentially causing cracks and reducing capacity over time.

Resting SOC: The state of charge at which a battery is left during periods of inactivity, known as resting SOC, can influence its aging. Storing a battery at high or low SOC levels for extended periods can accelerate degradation, a value of 30-50 % is suggested.

To maximize battery lifespan, it is crucial to consider these factors when designing battery systems and implementing operational strategies. Today's batteries based on Li-ion chemistry can reach a lifespan of up to 20 years, which are assumed to be constantly increased with research being made on battery cell materials. Depending on the configuration, the battery reaches End of Life (EoL) at a State of Health of 80 % to 60 % and is no longer operated. At that point, the fade of performance reached a limit, where its initial application for what the system was sized and designed for cannot be provided anymore. In most cases, the battery is taken out of service due to safety assessment reaching a specific level of degradation.

3.5 Safety

Safety remains a paramount concern in the operation of Li-ion batteries within BESS. Li-ion batteries combine substantial chemical energy density with flammable electrolytes, introducing significant potential hazards. These risks are rooted in the same chemical phenomena responsible for aging but can occur within a few seconds compared to battery aging. One critical factor is the self-sustaining temperature increase within the battery. Exothermic reactions catalyze additional exothermic reactions, eventually culminating in an unstoppable reaction chain – a so called thermal runaway. Chemical reactions occurring within the cell generate thermal energy. If this heat cannot be effectively dissipated, it leads to the acceleration of additional chemical reactions, further contributing to heat generation. Consequently, this cascade effect results in a continuous and cumulative rise in the overall heat production within the system.

During this process, the battery's separator may melt, potentially causing a short circuit and releasing a substantial amount of energy. Subsequently, decomposition and gasification of the cell's components occur, with the housing ultimately bursting under pressure, leading to the release of flammable and hazardous gases.

In such scenarios, a battery cell can ignite or even explode, presenting a severe hazard to both human well-being and the environment. To mitigate these risks Li-ion batteries are subject to strict certification standards. The standards which must be applied are different in the US and Canada, Europe and most of the rest of the world. The content is very similar, but the details are different.

In US and Canada, the umbrella standard UL 1973:2022 "Batteries for Use in Stationary and motive Auxiliary Power Applications". And UL 9540:2022 "Energy Storage Systems and Equipment" together with UL 9540A "Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Storage Systems" must be applied. UL 9540A aims to determine if the evaluated ESS meets the requirements set forth in the revised UL 9540. This test method involves measuring various metrics during a thermal runaway event, occurring at the module, unit, and installation levels. The results help define the system's behavior and performance under thermal runaway conditions, specifically in terms of fire propagation.

Until now in Europe and many other countries in the world the following 2 umbrella standards must be applied, sometimes with national supplements:
IEC 62619: 2022 "Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications" and IEC 63056:2020 "Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems".
In July 2023, a new battery regulation "2023/1542 was approved by the EU [8] in which manufacturers will be required to affix the CE marking to batteries starting from August 2024. The technical requirements and tests that must be fulfilled in order to be allowed to affix the CE mark are mainly described in the two IEC standards mentioned [9]. But the European standardization bodies are committed to harmonize the above-mentioned standards, this means it can be expected that at the end of the year 2025 in all European country the same standards are valid sometimes with little national supplements.

Nevertheless, the UL 9540 gives very detailed construction details for battery systems especially for battery containers and UL 9540A describe the fire propagation tests in a more detailed manner in comparison to IEC 62619 especially if several battery racks or containers are used. This means in some cases the clients outside of US and Canada require compliance with UL 9540 and UL 9540A.

Operating within the certified operational range, defined by specific temperature and voltage levels, is considered safe. Constant monitoring of the temperature and voltage of each cell helps identify critical states. Specific cells can be isolated, critical battery strings disconnected, or the entire BESS separated from the grid in the event of a critical condition.

Furthermore, proactive measures are taken to prevent even minor damage that could escalate into uncontrollable thermal runaways. Stationary batteries incorporate a range of safety features, e.g. constant cooling of cells, thermal insulation, fire suppression layers between modules, systems for smoke and explosive gas detection.

It's worth noting that, despite these safety concerns, BESS based Li-ion cells can be operated safely when risks are effectively managed and controlled. These risks are well-documented and understood, and safety measures have been designed to prevent and respond to potential incidents.

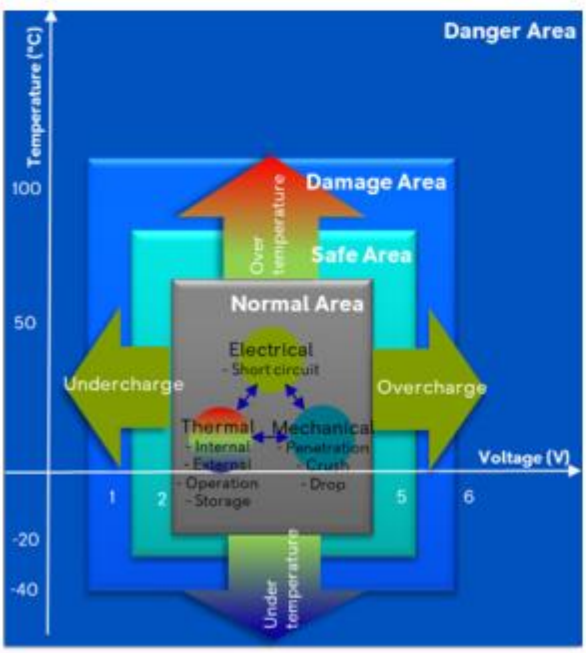


Figure 5: Safety operation diagram of Li-ion batteries [7].

3.6 Charging technology

Like lead-acid batteries, lithium-ion batteries are charged according to a 'constant current constant voltage' (CCCV) characteristic charging algorithm. During the CC phase, the cells are charged with a constant current (fluctuating in PV systems depending on irradiation) until the charge voltage reaches the value specified in the data sheet, usually 4.2 V/cell for NMC or usually 3.6 V/cell for LFP. In the subsequent CV-phase, strict attention must be paid to the fact that even a slightly too high voltage can cause serious damage to the cells. Maintaining the maximum voltage for a longer period is harmful to the cell in the long run, which is why the time of the CV-charge phase must be limited. Finishing criteria for the U-phase is time (approximately 1h) or falling below a certain current (I30 - I10). Float charging, meaning keeping up CV-charge phase for long time. This is commonly recommended for lead-acid batteries. For Li-ion cells this must not be applied because of increased cell aging at the upper voltage limit. In autonomous power supplies, it is recommended to restart the CCCV charge when the voltage drops below 4 V/cell due to consumption or self-discharge.

Many manufacturers recommend using only 80-90 % of the rated capacity to achieve a higher number of cycles (about 1.5 times) and thus longer life. Then, the charge voltage should be reduced from 4.2 V/cell to approximately 4.1 V/cell or from 3.6 V/cell to approximately 3.55 V/cell, and possibly the discharge voltage should also be raised slightly.

Due to natural differences in the assembly of the battery cells, through production and different stages of cell degradation, the cells are not charged completely equally. Eventually, a battery cell may be at full SOC when other cells are not. In this case, the specific string could not be charged any further, due to overcharging effects and to avoid damaging. Therefore, to allow for the utilization of the full storage capacity balancing systems are installed. A cell balancing system can balance different cells passively or actively. Passive balancing dissipates energy from the highest charged batteries as heat through resistors until all cells are at the same state of charge. The dissipated energy remains unused, which always results in a loss of this energy. Active balancing draws energy from the highest charged battery to the one with the lowest SOC, which leads to reduced energy losses. However, active balancing requires a more complex cell and module architecture, thus increasing costs.

3.7 Intelligence and Operation Strategies

As previously discussed in preceding sections, the operational strategy designed to ensure both the battery system's performance and safety adheres to predetermined limits. Therefore, a complex monitoring and management system needs to be set up to ensure its longevity, prevent failure and to ensure a certain performance of the system. As the battery system is structured hierarchically, from individual cells to modules, to racks, and finally to the complete BESS, the management system must operate at all levels of the battery system design and relay information to the levels beneath. The Module Battery Management System (BMS) is responsible for measuring various cell temperatures and voltages and performs cell balancing. On the other hand, the Rack BMS manages a single string, measuring its current, calculating the state of charge and power output using data from the module BMS, and controlling the modules within the string. The master BMS gathers all the data from the two, filters it and supplies hat information to the BESS controller which operates at an aggregated level together with the integrated auxiliaries such as Heating, Ventilation and Air Conditioning (HVAC) system or other implemented features of the storage system. It acts as a gateway between the battery and the overall system.

As the BESS is only one component of the system, the different components need to be handled by an overarching control structure: the energy management system (EMS). The EMS controls and monitors the entire off-grid, optimizes the operation of generation and storage assets to supply the required load. It communicates with all the control systems and sensors in the off-grid system. It needs to supervise the grid stability by controlling the frequency and the dispatch of generators to meet the load. While the primary goal of the BMS is always to ensure safety and longevity of the battery, the EMS oversees the entire off-grid and acts toward different possible targets: minimize energy cost, maximize use of renewable energy, and maximize grid stability.

Batteries offering a range of flexibility options. Not only they provide a storage solution to shift energy, as they store excess intermittent renewable energy production and supply that energy at a later stage when high energy is needed, they can also be used in a number of technical applications in conjunction with the EMS, which are briefly explained below:

3.7.1 Energy Shifting

Energy shifting could be described as the most common application of a BESS in an off-grid system. As mentioned, renewables fluctuate in their production and are not able to match a specific load pattern. When the energy production exceeds the consumption, that energy is stored by the BESS and is supplied when the production is unable to match the load. Basically, the energy that is produced is stored and shifted to other times when it is needed.

3.7.2 Peak Shaving

A more precise approach compared to energy shifting is the strategy known as "peak shaving". A load profile may display a demand peak that surpasses the average load by a substantial margin, peak for which the consumer may be charged a significantly higher price per kWh than usual. Since these peaks are only occasional and for very short periods of time, sizing the main source of power to meet these is not economically feasible. Batteries are an efficient solution as they can provide the missing amount of energy between the peak and the average power output of the main power source.

3.7.3 Spinning Reserve

To quickly adapt to unexpected peaks in demand or failure of generation units, the off-grid controller decides which generator to run and at what capacity, always considering the remaining generation capacity of the battery and gensets. This capacity of generating reserve, also known as spinning reserve, is usually needed almost instantly, something a generator cannot handle. This is where the BESS comes in, as it is usually able to pick up the extra needed power in matters of second, ensuring the grid remains fully operational. Indeed, not being able to handle a sudden spike in the load can lead to the shutdown of overloaded generators, resulting in a black-out.

3.7.4 Voltage regulation

Grid stability is a critical aspect in off-grids. BESS can provide voltage support to prevent the grid from collapsing. When voltage levels of the grid are too low, the BESS is able to inject reactive power to raise the voltage, when the levels are exceeding a certain setpoint, the BESS can absorb reactive power, resulting in a lower voltage. This is especially necessary in off-grids with a high penetration of renewable energy sources as the BESS can smooth out fluctuations caused by intermittent production.

3.7.5 Frequency regulation

Frequency deviations can also be controlled by the BESS. When the grid frequency drops, as a result of excess load, the BESS provides active power to the grid, or it absorbs power when the frequency rises. In On-Grid operations this service can also be sold to grid operators. Frequency response offers several layers of reserves. The Frequency Containment Reserve FCR is dispatched within milliseconds. If after a few minutes the grid frequency could not be restored, the automatic Frequency Restoration Reserve (aFRR) is dispatched. The third line of response is manual Frequency Restauration Response (mFRR), reacting after 15 minutes. For ongoing need of frequency support the replacement Reserve takes into place. The BESS acts therefore as the primary frequency reserve, maintaining an acceptable grid frequency.

