PCREEE
Pacific Centre for Renewable Energy and Energy Efficiency
SE4ALL Centre of Excellence to Promote Sustainable Energy Markets, Industries and Innovation

UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Unlocking MG for sustainable development

5.2 Engineering Design

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MG in Bolivia by TTA


MG in Ethiopia by TTA

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CONTENTS

1. SESSION OBJECTIVES

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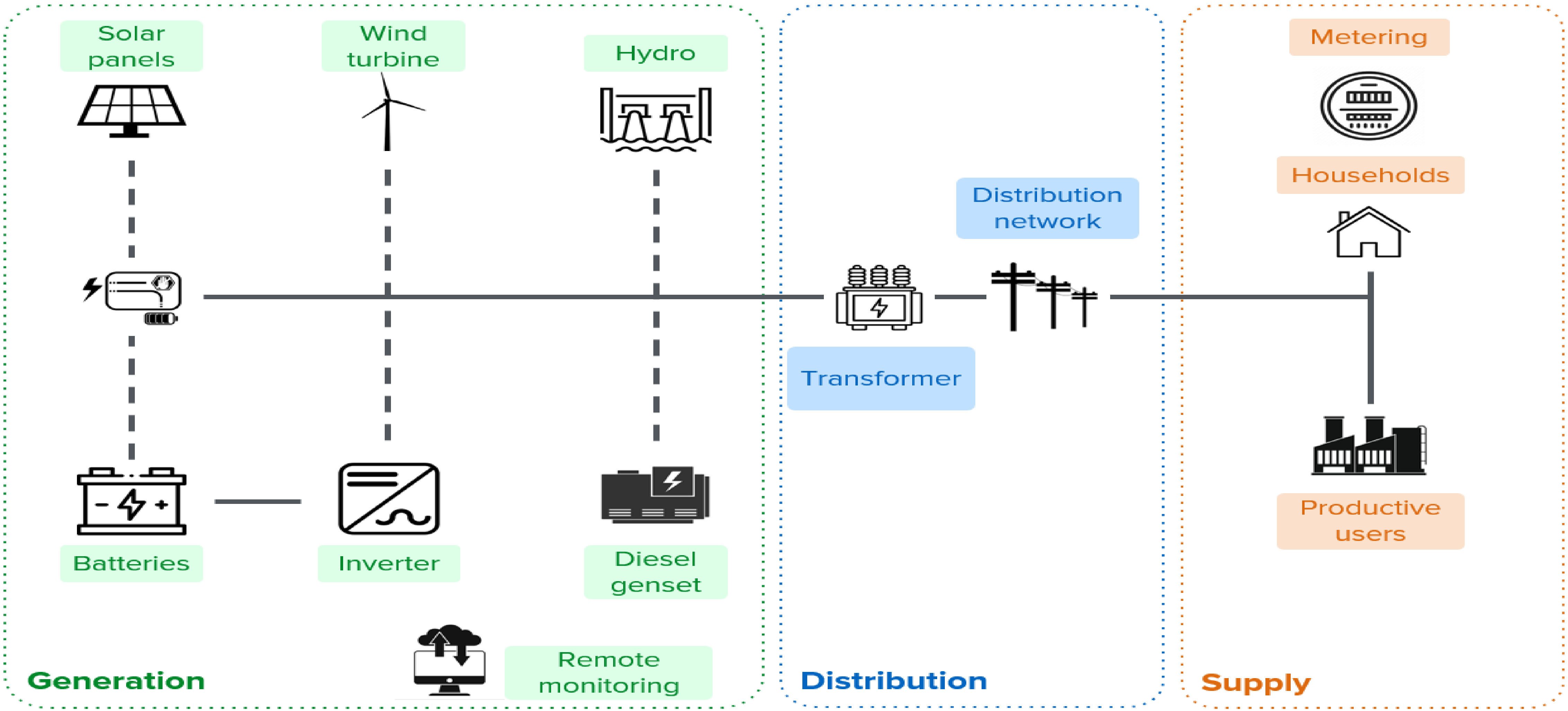
i) Discuss key aspects for the design of mini-grids.

ii) Provide recommendations

iii) Share experiences on design aspects from different countries

2. DESIGN PRINCIPLES

DEFINITIONS AND KEY COMPONENTS OF MINI-GRIDS



Design principles

Standardisation of components across different mini-grids facilitates:

- Operation and Maintenance of the plants, establishing same procedures and skills across different assets.
- Reduce considerably the need for spare parts as inventories are compatible for the all mini-grids.