These reserve capacities may exhibit less structured organization within off-grids, yet even in such scenarios, the battery must have some capabilities to react to sudden changes of the off-grid's frequency.

Traditionally, in off-grids the grid is formed by diesel-gensets, which provide a stable generation. In some cases, the battery is able to provide a stable baseload, so that diesel gensets can be turned off and the grid is total fed by the BESS. In that case the off-grid controller needs to keep the voltage and the frequency at a desired level, by suppling reactive power or absorbing or supplying active power. Of cause the battery needs to have enough charged energy, to provide these features. If the state of charge drops beneath a certain value, diesel generators are turned on again.

3.7.6 Ramp Rate Control

Renewable energy systems depend on natural sources like wind, water, sunlight and as these are varying also the output power of renewables fluctuate. For example, PV plants without storage solutions can show power variations of up to 90 % per minute in particular places. This can be caused by cloud coverage, that limit the power outcome of the PV plant immediately. In order to maintain grid stability, those fluctuations need to be ramped down slow. This is done by energy storage technologies, mainly batteries, offering the possibility to smooth out the intermittent power output. This can be a requirement from grid operators to keep the grid stable, but it is also important in off-grid applications to simultaneously ramp up gensets to avoid unnecessary power jumps.

3.8 Result

Batteries employed in the applications mentioned can offer diverse flexibility solutions while mitigating risks. They play a crucial role in integrating renewable energy sources, whether in small or large-scale projects, grid-connected or off-grid setups, ultimately contributing to the generation of emission-free electricity. Battery Energy Storage Systems, particularly those based on Li-Ion technology, have gained increasing interest due to their superior performance and energy density. Decentralized off-grid systems incorporating these advanced batteries are poised to make a significant contribution towards achieving Sustainable Development Goal 7 (SDG7) and electrifying communities worldwide.

4 CASE STUDY

The case study which is presented and analysed have a precise data record, it is only a cutout of a variety of systems and each system needs to be designed individually. The example should rather give the audience an idea of implementation design. To find representative case studies a questionnaire for EPCs (engineering, procurement and construction) has been created and subsequently distributed. Following the evaluation of the received questionnaires, the system integrators were requested to provide the necessary data.

Based on this data, systems were selected for analysis, considering the availability of data.

Table 4: Questionnaire to identify the case study

	Question
1	Name of the system
2	Size of the PV - hybrid system in kWp
3	Battery technology (e.g. NMC, LTO, LFP, Pb)
4	Type of the offgrid system (type of load e.g. mine, village)
5	Name of the battery manufacturer
6	Battery size nominal in kWh
7	Battery size usable in kWh
8	max battery inverter power kW
9	Maximum load in kW
10	Operation time of the System in years
11	System recommended for duplication
12	**Available Data: < 15min average values & min. 1 year time series**
12.1	Battery System (current, voltage, temperature, (SOC))
12.2	Solar irradiation, Solar power production
12.3	Diesel generator power production
12.4	ambient temperature, battery (room) temperature
12.5	load data
13	Block diagram of the system (single line)
14	picture of the system
15	Success factors of the System
16	Location of the system
17	Which end customers billing system exists (e.g. pay as you go, monthly fixed fee, take or pay)
18	O&M support from battery manufacturer available
19	Operation and maintainance plan in place

In Table 4 you can see the Questionnaire which was send around to the system integrators. The questionnaire has different questions on the characteristics and specifications of the system. The most important question of the questionnaire is the availability of data, which is important to analyse the systems. In total five different system integrators with a wide expertise gave us feedback on the questionnaire. After the evaluation of the questionnaire and the data, two “cases” were chosen.

Selected system:

The system is based in Haiti which lies in the tropical climate zone. Therefore, the system needs to sustain very warm climate. It is a standalone microgrid for a hospital based on a Li-ion battery combined with PV-plant and gensets. It will now be presented and thoroughly examined in terms of its usage.

4.1 System analysis: Haiti

The system is based in Haiti's Lower Artibonite Valley, at the Hôpital Albert Schweitzer Haiti (HAS Haiti), and was installed in partnership with the Swiss Partnership HAS Haiti (SPHASH). Due to the absence of a centralized electricity grid in Haiti, the hospital initially relied on four diesel generators for power.

The installed solar panels and batteries are now reducing the fuel costs by approximately 200,000 CHF per year. These savings are being redirected to enhance healthcare services for the local population. HAS Haiti is the only 24/7 full-service hospital in the region, providing 200 beds and serving over 350,000 people [10].

4.1.1 System description

Figure 6 represents the components of the power system that supplies the hospital. The system includes two PV fields with the power of 232 kWp and 210 kWp, respectively. These PV fields harness solar energy and convert it into electrical power to meet the energy requirements of the hospital. Each PV field is equipped with inverters that converts the direct current (DC) electricity generated by the PV panels into alternating current (AC) electricity. The inverters ensure compatibility with the hospital's electrical load and enable the utilization of solar-generated power. The system consists of four gensets, which are two units with a rated power of 200 kVA and two units with a rated power of 400 kVA.

The gensets serve as a backup power sources to supplement the electricity supply during periods of low solar irradiation or in the event of a failure of the PV, PV inverters or the battery system. They provide additional power to meet the hospital's energy demands. The system has two Li-ion BESS. The first BESS has a rated power of 200 kVA and a rated capacity of 224 kWh, while the second BESS has a

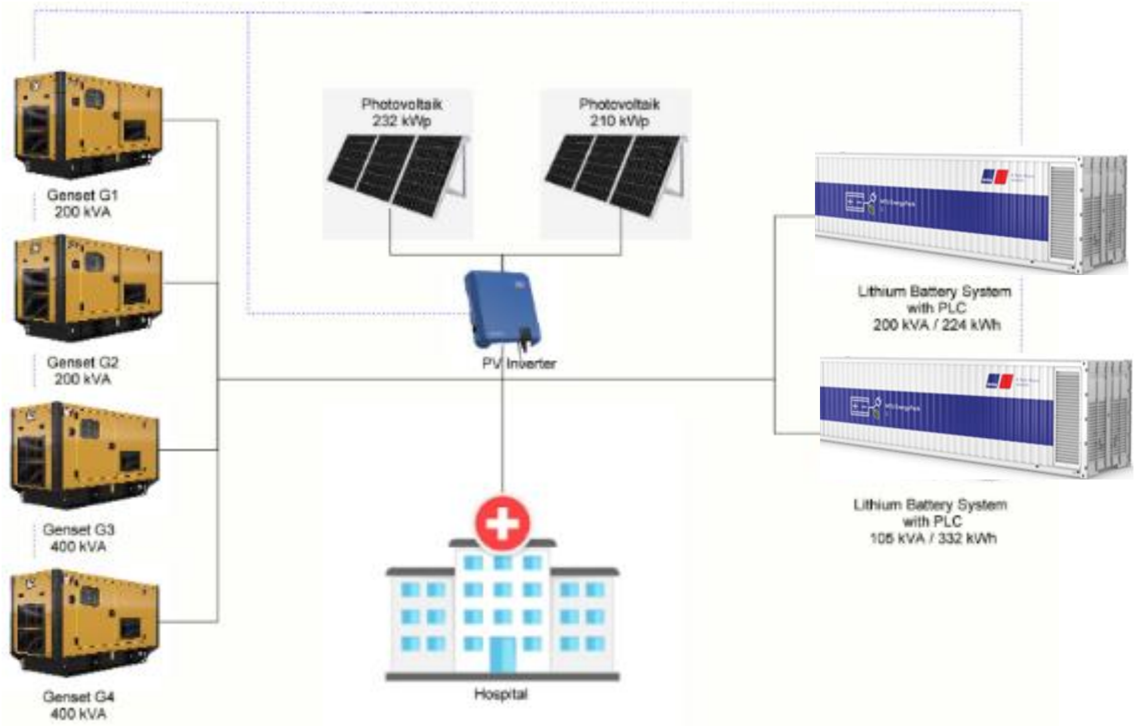


Figure 6: Block diagram of the system with the gensets, PV plant, inverters, BESS and Load.

rated power of 105 kVA and a rated capacity of 332 kWh. These BESS systems store excess energy generated by the PV generator and gensets. The latter ensure a reliable power supply during peak demand or when solar generation is insufficient. The power system also includes a communication system that enables centralized control and coordination of the various components. This guarantees a reliable communication between the PV fields, gensets, BESS systems, and other elements of the power infrastructure.

Figure 7: The installed PV plant on the roof of the clinic.

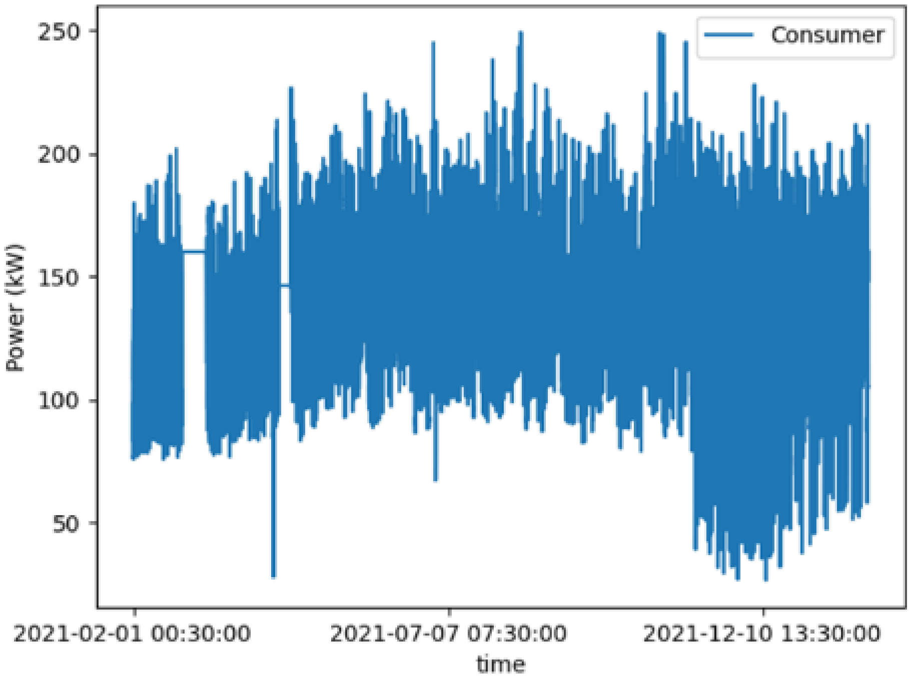
Figure 8: The four diesel genset of the off-grid system.

The system also includes a monitoring system that continuously tracks and assesses the performance and status of the components. This monitoring functionality enables real-time monitoring of energy generation, storage levels, and overall system health.

Figure 7: The BESS setup from the outside and the inside.

In Figure 8, the yearly load profile of the hospital is represented. The mean average load demand of the system is at around 130 kW. The load profile indicates the varying levels of active load, which represents the total power consumed by the hospital during different time periods. The graph displays the maximum active load of 250 kW, which represents the peak power demand of the hospital. This result in a maximum C-Rate for the battery of 0.44 C. On the other hand, the graph also shows the minimum active load of 25 kW.

Figure 8: Load profile of the off-grid system over a period of one year.



4.1.2 Analysis of the system

Figure 9 illustrates various components of an energy system and their interactions. The blue line represents the consumer's energy consumption, while the red line indicates the power generated by the genset and the green line represents power generated by the PV system. Additionally, the graph includes an orange line representing BESS, which is used for storing excess energy. The doted violet line represents the SOC of the battery.

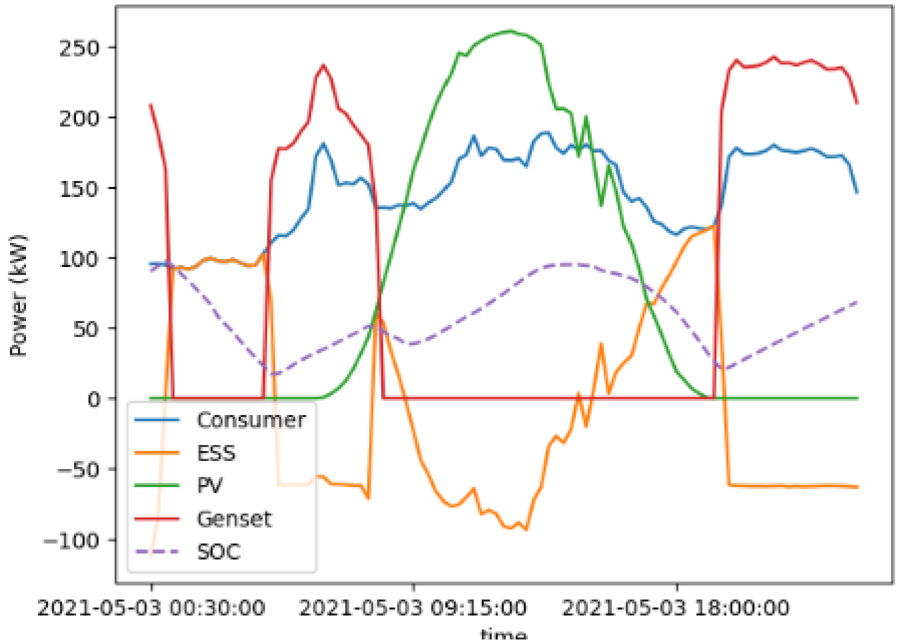


Figure 9: Load- source profile for one day with the additional SOC of the BESS

During the day, when the solar fraction is high, most of the PV energy supplies directly the load. The remaining produced energy is used to charge the battery, as shown by an increase in the SOC represented by the violet line. In the evening, when the solar generation decreases, the battery is discharged to meet the consumer's energy demand, as indicated by a decrease in the SOC.

The load, represented by the consumer's energy consumption (blue line), fluctuates between 100 kW and 200 kW throughout the observed day. If the battery's SOC falls below a certain threshold, the genset (red line) takes over to provide additional power and ensure a continuous supply of electricity and charges the battery.

Overall, Figure 9 demonstrates the dynamic nature of the energy system, with the PV system and battery working together to maximize the utilization of renewable energy sources and minimize the reliance on the genset.

Figure 11 displays the SOC of two battery storage systems. Both batteries are utilized in an identical manner, this means the SOC of BESS 1 (orange curve) overlay the identical SOC of BESS 2 (blue curve). The maximum SOC level is approximately 100 %, indicating that the batteries are fully charged, while the minimum SOC level is around 20 %, rarely 10% indicating a relatively low charge.

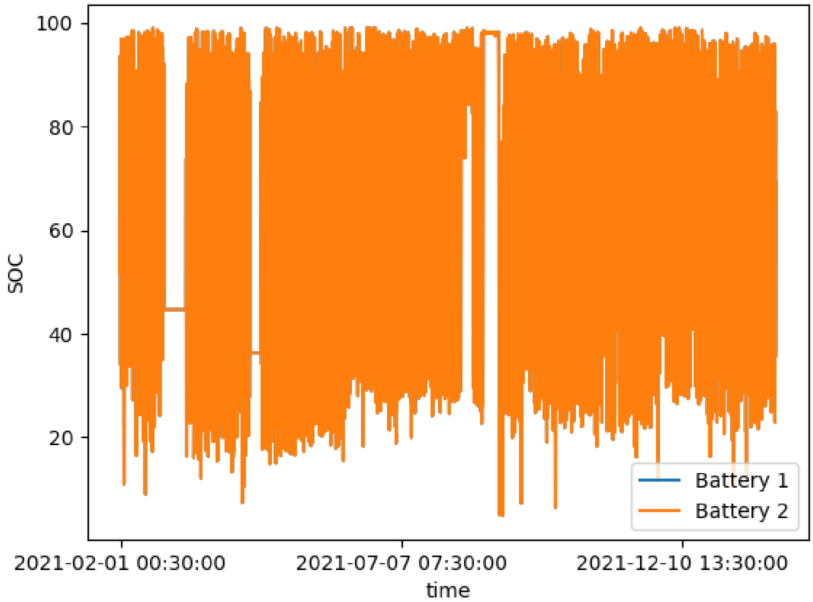


Figure 11: SOC over one year for both BESS.

Figure 10 demonstrates the grid frequency of the system, which is maintained at about 60 Hz. Throughout the one-year period, some measurement errors were observed. These errors may have caused minor deviations from the exact grid frequency. However, despite these errors, the graph clearly illustrates that the battery's contribution is instrumental in stabilizing the off-grid system. It helps maintain the frequency within an acceptable range, minimizing any significant deviations, this ensures that the electrical appliances and equipment connected to the system can operate efficiently and reliably.

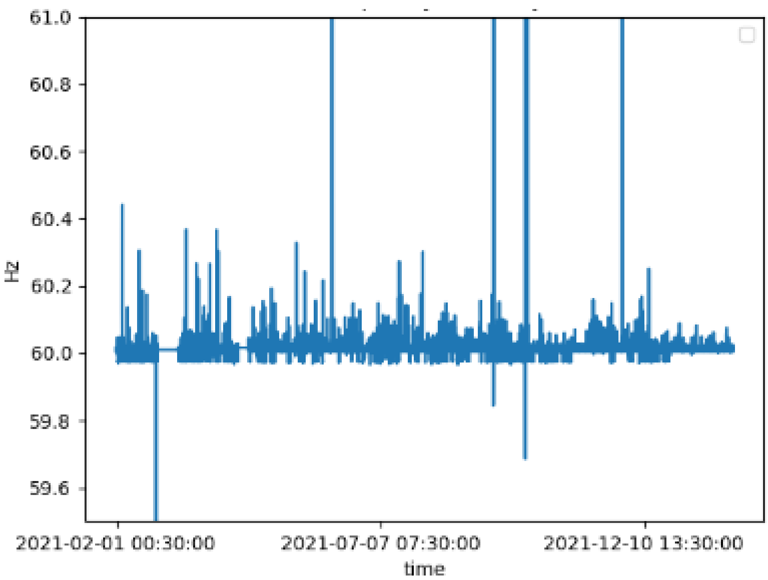


Figure 10: System frequency (60Hz) over a period of one

Classification of the case study

With the developed classification in chapter 2, the case study can be categorized. Therefore, the important parameters are calculated. With the results presented in, the system in Haiti can be assigned to the fourth class of off-grid systems.

Table 5: Classification of the system.

location	Haiti
Application /class	Hospital grid / 4
PVp size	442 kWp
Battery size	556 kWh
Genset size	1200 kVA
Final yield=Daily solar consumption/PVp	2.75
Usable battery energy/PVp	1.13
solar fraction	35%
Autonomy time	~ 3.83 hours
average discharge current	~ I_8 or C/8
Average cycle	deep cycles > one cycle a day
Summarized equivalent full cycles per year	460
SOC	~10 - 100%
Recommended battery	Li-Ion
Max. load power	249.1 kW
Performance Ratio PV	~80%

5 PERFORMANCE COMPARISON LI-ION VS. LEAD-ACID

The innovation in the battery sector brought a huge variety of different Li-ion batteries in a wide power and energy range to the market for nearly all kind of applications. Especially the automotive industry realizes a breakthrough into a new era of electrical mobility. Furthermore Li-ion batteries offer new possibilities in all kinds of stationary applications. Only three of these shall be mentioned here.

- Solar Home Batteries in family homes which are permanently connected to the grid support the installed PV system and lead to a respectable autonomy ratio of the house,

- Used automotive batteries are used in second life for Megawatt energy storages to support a local grid or to realize peak shaving for industrial applications,

- All kind of remote applications in PV off-grid areas can be powered by Li-ion batteries. This especially applies to the megawatt range.

5.1 Scope of work

This chapter shall look into PV off-grid systems world-wide. Such systems are installed in a wide power and application range. Especially the category 4 systems (Table) are in the focus of the considerations.

The basic idea of this chapter is to select several best practice systems installed in the field in different locations around the world. Detailed components data including financial boundary conditions need to be available. Monitoring data of the systems are required over a period of minimum one year. Based on this information a virtual twin of the systems was created in a suitable simulation environment. Once the simulation has been validated in a way that it reflects the performance of the real system any parameter variation can be performed to analyze the significance of the influence to the system behavior.

This virtual set-up shall be used to investigate the performance difference between Lead-acid and Li-ion batteries in the selected PV off-grid systems. In order to evaluate the simulation result performance criteria could be applied to the simulation outcome.

The most important performance criterion is the levelized cost of energy (LCOE) per kWh including all necessary investment, replacement, repair and maintenance costs.

5.2 Selected PV Hybrid Systems

Initially three systems have been selected for the performance evaluation. All are village power supply systems. One system is in Bolivia and two systems in Australia. One of the two Australian sites does not have a renewable system up to now but is powered by diesel generators.

5.2.1 Puerto Villazón, Bolivia

A PV Hybrid system in Bolivia has been selected to demonstrate a typical Village power supply system. It is located in Puerto Villazón Community, Municipio de Baures, Provincia Iténez del Departamento del Beni, in the Amazonas region of Bolivia, close to the border with Brazil. The access to the village and the system is very difficult.

Figure 12: Puerto Villazon Bolivia

5.2.1.1 General information

The village consists 95 households and covers an area of about 0.5 km x 1 km. The system to power this area consists of

- 156 kWp PV array on a ground-mounted structure with 15 deg tilt. The PV module model is Jinko JKM 330PP-72.
- 6 * 20 kW PV inverters, SMA Sunny Tripower 20000TL
- 15 * 6 kW battery inverters, SMA Sunny Island 8.0H-12.
- 624 kWh Li-Ion Battery, Tesvolt TS, with a nominal voltage of 48V and consisting of Samsung SDI Li-NMC cells.
- The existing 88 kVA Perkins diesel generator.
- SMA monitoring system.

Figure 13: Google maps photo of Pto. Vilazon

The system was installed in 2019, and at that time it was the biggest off-grid system with Li-ion batteries in South America. All relevant project information is available so that a digital model of the system could be built with HOMER PRO. The system was installed by an association between SIE (Bolivian EPC), MORA (Bolivian civil works contractor) and Trama Tecno Ambiental (Spanish engineering and consultancy firm) [11].

5.2.1.2 Puerto Villazon Load Profile

The load profile used for the simulations is from 1.1.2022 to 31.12.2022. The statistical load data can be seen in table 6.

Table 6: Load demands of the system.

Average Load	Peak demand	Daily demand	Average demand per household	Energy demand per household
23.2 kW	83.3 kW	556 kWh/d	240 W/household	5.8 kWh/(d*household)

Figure 14 shows the characteristics of the load profile. The average daily profile is a typical consumer load with a peak demand in the evening. The monthly profile shows no significant seasonal changes. This is not a summer or winter peaking profile, but very typical for many tropical locations around the world. The load histogram summarizes the information of the daily and seasonal profile. It shows that November to be an exception as the night load is very low while the day load is higher than the average. This is a result of corrective maintenance activities undertaken in the diesel generator.