Modularity and expandability

Generation, storage and distribution should be designed to be easily expanded when the system is not capable of meeting the growing demand. The expansion of the system should be:

- *Cost-effective*: allowing system expansion in small increments. The expansion should not require the replacement of any existing devices.
- *Flexible*: Allowing system expansion by adding capacity following a distributed or centralized approach. It should be possible to add capacity both in the DC or AC bus. This should be achieved in a technically sound manner without compromising communication, monitoring and control capabilities.

Suitability to local environmental conditions

- Capable to resist extreme weather events.
- Rated for operational environmental conditions (high humidity and salinity)

Design principles

Minimize dependance on fossil fuels

Oil price is very often subject to considerable fluctuations, influenced by unexpected global or regional events (i.e. COVID-19 pandemic) or geopolitic dynamics and conflicts (i.e. Russian invasion of Ukraine).

- This comes with a **financial risk** if this variable component is not taken into account in the tariff.
- It can compromise the **affordability** of the service.
- Increasing taxes on CO_2 emissions.

3. TOPOLOGY

Topology

1. Centralized MV/LV mini-grid powering all the island.

- Both generation and storage components are located in a common central location.
- The electricitity is carried around the area by MV lines, then distributed locally to the users with LV lines.
- Requires a larger site to locate the generation assets.
- Well suited for larger communities with a densely populated area larger than approx. 3 km distance from the generation asset.

2. Several distributed LV mini-grids powering communities or clusters of communities.

- Both generation and storage plants are strategically distributed in different locations.
- Well suited for communities where the population is scattered in different clusters as the generation is located closer to the loads to be supplied.
- Requires securing different sites where the equipment can be located. The sites can be either a piece of land or a building's roof, in the case of solar.

3. Solar kits to power each user.

- Stand-alone systems are provided to each user, including a small generation and storage asset.
- Well suited for scattered communities with very low population density

4. Hybrid topology combining different approach.

- For example, use topology 1 or 2 to supply most of the users and provide solar kits to small isolated users, too far from the distribution network.

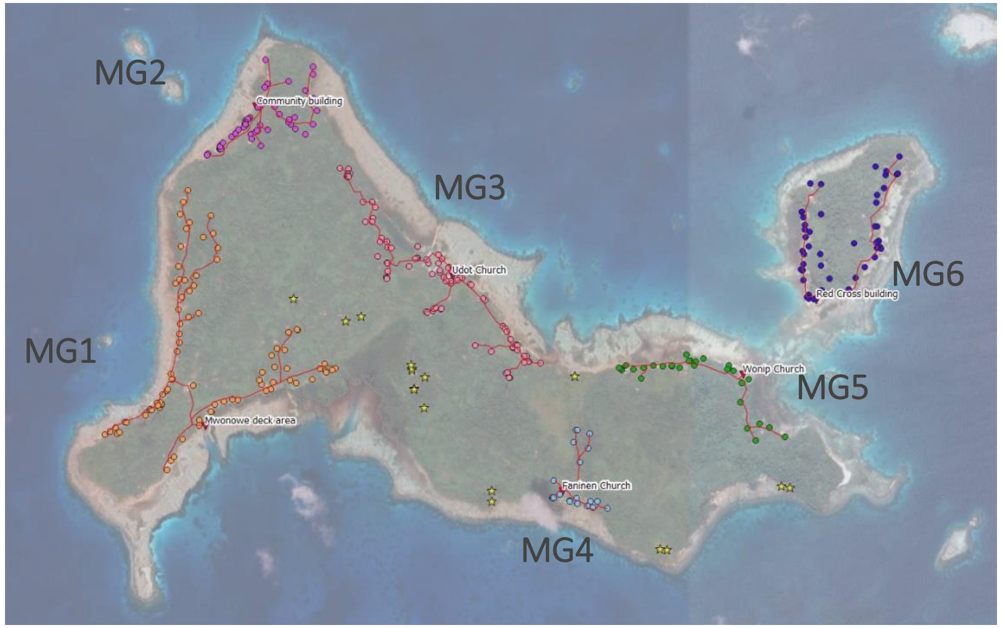
Topology - Examples

Parameters that influence the selection of the optimal topology:

- Population
- Population density
- Distance between communities
- Land extension of the community
- Cost analysis
- Topography of the territory
- Availability of skilled linesman
- Accessibility of the sites
- Renewable energy resources