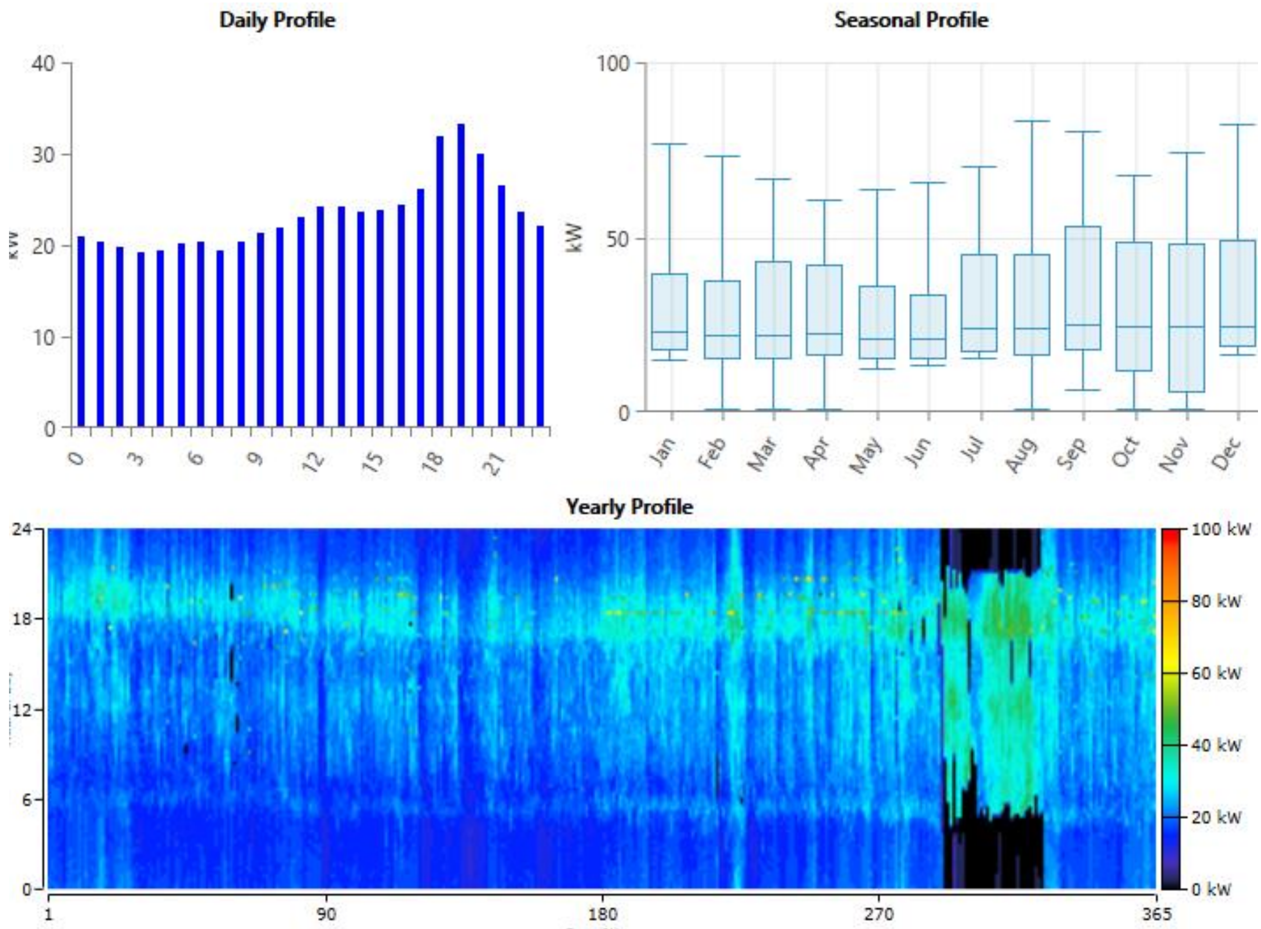


Figure 14: Pto Villazon Load Profile

5.2.1.3 Solar and wind resource data

The solar irradiation data have been taken from the Nasa database [12]. Figure 15 shows the solar profile of Puerto Villazon. The average irradiation is 4.93 kWh/m²/d. The wind data also come from the NASA database. The average is 2.38 m/s. This is within wind speed category I and a light breeze which is not suitable for the use of wind turbines in the system.

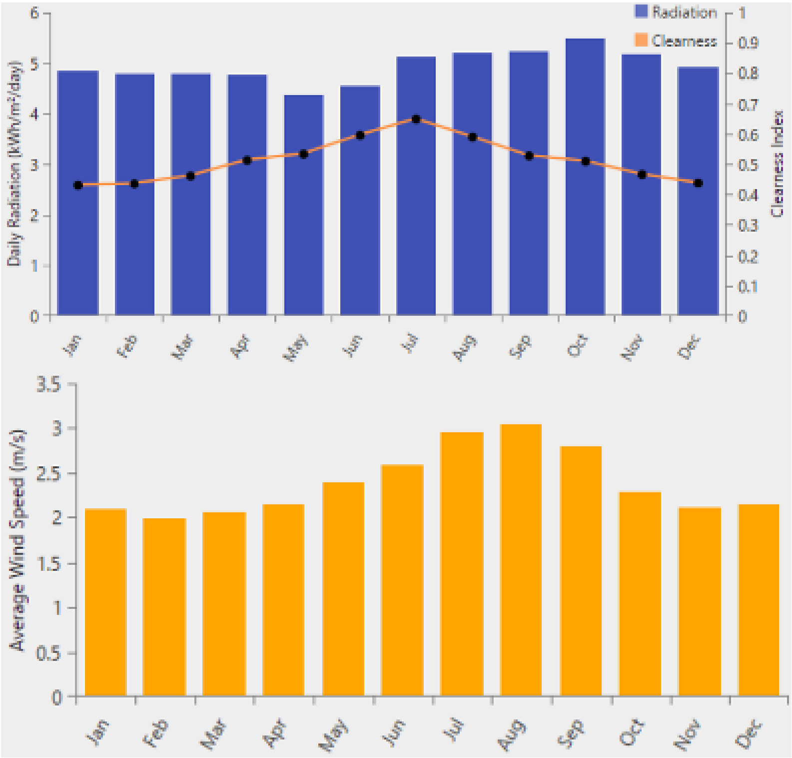


Figure 15: Solar and wind data Pto.Villazon

5.2.2 Daly River, Australia

Daly River is a remote area within the Northern Territory of Australia. The installed Microgrid supplies power to about 350 widespread households. Detailed information on the project can be found at [13].

The system consists of:

- 1 MWp Solar array
- 1.9 MWh, 800 kW Li-ion Battery
- 3 diesel generators
  460 kW, 580 kW, 800 kW
- 72.000 liter fuel storage
- Load Supply :
  - 9300 kWh/day
  - 3.394.500 kWh/year
  - 26 kWh/(d*household)

Figure 16: DalyRiver solar microgrid Photo by Amanda Byrd.

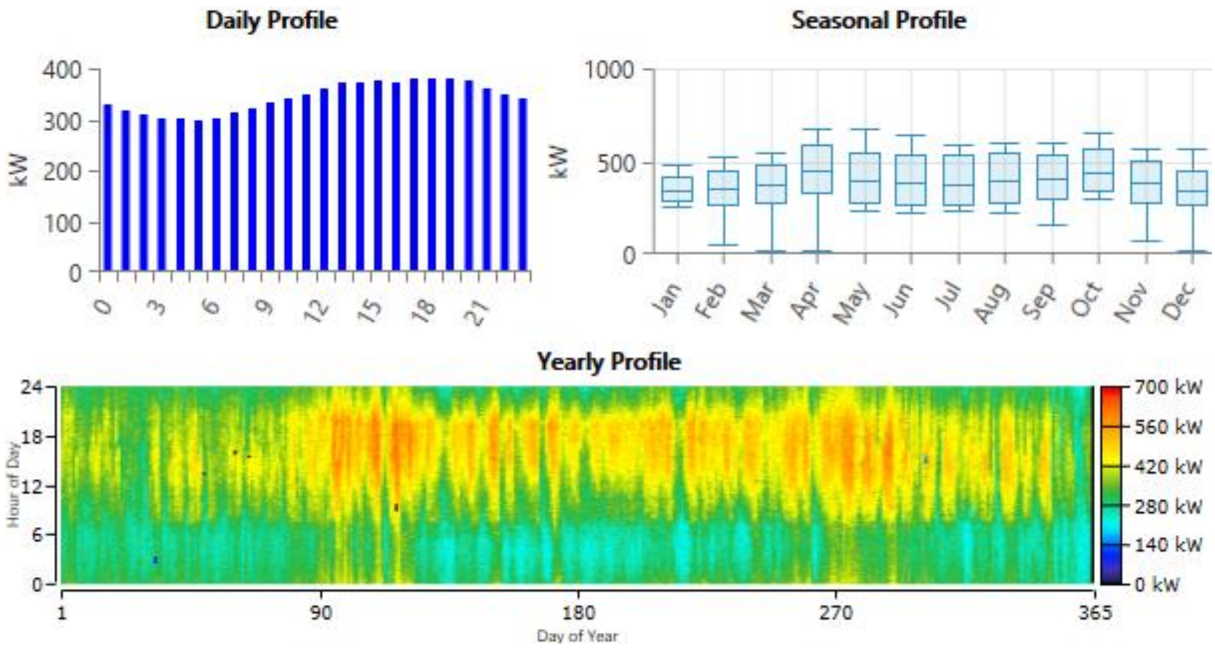


Figure 17: Load of DalyRiver.

A detailed report on the lessons learned of the DalyRiver microgrid was published and can be downloaded for free [14].

The DalyRiver load profile does not show the typical evening-peak. It is more equally distributed which is due to high air conditioning loads during the day.

As it is a desert location also the seasonal profile is quite equally distributed. Thanks to the Power Water Corporation (PWC), Australia which submitted the given data [15].

5.2.3 Mutitjulu Village NT, Australia

The Mutitjulu Village is located close to the famous Uluru National Park in the Northern Territory of Australia [16].

Figure 18: Mutitjulu location from GoogleMaps.

The power system is currently a diesel only generator while a solar and battery system shall be installed. Currently about 300 people life in the village.

The load shows the following characteristics:

- 4969 kWh/day
- 1.813.685 kWh/year
- 16.5 kWh/(d*household)

The profile of the load has a mid-day peak as well as a rather high load during the night.

The seasonal profile is quite equally distributed due to desert location.

Thanks to Ekistika from Alice Springs, Australia which submitted the information [17].

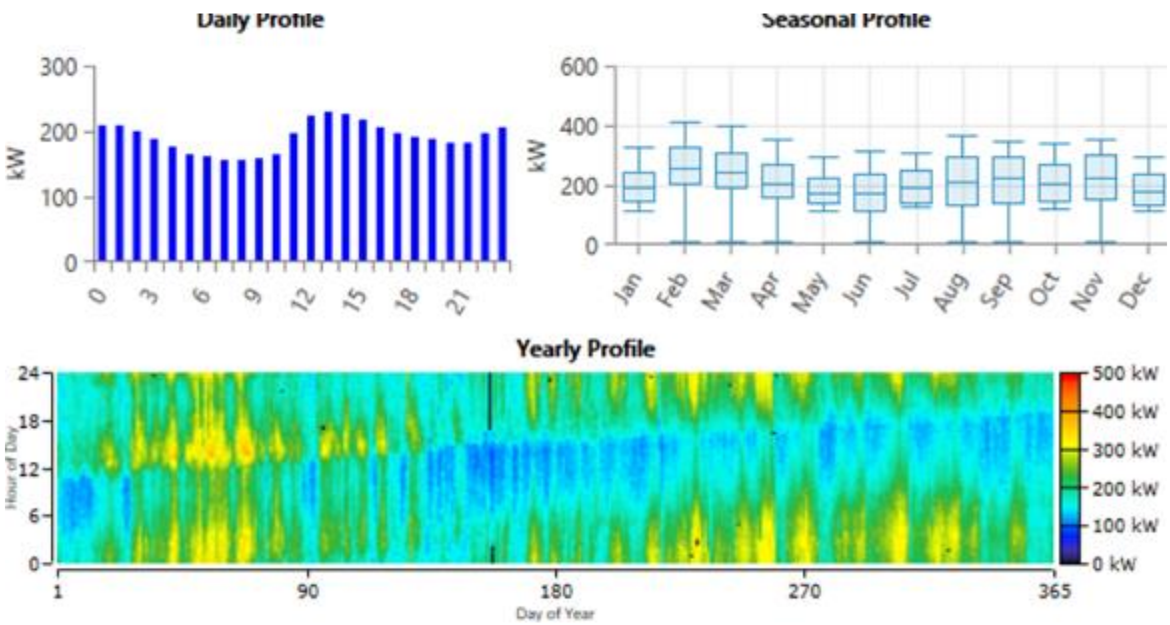


Figure 19: Mutitjulu Load Profile.

5.3 Simulations

Simulation calculations have been performed. The real life system with the existing load profile was put into the simulation environment. As the central simulation tool the HOMER Pro tool from homerenergy was used [18]. For each of the three described systems a digital twin was created within HOMER Pro. In a first step the HOMER Pro Optimization Algorithm had to size the systems. The results have been compared with the data provided from the field. After several modifications and optimizations, the digital model did reflect the reality. The results reflected the behavior and performance of the installed systems in the field. The simulations have been realized on the base of the topology of an AC coupled PV Hybrid System as it can be seen in Figure 20. The generation side consists of the AC coupled PV-array, one or more wind turbines and one or more diesel generators. Even though there is only low wind speed available at the sites the option was offered to the optimization algorithm. By scaling the load profile additional wind turbines might increase the efficiency of the system. The load is connected directly to the AC-bus.

Bidirectional power converters connect different types of batteries to the AC-bus. In order to analyze which type of battery performs best for a certain system configuration and location, three different battery types have been selected:

- As a reference battery, a typical Li-ion battery pack was selected for the usage in stationary applications. The Tesvolt TS HV70 was used as an example. It is a 77kWh storage and consists of 16 modules. Prismatic NMC cells from Samsung SDI are the base of the storage [19].

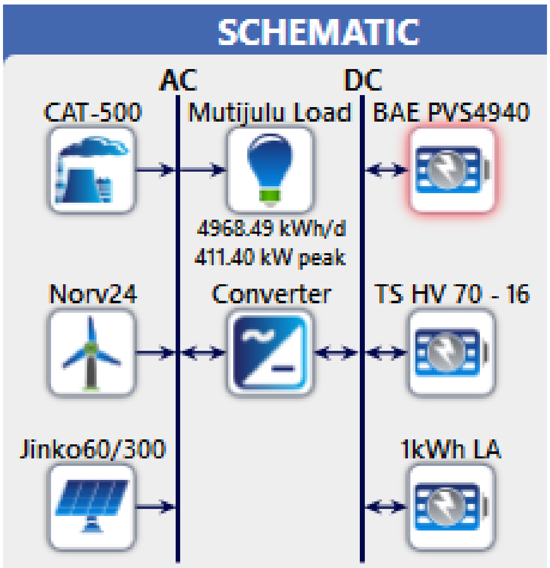


Figure 20: System Topology as an example from Mutijulu.

- A simple standard lead-acid battery with 12V@85Ah which reflects a 1 kWh storage. Such batteries are available world-wide at very attractive prices from many manufacturers and can be used to build big stationary battery banks.

- A high-end Lead-acid battery suitable for big stationary applications. Many manufacturers offer such cells. As an example, the BAE PVS4940 shall be used. It is a 2V cell with C_{10h} = 3480 Ah. One cell is a 7 kWh unit with dimensions of 215x580x815mm. Such a cell can be used to build a Lead-acid battery storage in the megawatt range.

5.3.1 Parameter variations

The key idea to perform the simulations is to configure several PV Hybrid Systems based on the load profiles and local conditions of the location. The Homer Pro system optimizer should then select the most cost-efficient battery setup for the given system design.

Based on a two parameters variation a two-dimensional optimization was realized.

The first parameter is the energy demand of the system. To use this as a parameter, the load profile was scaled according to the targeted annual energy consumption. The Parameter range was scaled from 1 kWh/d up to 5000 kWh/d for Puerto Villazón and Mutijulu. The DalyRiver load profile was scaled from 1 kWh/d up to 10000 kWh/d. This corresponds with an annual energy demand from 365 kWh/a up to 3650 MWh/a. This reflects a wide range of systems within all specified categories of systems.

The second parameter for the variation is the type of battery to be used. Either the described Li-ion storage or one of the two different lead-acid battery types could be selected by the Homer Pro optimization algorithm. The size of the batteries was optimized by Homer pro.

The optimization goal is a least cost net energy price over the defined lifetime of the system.

5.4 Boundary Conditions

The boundary conditions of the simulation are summarized in table 7. The baseline costs are indicated as average costs to be found by internet search in the year 2024.

Table 7: Simulation boundary conditions.

	Type	Power	Costs	Lifetime
PV array	Standard PV module 60 monocrystalline PERC cells	300 Wp	900.- €/kWp including mounting structure and installation	30 years
Wind turbine	Standard wind turbine with 36 m high hub	100 kW	300.000.- € including installation	20 years
Diesel generator	Standard generator	Scalable	1000.- €/kW capital c. 20.- €/h operating hour 1.20 €/liter diesel	40.000 op.hours
Power converter	Standard bidirectional inverters	Scalable	500.- €/kW	15 years
Low cost Lead-acid battery	Standard Lead-acid 12 V@85 Ah battery	Scalable 1 kWh	90.- € /kWh	600 kWh throughput
High end Lead-acid battery	BAE PVS4940 block 2 V@4630 Ah	Scalable 9.3 kWh	170.- €/kWh	1000 kWh throughput
Li-ion storage	TS HV70 800 V@77 kWh battery	Scalable 77 kWh	650.- €/kWh	280000 kWh throughput

5.5 Simulation Results

The simulations have been realized under the parameters described in the boundary conditions chapter. For all three described systems, a digital twin was created. All three systems parameter variation simulations have been done. For each parameter value in each system the optimization algorithm calculated the component sizes of the least cost system.

5.5.1 Description of the simulations

The results of the simulations are displayed in a colored graph which indicates a 3-dimensional output. Such an output comes with 3 axis, x- y- and z-axis. Each axis represents a specific parameter:

- The x-axis reflects the price of the battery system. This axis shows a relative price relation function such as actual price divided by nominal price. The calculation incorporates relative price functions for both the Li-ion and the Lead-acid battery as it is defined in the boundary conditions. The price of the small simple 1 kWh lead acid battery is fixed in the simulation. The price of the high-end Lead-acid 2V at 3500 Ah block is also fixed. Therefore the price relation between the low-cost and the high-end Lead-acid battery is also fixed.

The idea behind fixing these prices is the assumption that the price- and technology changes in the field of Lead-acid batteries is rather small compared to the changes in the field of Li-Ion storages. Furthermore, the market size of Lead-acid batteries is fluctuating, but mainly it is an existing well-established market with selling, support and recycling infrastructure.
The applied price of the Li-ion storage is defined in the boundary conditions and reflects the actual market situation. This price is put under the scheme of a sensitivity variable to modify the parameter. The x-axis value reflects this price. The applied range is from 0.2 up to 1.2. A value of 1 means the price of the Li-ion storage of today is applied. A factor of 0.5 in the x-axis means half of the Li-ion price of today is applied to the simulation. The lower the factor the cheaper the price assumption of the Li-ion storages. The price of the lead-acid batteries always remains on the same level.
With this mechanism, it is possible to evaluate in which way the system design is changing if the prices of Li-ion batteries drop down significantly.

- The y-axis describes the size of the system. This parameter is also a sensitivity variable, and it is applied by scaling the annual energy demand of the system based on the load profile implemented into the system. The energy demand is displayed as values of [kWh/d]. The applied range is from 1 kWh/d up to 10000 kWh/d. Through this, the y-axis reflects the size of the load in the shape of the applied load profile.

- The z-axis shows the result and indicates the cheapest system design. The color of the graph indicates the type of the system. Generally, all green shaded colors indicates the usage of a Li-ion storage while all blue/purple shaded colors reflect the usage of Lead-acid batteries. All blue shaded colors show that the low-cost 1 kWh batteries are applied, while purple colors show the usage of the high end 2V / 3500 Ah block.
The color shapes indicate the type of system. A color table can be seen in table 8. Pure PV-Battery system is light color, a PV-Battery-Diesel genset as standard PV-Hybrid system is normal color shape and the PV-Battery-Diesel genset + Wind turbine system the dark color mode.

Table 8: System type colors.

	PV + Battery	PV + Battery + Diesel	PV + Battery + Diesel + Wind
Li-ion	Light green	Green	Dark green
Lead-acid low	Light blue	Blue	Dark blue
Lead-acid high	Light purple	Purple	Dark purple

5.5.2 Results for Puerto Villazón

The result for Puerto Villazón can be seen in figure 21:

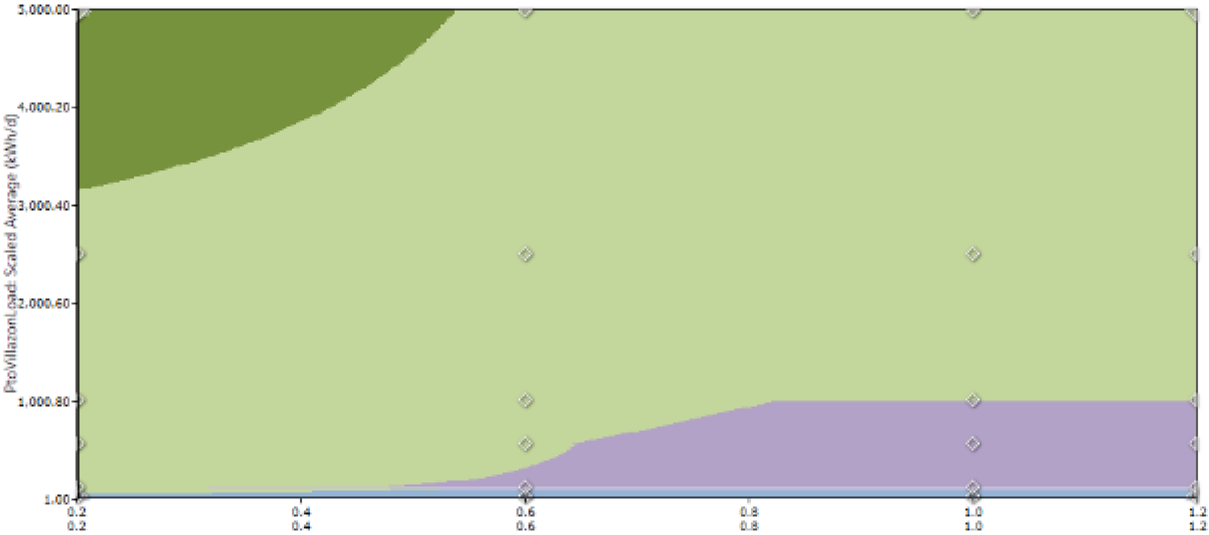


Figure 21: Puerto Villazón result.

The result for Puerto Villazón in Figure 21 shows mainly 4 areas:

- A blue area in the bottom of the figure reflects a standard PV-Hybrid System with diesel generator and a low-cost Lead-acid battery. The area is small and flat over the whole price range. Small systems nearly independent from the battery price can be realized with low-cost Lead-acid batteries,

- A purple area between the price factor of 0.6 up to 1.2 and system sizes up to 1000kWh/d. Such system can be built with a PV Hybrid system including Diesel based on high end big size Lead-acid batteries,

- A green area covers most of the graph and shows that this system can be realised in a wide parameter range with the help of PV Hybrid System with diesel generator and Li-Ion battery storages,

- A dark green area in the left upper corner reflects very big systems. In this area additionally to the PV Hybrid System with Li-Ion battery a wind turbine shall be installed.