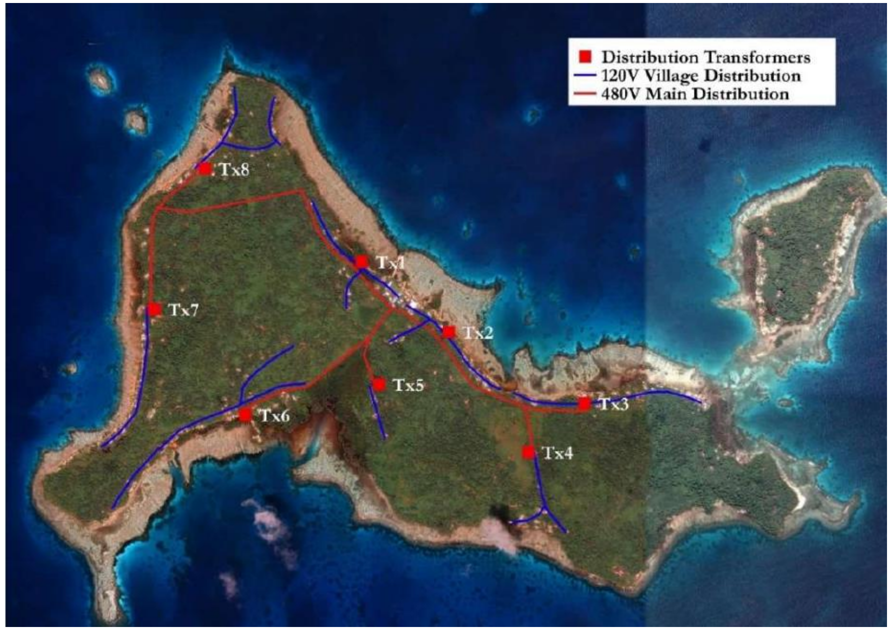
Topology - Examples

Udot, Chuuk, Federate States of Micronesia



Distributed hybrid topology,
LV mini-grids + SHS

VS



Centralized topology,
single mini-grid

Topology - Examples

Vanuatu, Malekula island

*areas marked in blue define existing communities

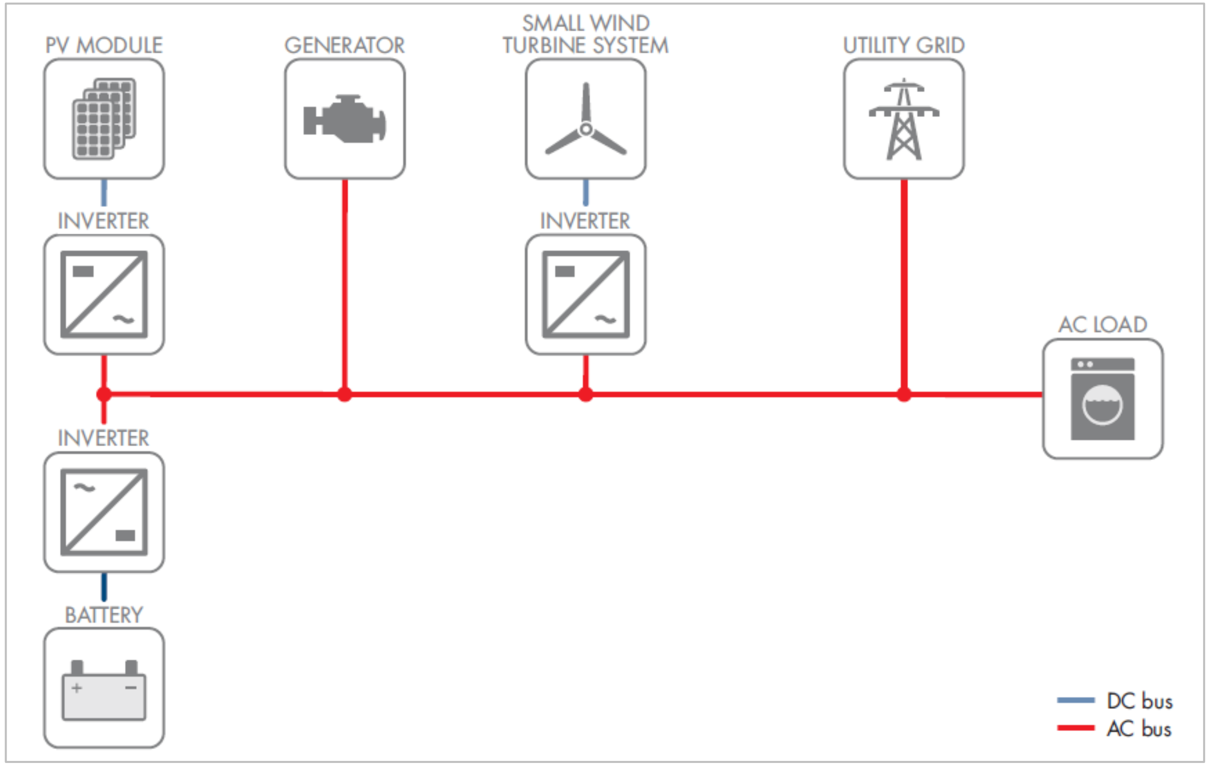
Centralized topology, single mini-grid

Abundant hydro resource in one location that could supply all the surrounding communities