5.5.3 Results for DalyRiver

The Daly River system can be seen in Figure 22.

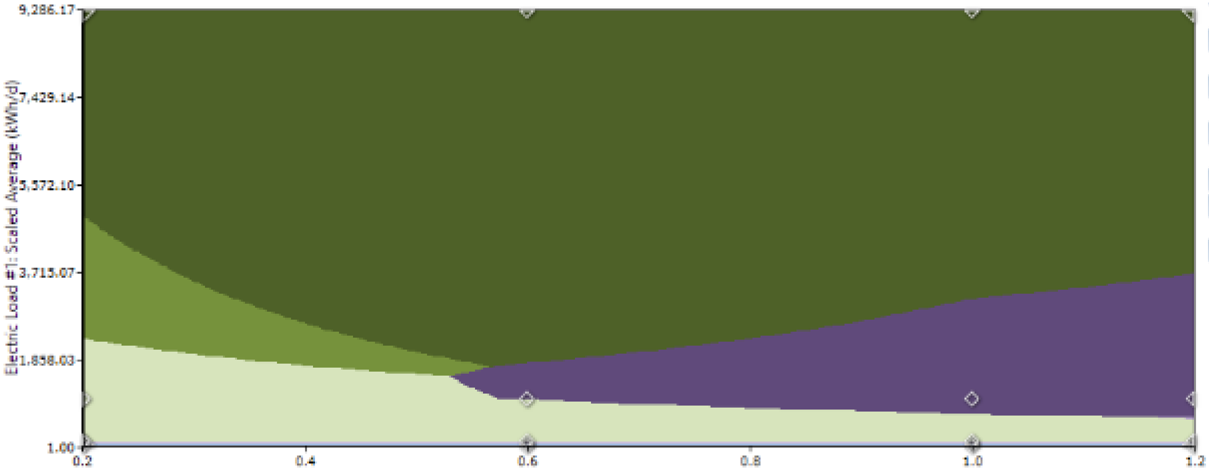


Figure 22: DalyRiver result.

The result for Daly River can summarized as follows:

- The very small systems, nearly not visible in the picture up to about 50 kWh/d can be realised with low-cost Lead-acid batteries,
- A pure PV Li-ion battery system (light green color) dominates the system design up to 1100 kWh/d load demand at very low Li-ion prices and up to about 400 kWh/d at high Li-ion prices,
- A PV-Wind Diesel Hybrid system with high end Lead-acid batteries (dark purple) is feasible at high Li-ion prices up to about the half of the actual Li-ion battery price. At high Li-ion prices up to 3500 kWh/d and at low Li-ion prices up to 1800 kWh/d,
- At very low Lithium prices the PV Hybrid system with Diesel and Li-ion battery is feasible up to 5000 kWh/d,
- All other systems up to 10000 kWh/d are most efficient with a PV-Wind-Diesel Hybrid system based on Li-ion storages regardless the price of Li-ion storages.

5.5.4 Results for Mutijulu Village

The Mutijulu Village simulation shows the following result in Figure 23:

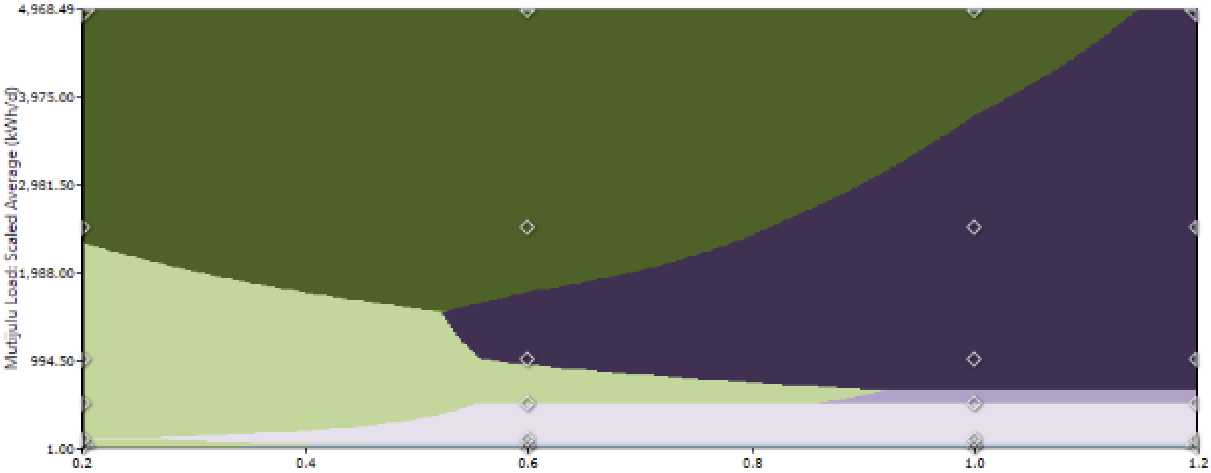


Figure 23: Mutijulu result.

The result for Mutijulu shows:

- The very small systems up to about 50 kWh/d (blue) can be done with low-cost Lead-acid batteries in a PV-Diesel Hybrid System (light blue). This is difficult to see in in Figure 23 as it is only an extremely thin line in the very bottom of the graph.

- High end Lead-acid batteries can support up to 5000 kWh/d systems as long as the Li-ion prices are not less than half of the price defined in the boundary conditions. The higher the load demand the more generating sources should join the systems:

    - Up to about 500 kWh/d a pure PV battery system (light purple),
    - Up to about 750 kWh/d a PV battery and diesel generator system (purple),
    - Up to about 5000 kWh/d a PV-Wind-Diesel Hybrid system (dark purple).

- Li-ion batteries dominate all systems if the prices are less than half of the defined prices in the boundary conditions.

    - Up to about 2000 kWh/d pure PV battery systems (light green),
    - Above about 2000 kWh/d with PV-Wind-Diesel Hybrid Systems (dark green).

5.6 Recommendations

The result can be summarised over these three system simulations:

- PV off-grid Microgrids with an energy demand up to about 50 kWh/day can be realised with low-cost Lead-acid batteries in a pure PV battery system or typically with a generator.

- PV off-grid Minigrids up to about a maximum of 5000 kWh/day can run with high end lead-acid batteries if enough additional generators like wind-turbines and diesel generators are applied. There is a need to make sure the battery energy throughput is limited and most of the load is supplied directly from one of the generators.

- Once the price of Li-ion batteries is about half of the applied normalized price from June 2024 in the defined boundary conditions all systems can be very efficiently supported by Li-ion batteries.

    - Smaller systems up to about 2000 kWh/d with PV-battery systems without additional gensets
    - Midsize systems up to about 4000 kWh/d with PV-Diesel Hybrid systems,
    - Big systems up to about 10000 kWh/d load demand with the help of PV-Wind-Diesel Hybrid systems if enough wind resource is available.

6 FACTORS FOR SUCCESSFUL OPERATION

There is always an overall goal or need to install a BESS into a PV off-grid system and a successful operation is achieved if these goals are met. Unfortunately, those requirements are often not clear in the beginning or the design assumptions change at a later stage and therefor during operation the design criteria need to be considered. Therefore, it is highly project-specific, and its operational success hinges on the thoroughness of the needs assessment and design work, which enable the operation teams to effectively operate the PV off-grid system, as depicted in Figure 1. Of course, over-performance might be required to meet expectations, but cost considerations are also limiting the ideal operation and it is often the reason for failing systems or limits in the operation.

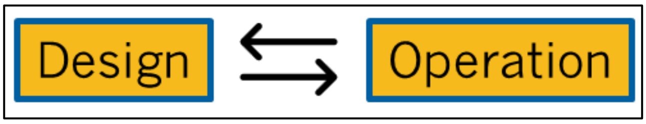


Figure 24: Interchangeable success between Design and Operation

This chapter explains the factors that affect the successful operation of an off-grid PV system, and the considerations are divided into the early needs assessment and design phase, the implementation phase and finally the operation phase.

A comprehensive approach that goes beyond technical specifications is required to design a robust off-grid PV system. Priority is given to reliability, resilience and component selection based on proven performance and regulatory compliance, with redundancy incorporated where appropriate. Efficiency, scalability and ease of maintenance are essential, as are the seamless integration of the components and environmental considerations. Cost effectiveness, and a social, economic and organizational framework [20] adapted to local conditions are also critical to long-term success.

Optimal operational practices, including charge/discharge patterns and temperature management, are emphasised for system longevity. Regular monitoring, particularly of battery health, and user training are also essential. In addition, adaptive management strategies ensure continued efficiency as conditions change.

Finally, addressing end-of-life concerns involves planning for the time after the active operation of the off-grid PV system, including comprehensive decommissioning, dismantling of components and safe disposal of materials. Particular attention is paid to environmentally sound recycling, especially for Li-ion batteries, and compliance with local regulations.

6.1 Design

Designing an effective and efficient Li-ion battery system for photovoltaic (PV) off-grid solutions is a multifaceted process that demands careful consideration of various factors. This section delves into the critical aspects of load evaluation, sizing and lifetime expectations, technological selection, and electrical design.

6.1.1 Load evaluation / need-assessment

In the design phase, focus is not only on load evaluation but also on defining the application precisely. The application scope of an off-grid PV system spans practical use beyond technical aspects, serving remote communities, communication networks, research facilities and other remote loads. Tailoring the system's design to these applications involves understanding diverse energy needs, usage patterns, and critical performance parameters influencing decisions. An analysis of energy consumption and load requirements, using historical data, aids in accurately estimating expected loads. This information is pivotal for sizing Li-ion batteries and determining system capacity to reliably meet energy demands without overload or underperformance.

6.1.2 Pre-condition / location / Environmental conditions

To design an off-grid PV systems a careful examination of the multiple environmental factors that are critical to optimal system performance need to be conducted. Solar irradiance is of utmost importance, with high irradiance areas being sought to maximise the energy output of the PV panels. Conversely, extreme temperature fluctuations have a significant impact on the performance and longevity of Li-ion batteries. In addition, altitude and proximity to seawater introduce nuanced complexities that influence atmospheric conditions and require specialised protection measures.

When assessing the risk of impact in areas such as nature reserves or high-risk regions, it's important to consider how the installation or operation of the system may affect these sensitive locations. For example, the installation of off-grid PV systems in conservation areas may require compliance with specific environmental regulations to mitigate disruption to local ecosystems. Similarly, in high-risk areas prone to natural disasters, additional protective measures may be required to protect both the system and the surrounding environment.

In addition, the presence or easy access of qualified personnel on site is essential for timely maintenance and troubleshooting, minimising technical problems and ensuring smooth system operation. If the remote side is not easily accessible, design considerations (e.g. redundancy) need to be considered. Equally important is a reliable Internet connection to facilitate remote monitoring and rapid response to system problems or emergencies.

6.1.3 Sizing / lifetime expectations

The focus now shifts to sizing considerations and establishing lifetime expectations. This involves accurately determining the capacity of components, such as PV panels, electronics and Li-Ion batteries, to meet identified load requirements. Sizing decisions are crucial for optimizing energy generation, storage, and distribution within the off-grid PV system.

Determining the appropriate sizing of Li-ion batteries is fundamental in off-grid PV systems. This process involves calculating the storage capacity required to effectively contain the excess energy generated by the PV panels, particularly during peak solar periods. Accurate sizing is critical to ensure that the batteries have sufficient capacity to meet the energy requirements of the application, especially in scenarios with limited or no sunlight. Emphasizing autonomy is a key objective to reduce reliance on external sources such as diesel generators, especially during periods of low renewable energy availability or system maintenance.

The following factors that are also explained in Chapter 3.4.1 need to be considered:

- DoD
- Number of Cycles
- C-rate

Concurrently, attention is given to setting realistic lifetime expectations, particularly in the BESS warranties and their associated conditions. This includes a careful examination of warranty terms, considering factors like cycle life, depth of discharge capabilities, and the manufacturer's stipulations. The interplay between sizing decisions, oversizing considerations, and lifetime expectations ensures that the design aligns with both performance goals and warranty conditions, promoting a robust and reliable off-grid PV system.

These principles form the basis of a robust and efficient off-grid PV system design philosophy.

6.1.4 Selection of technology / supplier

The success of an off-grid photovoltaic system hinges on a comprehensive evaluation of available suppliers and technologies. This assessment prioritizes technology reliability, scrutinizing its performance history, durability, and adaptability to various conditions. Additionally, ensuring the reliability and accessibility of technical support from chosen suppliers is crucial for swift issue resolution, safeguarding continuous system operation. Portability considerations are vital, particularly for systems requiring mobility or reconfiguration.

The functional compatibility of components from different manufacturers should be verified, particularly in conjunction with Li-ion batteries, and obtaining approval from all parties involved will ensure warranty. It also requires careful selection and adaptation of the appropriate charging/discharging algorithm. Charge controllers oversee the charging process while preventing potential issues such as overcharging or over-discharging, ensuring the system's stable performance. Likewise, selecting a pure sine wave inverter is crucial to guarantee compliance with sensitive electronics. In addition, tailoring the system to specific applications, such as the Integrated Energy Storage and Multimode Inverter solution, is vital. This mitigates the risks associated with potential mismatches between equipment and application requirements, such as the inverter's efficiency curve not matching the load profile or the battery technology not meeting the desired DOD. The success of these components lies in their seamless integration with the BMS, facilitating robust communication and control mechanisms, thus reducing potential system failure points (e.g. inaccurate readings or improper voltage regulation) and optimizing overall performance.

Different Li-ion chemistries e.g., lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC) (see chapter 3) have varying characteristics, and are directly impacting factors like energy density, lifespan, safety, and performance under varying environmental conditions. LFP batteries are known for their robust safety features, longer lifespan, and enhanced thermal stability, making them less prone to thermal runaway. On the other hand, NMC batteries typically offer higher energy density, providing greater energy storage capacity in comparison to LFP batteries. Hence, choosing the appropriate Li-ion chemistry aligned with the specific requirements of the off-grid PV system is crucial to optimize its functionality, safety, and longevity.

Following product selection, simulations can be instrumental in reevaluating the system design. This process might entail modifications to accommodate precise product specifications, ensuring seamless integration and compatibility among selected components. Simulations offer a proactive approach, allowing the identification of potential constraints that may have surfaced during product selection. By incorporating simulation tools, the design can be refined to tackle these issues while aligning with the overarching objectives of the off-grid PV system.

6.1.5 Electrical design

In exploring the complexities of electrical design, particular emphasis is placed on the DC bus voltage. This exploration extends to the impact of this design decision on the overall system, with a particular focus on its direct influence on the availability and efficiency of the technology, regardless of the specific type. The exploration delves into the intricacies of optimising the electrical design to suit the specific characteristics and requirements of the chosen energy storage technology. Factors such as voltage levels, power conversion efficiency and system stability are carefully examined to ensure that the electrical design utilises the full potential of the chosen technology within the broader context of the off-grid PV system.

Another aspect is the safety of the O&M personnel: with low voltage systems (<60VDC), there is no risk of electric shock, while high voltage systems (typically 120-1500VDC) require specially trained personnel and equipment.

6.1.6 General setup

Expanding the perspective to the general setup of the off-grid PV system, various crucial aspects are addressed. Examining strategies for effective cooling mechanisms is pivotal in maintaining optimal operating temperatures for system components, thereby mitigating the risk of overheating and performance degradation. Environmental influences, including weather conditions and climate variations, are assessed and protective measures are implemented to safeguard the system. Remote monitoring systems that provide real-time insight into the operation and health of the off-grid PV system are installed. Consideration is given to the housing, enclosure and racking of the BESS. Strategic placement of the BESS is critical, with fire risk mitigation and compliance with safety protocols a priority. Careful planning minimises fire risks and ensures compliance with safety regulations. In flood-prone regions, waterways must be carefully assessed to avoid vulnerable locations that could be damaged by water during BESS installation.

6.2 Implementation

This sub-chapter explores the crucial phase of implementing Li-ion batteries in PV off-grid systems. It covers the essential steps of transportation, installation, testing, commissioning, and training, emphasizing their collective impact on the system's functionality and longevity.

6.2.1 Transportation

In the transportation phase, strategic planning is imperative to facilitate the safe and efficient movement of Li-ion stationary batteries to the respective location.

Transporting Li-ion batteries safely demands a rigorous logistics assessment involving reputable transport providers skilled in handling the sensitive nature of the batteries. Compliance with safety regulations governing the transportation of hazardous materials is a non-negotiable aspect, ensuring adherence to legal requirements, see UN 3480 and 3481 and must fulfill the requirements of the “UN manual of tests and criteria chapter 38.3” which is internationally described in IEC 62281.

Packaging requirements assume great significance, demanding robust and protective packaging to shield the batteries from potential damage during transit. Special attention is paid to safety measures during transportation, emphasizing secure fastening of batteries to prevent movement, proper labelling of packages to communicate their hazardous nature, and establishing clear emergency response protocols in case of unforeseen incidents. This holistic approach to transportation ensures the integrity of Li-ion batteries upon arrival at the designated off-grid PV system location.

Additionally, prolonged transport, particularly to distant locations like Africa, may necessitate recharging Li-ion batteries due to extended periods without immediate installation. The duration and impact of this situation can vary depending on warranty conditions. Transport and waiting times, including customs clearance and associated challenges, further compound the issue. In extremely remote areas, transporting, installing, and maintaining Li-ion batteries becomes even more challenging. It's important to consider calendric aging that is discussed in chapter 3.4 in such scenarios, which can affect the batteries' performance over time.

6.2.2 Training

In the training phase, the focus shifts first to the installers who will proficiently set up Li-ion stationary batteries within the off-grid PV system. The focus then shifts to operators and maintenance personnel, providing them with the knowledge and skills necessary for efficient system operation and maintenance.

This comprehensive training includes guidance on system operation and routine maintenance procedures, covering essential procedures for starting and stopping, interpreting system indicators and developing troubleshooting skills to quickly resolve common problems. In addition, the training covers ancillary equipment such as air conditioning and fire detection and suppression systems, ensuring that personnel are well prepared to manage all facets of the system's functionality and to deal with emergencies and potential hazards associated with Li-ion batteries.

By ensuring that personnel are well prepared and competent, the training phase contributes significantly to the ongoing reliability and successful operation of the off-grid PV system.

6.2.3 Installation

Ensuring proper ventilation is then essential to prepare the site properly. The installation of Li-ion batteries requires careful spacing, secure anchoring, and adherence to safety guidelines. Careful handling of Li-ion batteries is of the utmost importance, yet many problems arise from improper installation methods. Even skilled installers, fatigued after long days in harsh environments, can inadvertently make mistakes. Mishandling of batteries during installation often results in mistakes such as incorrect wiring connections, inadequate insulation, or inadequate securing of the batteries in their housings or racks. These mistakes can lead to operational inefficiencies, safety hazards, or even premature battery degradation. Given the sensitivity of Li-ion batteries to environmental conditions and their intricate design, installation errors can have a significant impact on the overall performance and longevity of the off-grid PV system.

6.2.4 Testing

Following the installation verification, the focus shifts to capacity testing, a process that evaluates the actual energy storage capacity of Li-ion batteries against the manufacturer's specifications. Voltage checks to ensure that both individual cells and the entire battery pack are operating within specified voltage ranges, usually monitored by the BMS, are equally important. In addition, diagnostic techniques such as thermal imaging are used at this stage to identify potential problems that could affect battery performance. Through these rigorous testing protocols, any anomalies or deviations are identified and addressed, ensuring the reliability and efficiency of the energy storage system.

6.2.5 Commissioning

Upon successful testing, the commissioning phase begins, representing the formal initiation of Li-ion stationary batteries into the operational fabric of the off-grid PV system. This phase involves configuring specific settings on the BMS or other control systems, ensuring that parameters match precisely with the system requirements. Simultaneously, a particular validation process is undertaken to ensure seamless communication interfaces between Li-ion batteries and other components of the PV system. This step is critical for the cohesive integration of the batteries into the broader energy storage system, paving the way for their reliable contribution to the overall functionality of the off-grid PV system.

6.3 Operation

Operating Li-ion battery systems in off-grid photovoltaic (PV) environments requires a sophisticated understanding of the factors that influence their efficiency and lifetime. This chapter explores the intricacies of ensuring successful, reliable, and sustainable operations. From user training and awareness to system sizing and technology selection, the chapter highlights the importance of key considerations in maximizing the potential. It looks at operational strategies that determine the life of the system, addressing issues as maintenance, remote monitoring, temperature regulation, safety protocols, and regulatory compliance.

6.3.1 Maintenance

Understanding the purported "maintenance-free" status of Li-Ion stationary batteries is a nuanced exploration. While celebrated for lower maintenance needs compared to traditional counterparts, deeming them entirely maintenance-free is a misconception. Recognizing this, it becomes apparent that ongoing oversight and periodic checks are essential, dispelling the myth and guiding users toward proactive measures for the battery system's longevity and optimal performance.

Ensuring the proper qualification and certification of manufacturer-approved personnel is essential for the maintenance of Li-ion systems due to their more complex technology compared to Lead-acid batteries. Building on this understanding, the discussion delves into specific facets of low-maintenance considerations for Li-ion batteries. Simultaneously, a reminder surfaces regarding the significance of adhering to manufacturer guidelines and periodic inspections, underscoring that despite reduced maintenance, a diligent approach remains integral for sustained reliability and performance. In the absence of remote monitoring, maintenance tasks are to be executed locally, requiring on-site personnel to conduct regular inspections, performance assessments, and necessary activities.

In light of these considerations, the transition moves seamlessly to implementing a structured maintenance schedule for Li-ion battery systems. This pivotal step introduces a methodical approach to routine checks, including a focus on scrutinizing for loose connections during regular inspections. The emphasis is on addressing potential issues proactively to prevent their escalation. Additionally, strict adherence to manufacturer recommendations for maintenance and timely component replacement becomes intrinsic to this maintenance narrative, reinforcing the commitment to preserving optimal operating conditions.

Beyond the batteries themselves, the focus shifts to support systems, particularly cooling systems, which are critical to regulating Li-ion battery temperatures. Detailed maintenance protocols emphasise regular checks, cleaning and troubleshooting for cooling systems. Technicians also ensure the functionality of fire suppression systems, including adequate charging and positioning for effective use in the event of a fire.

This holistic approach recognizes the interdependence between batteries and their infrastructure, highlighting the importance of a comprehensive strategy to ensure the PV off-grid system's sustained success.

6.3.2 Remote monitoring

In the dynamic landscape of off-grid PV systems, remote monitoring plays a key role in ensuring the health and efficiency of stationary Li-ion batteries. This section explores the multifaceted aspects of remote monitoring and its role in advancing system analysis and maintenance practices. If remote monitoring is not possible, the following tasks are to be executed locally, requiring trained on-site personnel or external personal which travel regularly and on demand to the site.

6.3.2.1 Intra-system Communication (Batteries – BMS – Inverter)

Any interruption in intra-system communication can lead to inefficiencies and system downtime, as components such as batteries, BMS and inverters rely on seamless communication to coordinate operations effectively. With a robust Internet connection, continuous monitoring and management of the batteries is possible, ensuring optimum performance and early detection of any issues that may arise as they require increased remote monitoring by the BMS.

6.3.2.2 Advanced Battery Analysis

Remote monitoring transcends traditional oversight, offering a sophisticated lens into the intricate dynamics of Li-ion batteries. Advanced battery analysis becomes a cornerstone of this capability, providing real-time insights into the performance metrics of individual cells and the overall battery pack.