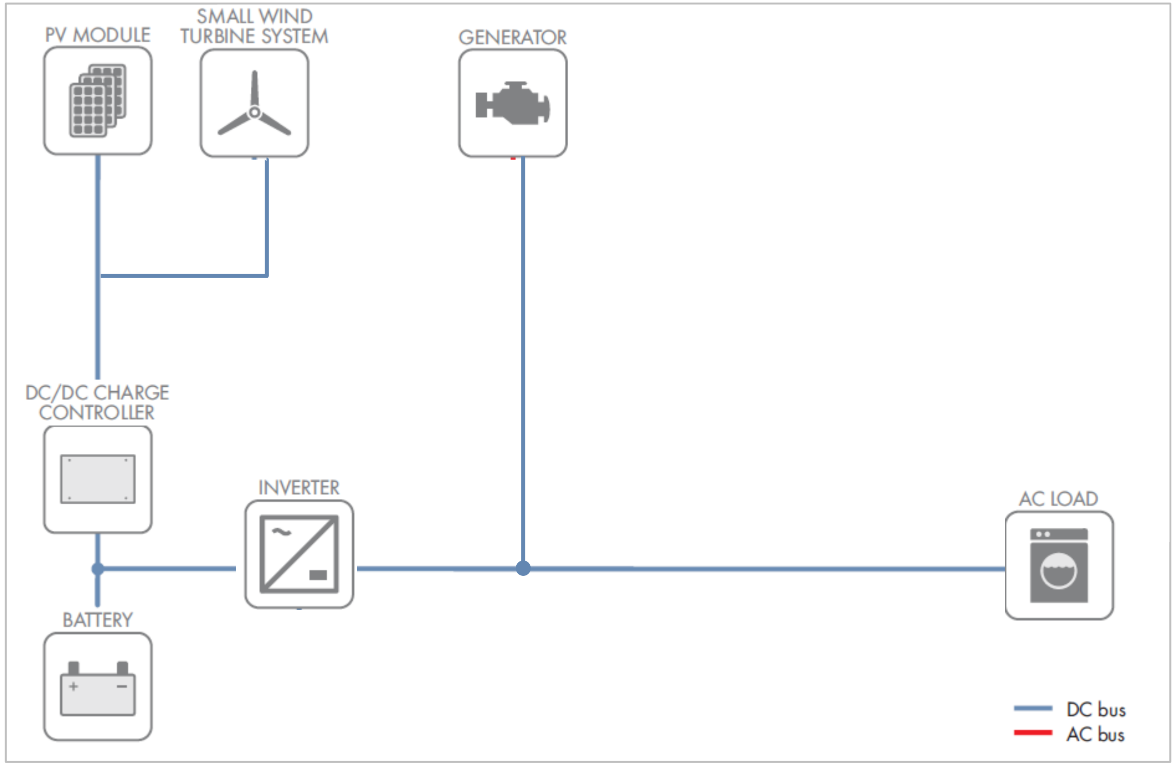
4. ELECTRICAL COUPLING

Electrical Coupling

AC coupled system

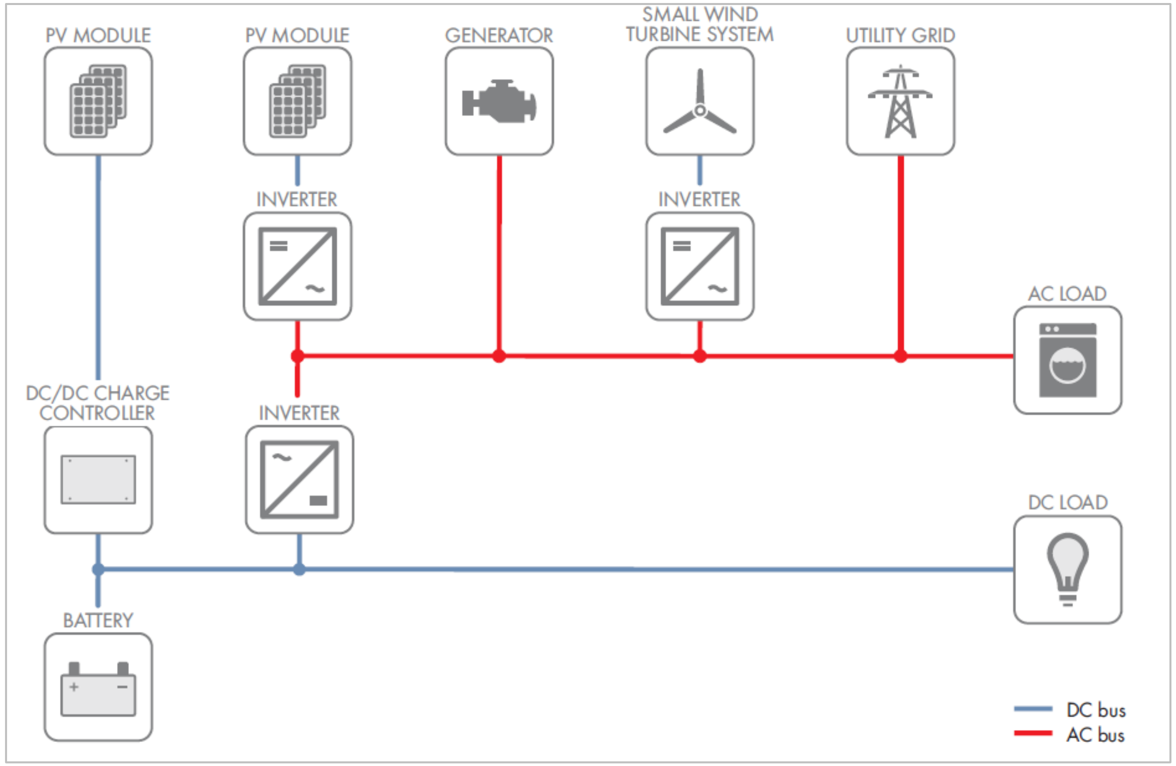


DC coupled system



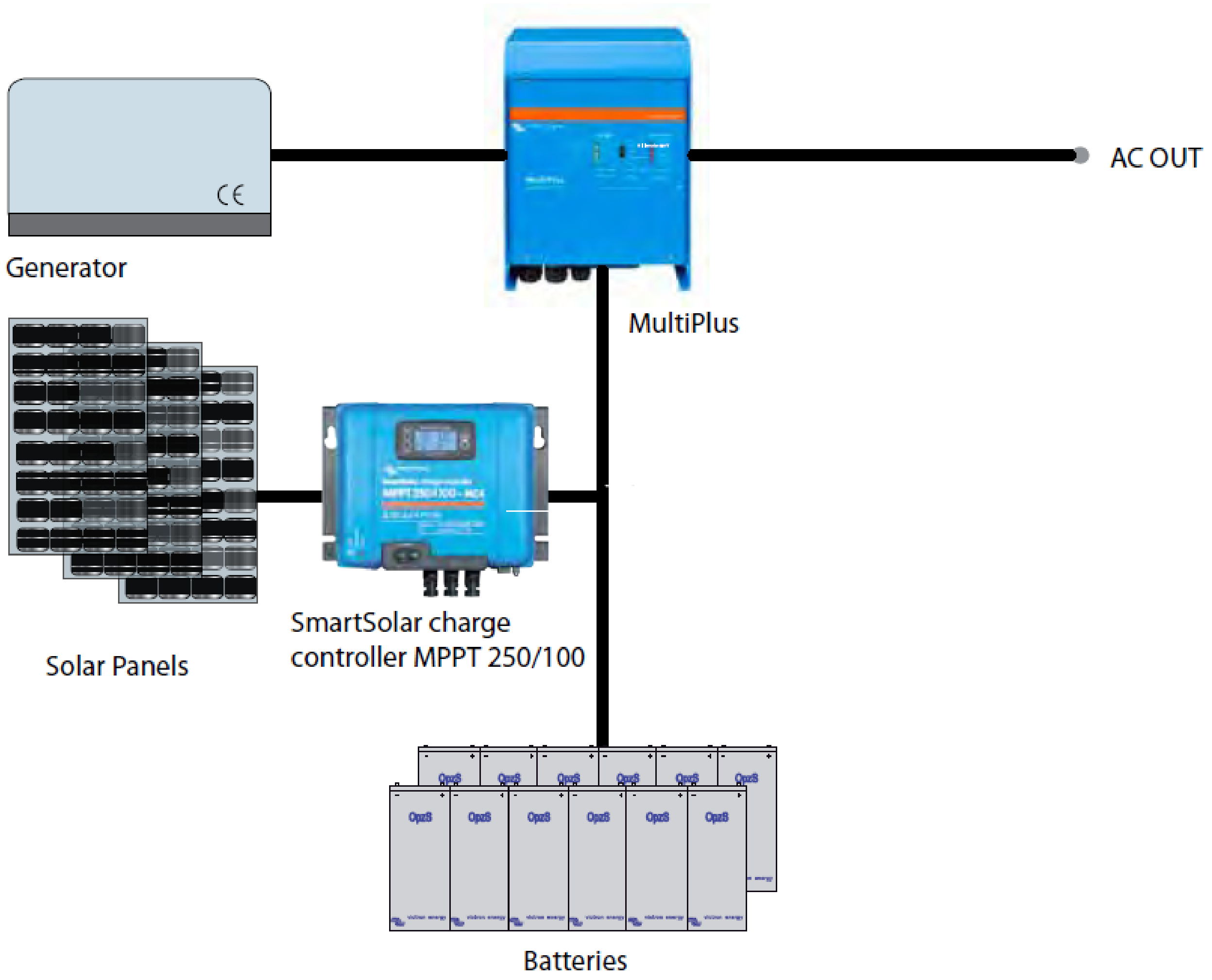
Electrical Coupling

Hybrid AC and DC coupled system



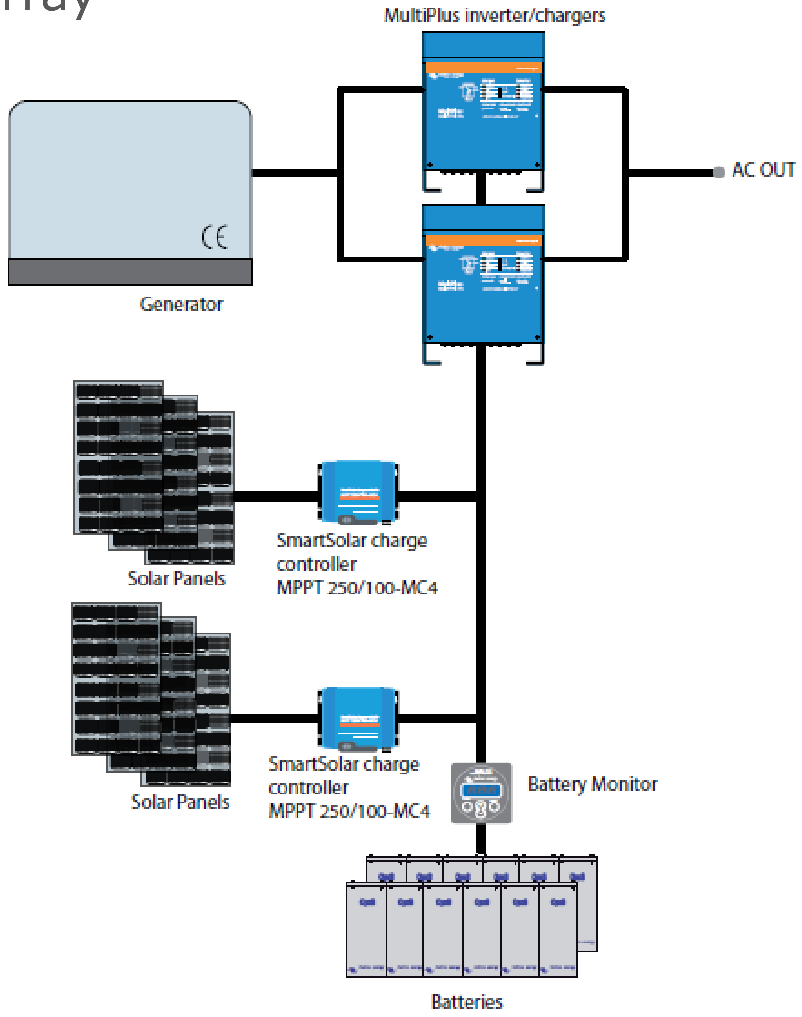
Electrical Coupling - Examples

DC couple



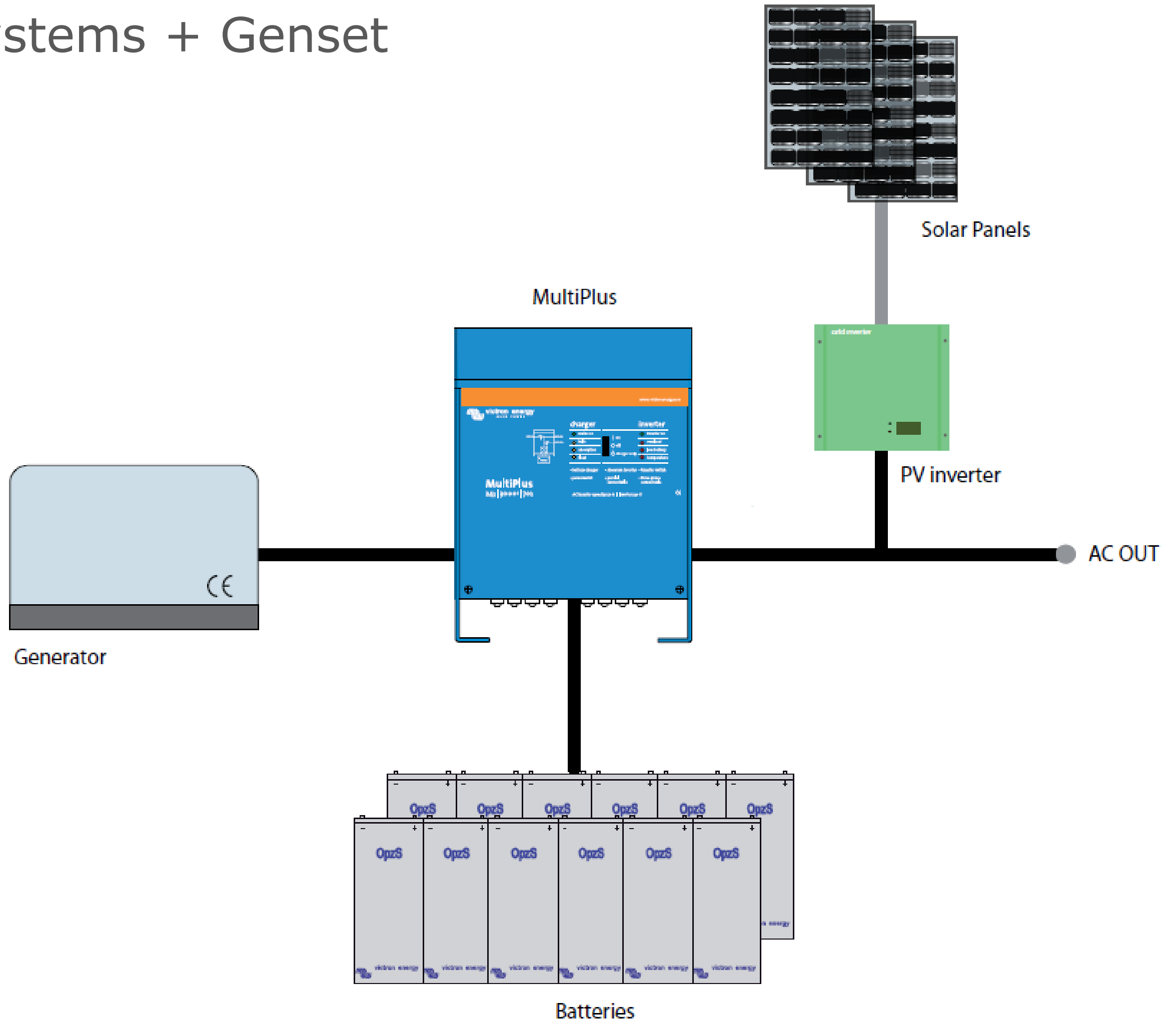
Electrical Coupling - Examples

Differents PV array