From voltage levels to discharge rates, this level of granularity allows for a nuanced understanding of battery behaviour. The transformative power of advanced battery analysis empowers users to make informed decisions, identify potential issues pre-emptively, and optimize system performance based on real-time data.

6.3.2.3 Early Alarming Systems

One of the key benefits of remote monitoring is its ability to act as an early warning system. Remote monitoring can quickly detect anomalies or deviations from expected behaviour, acting as a vigilant guardian. Whether it's an unexpected voltage drop or irregular charging patterns, early warning systems are critical in mitigating potential risks by providing timely alerts that enable users to take proactive action. This aspect highlights the importance of early warning in preventing potential faults and ensuring the integrity of the Li-ion battery system.

6.3.2.4 Predictive Maintenance

Remote monitoring exceeds reactive measures, paving the way for a paradigm shift toward predictive maintenance strategies. By harnessing the wealth of data generated through continuous monitoring, predictive maintenance becomes a reality. This aspect explores how predictive algorithms can anticipate potential failures or performance degradation, allowing for interventions before issues manifest. Predictive maintenance not only minimizes downtime but also extends the lifespan of Li-ion batteries by addressing concerns at their nascent stages. This includes checking the operation of the overvoltage and overcurrent protection systems, confirming that all batteries are communicating properly with the BMS, visually inspecting cables for any defects or cracks, ensuring that cooling systems are functioning and confirming that fire detection and suppression systems are operating correctly. The transformative impact of predictive maintenance in optimizing system reliability and reducing long-term operational costs is underscored.

6.3.2.5 Compliance with Cycling Conditions (Potential Warranty Requirement)

Beyond performance optimization, remote monitoring assumes a crucial role in ensuring compliance with cycling conditions, which may even be a warranty requirement. This aspect navigates the intersection of remote monitoring and warranty adherence, emphasizing the role of continuous data tracking in providing evidence of cycling conditions. Compliance with prescribed cycling parameters not only safeguards warranty agreements but also enhances the overall accountability and transparency of system operation. The narrative elucidates how remote monitoring becomes a valuable tool in meeting warranty criteria, underscoring its integral role in the broader framework of Li-ion battery system management.

6.3.3 Conditions

Navigating the complexities of environmental considerations is crucial for ensuring the longevity and optimal performance of Li-ion stationary batteries in PV off-grid systems. In Section 3.4.1, we discussed the critical influence of the temperature, SOC, DoD, and C-rate on Li-ion battery performance.

Consequently, effective temperature control is particularly important in remote areas with high ambient temperatures. However, the complexity and reliance on specialist technicians for active cooling systems can be a challenge, potentially leading to failures or thermal issues such as runaway fires. While cylindrical cell LFP batteries have better heat-tolerance compared to NMC or LFP prismatic/pouch variants, passive cooling methods can be a viable alternative to complex active systems, reducing reliance on specialist personnel. In cases where cooling requirements become unmanageable for Li-ion, VRLA batteries may offer a more practical solution.

SOC monitoring is required for Li-ion batteries in off-grid PV systems, as maintaining high SOC levels can shorten battery life. Accurate SOC assessments guide users in optimising energy storage levels, validating initial forecasts and enabling operational adjustments to improve system availability, longevity and robustness.

Adherence to manufacturer-recommended charge and discharge rates is integral to preventing excessive heat generation, thereby preserving battery life and ensuring the long-term health of off-grid PV systems. This underlines the importance of careful consideration and strict adherence to guidelines to effectively optimise processes.

6.3.4 Safety

Ensuring the safety of stationary Li-ion batteries in off-grid PV systems involves a comprehensive set of measures designed to mitigate potential risks and protect both the system and its surroundings. Chapter 3.1.6 already highlighted some key facts about the management system that encompasses the safety and reliability of Li-ion batteries, which requires the implementation of an advanced BMS to control parameters and implement stringent safety measures at the battery cell level to prevent malfunctions and optimise performance.

6.3.4.1 Overall System Security Considerations

Taking a holistic view of the safety of Li-ion battery systems, the discussion extends to the integration of various components, protocols, and fail-safes. Emphasis is placed on compliance with local regulations and building codes to ensure overall safety and regulatory compliance. Although not explicitly stated, the implicit consideration within this broader context is to align the Li-ion battery system with relevant standards and regulations, thereby enhancing the safety and reliability of the system.

6.3.4.2 Fire Extinguisher Systems and Safety Measures

Fire safety is paramount in Li-ion battery systems. The incorporation of fire extinguisher systems, along with safety measures such as fire-resistant enclosures, smoke detectors, and emergency shutdown procedures, is a crucial element in mitigating the risk of fire incidents. These safety measures are integral components of the broader safety strategy for Li-ion batteries.

6.3.4.3 Cooling Safety Protocols

Given the sensitivity of Li-ion batteries to temperature variations, cooling safety protocols play a key role. Exploring the strategies employed to ensure effective cooling while maintaining safety, from regular maintenance checks to automated cooling systems. Implementing robust cooling safety protocols contributes to the longevity and safety of the Li-ion battery system.

6.3.4.4 Redundancy Strategies

The incorporation of redundancy strategies is a fundamental element for safety improvement. This includes the use of redundant components or systems that can seamlessly take over in the event of a failure, minimizing the likelihood of critical failures and ensuring continuous operation even under challenging conditions.

6.3.4.5 Health and Safety (H&S) Measures

The well-being of personnel involved in the operation and maintenance of the Li-ion battery system is paramount. The Health and Safety (H&S) measures implemented encompasses training protocols, protective equipment, and guidelines for safe handling, contributing to the overall risk mitigation strategy for the PV off-grid system. Li-ion batteries pose higher safety complexity, requiring certified electricians for systems operating above 60 volts. However, it's worth noting that most old systems typically operate at extra low voltages (< 60 volts), subject to regulatory requirements.

6.3.4.6 Strategic BESS Location to Reduce Risks to Other Structures

The strategic location of the BESS is a key consideration in overall safety planning. The study includes how the placement of the BESS is carefully evaluated to minimize risks to other structures, ensuring the safety not only of the Li-ion battery system but also of the surrounding environment.

6.4 Ownership and End-of-Life

While the technical aspects of an off-grid PV system are often emphasized, it's important to recognize the importance of economic considerations such as investment costs, as well as the significant impact of social and environmental factors.

6.4.1 Sense of Ownership

Ultimately, the success of an off-grid solar system also depends on the collective effort and involvement of various stakeholders within the community, including electricians, technicians and the inhabitants who will benefit from the system [20] . A sense of community ownership of an off-grid PV system can influence its sustainability by encouraging care and protection, reducing the risk of damage from vandalism.

Challenges can arise in many remote communities where, active cooling systems are not available, the implementation of such systems solely for battery energy storage can lead to social discontent. This is due to inequalities in access to cooling, which may result in people wanting to utilize the cooled space for different purposes, affecting overall community dynamics and creating tensions. For instance, technicians sleeping in cooled rooms may inadvertently open doors to allow light and air circulation, triggering alarms and compromising the efficiency of cooling systems.

6.4.2 End-of-Life Considerations

As we approach the end of the system's lifecycle, it becomes crucial to consider the end-of-life of individual components and their replacement. For example, when an inverter fails, it disrupts the operation of the system, highlighting the need for a quick fix to maintain performance. However, in remote locations, rapid repairs can be a challenge. Implementing predictive maintenance strategies can help identify potential problems before they escalate. In addition, maintaining a stock of spare parts or having quick replacement options available is essential. Board exchange options, rather than replacing entire electrical devices, can also speed up repairs and minimise downtime.

Managing Li-ion batteries in off-grid PV systems at the end of their useful life means prioritising responsible disposal and recycling practices to meet environmental obligations. As off-grid PV systems are typically located in remote areas, the challenge of distant recycling facilities must be addressed, which not only complicates logistics, but also increases carbon emissions from battery transportation. It's therefore crucial to assess recycling costs and allocate them in project development costs.

The main focus is to reduce the environmental impact through environmentally friendly battery recycling practices. It aims to align disposal methods with environmental regulations and explore recycling options to meet compliance standards and support sustainable waste management. Despite logistical challenges, working with recycling facilities is essential to implement environmentally friendly practices and minimise environmental impact.

In regions such as Africa, recycling facilities for Li-ion batteries currently do not exist, or where they do exist, they do not meet standards, making responsible disposal a challenge. Meanwhile, there are significant costs associated with exporting batteries to recycling facilities in other regions, mainly due to the complexities of shipping and the difficulties of transporting waste. And while there's potential for the future development of local recycling solutions, the additional costs associated with logistics and transport need to be carefully considered. Shipping restrictions and the complexity of waste transport add to these challenges.

6.5 O&M summary

Success in operating Li-ion stationary batteries in PV off-grid systems hinges on various factors before and after the design phase. This emphasizes critical pre-conditions, careful design considerations, and diligent implementation processes including the social, economic and organizational framework. Maintenance, remote monitoring, and condition management play crucial roles during operation, along with security measures and strategic BESS siting. Throughout the lifecycle, fostering a sense of ownership and addressing end-of-life considerations are vital, emphasizing responsible environmental practices, regulatory compliance, and collaboration with recycling facilities.

Collectively, this in-depth review underscores that the success of stationary Li-ion batteries in off-grid PV systems depends on a holistic understanding and effective management of factors that span the entire lifecycle of these systems. By carefully considering and addressing each facet, practitioners can not only optimize performance and reliability but also contribute to the sustainability of these energy storage solutions in off-grid solar applications.

7 CONCLUSION

The success of an off-grid photovoltaic system hinges on a comprehensive evaluation of available suppliers and technologies. This assessment prioritizes technology reliability, scrutinizing its performance history, durability, and adaptability to various conditions. Additionally, ensuring the reliability and accessibility of technical support from chosen suppliers is crucial for swift issue resolution, safeguarding continuous system operation. Portability considerations are vital, particularly for systems requiring mobility or reconfiguration.

In this report, a classification table for off-grid systems is introduced. An introduction into the Li-ion technology was presented and a comparison of the Li-ion technology and the Lead-acid technology was simulated with the HOMER Pro software. Furthermore, one case study of battery off-grid systems is shown and analysed. It is a diesel PV off-grid Microgrid in Haiti with a renewable share of around 50 %. Additionally, an operation and maintenance guidance were presented, which can help develop, maintain and operate successfully an off-grid BESS system. The key take aways of the paper are gathered in the following listing:

- A Classification of PV Mini-Grids in terms of the size of the system components helps for a better overview and identification of off-grid systems,
- Li-ion technology is very often the cheapest solution,
- The usage of Li-ion in off-grid systems needs a responsible decision, due to the recycling topic and the software thematic (e.g. software update),
- The BESS guarantee a stable grid frequency with a low power outage failure,
- A regular monitoring and maintenance are very important for reliable system operation

Different Li-ion chemistries e.g., lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC) (see chapter 3) have varying characteristics, and are directly impacting factors like energy density, lifespan, safety, and performance under varying environmental conditions. LFP batteries are known for their robust safety features, longer lifespan, and enhanced thermal stability, making them less prone to thermal runaway. On the other hand, NMC batteries typically offer higher energy density, providing greater energy storage capacity in comparison to LFP batteries. Hence, choosing the appropriate Li-ion chemistry aligned with the specific requirements of the off-grid PV system is crucial to optimize its functionality, safety, and longevity.

Following product selection, simulations can be instrumental in reevaluating the system design. This process might entail modifications to accommodate precise product specifications, ensuring seamless integration and compatibility among selected components. Simulations offer a proactive approach, allowing the identification of potential constraints that may have surfaced during product selection. By incorporating simulation tools, the design can be refined to tackle these issues while aligning with the overarching objectives of the off-grid PV system.

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