Electrical Coupling - Examples

AC systems + Genset



Electrical Coupling – Pros and Cons

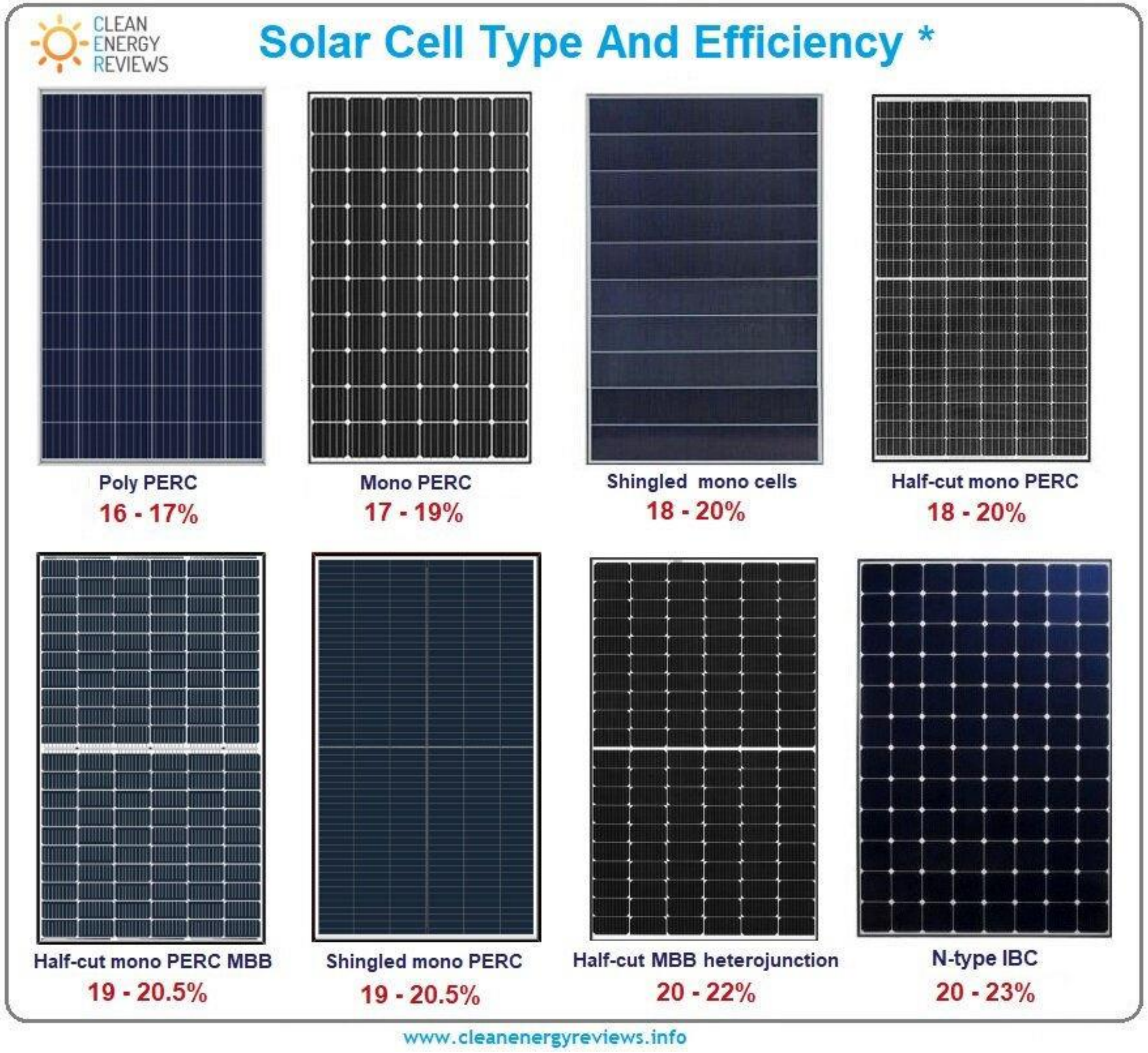
Type	Advantages	Disadvantages
DC-coupling	• Higher overall efficiency with typical rural demand profiles with evening peak due to fewer conversion steps. Most PV power is directly stored in the battery with just one power conversion step in the PV charge controller. • Allows PV generators with intrinsic electric safety with PV string voltages below 120 Vdc – Extra Low Voltage (ELV). • Robust design with decades of good track record. • Higher reliability. The battery will get charged with PV power regardless of the AC grid status and the battery´s SoC level.	• Higher cost of PV power conditioning: 330-630 USD/kWp • Higher number of components, which increases wiring complexity. In 48 Vdc battery systems, standard PV charge controllers have rated power outputs of up to 5 kW.
AC-coupling	• Lower cost of PV power conditioning: 110 USD/kWp • Fewer components needed, with standard PV string inverters in the range between 20 and 100+ kW. • Simpler wiring complexity with long PV strings with up to 20+ PV modules connected in series.	• Lower overall efficiency with typical rural power demand profiles with evening peak, due to a higher amount of power conversion steps. Most PV power is converted from DC to AC and again from AC to DC to charge the battery. • Long PV strings have voltages of 600+ Vdc, which can be lethal if the O&M staff is not properly qualified and trained. • Lower reliability. The PV inverters are grid-following and can only feed power if the grid is available. If the battery SoC is too low, the battery inverter will disconnect and will stop forming the grid, so the PV inverters will disconnect as well. The battery will not be able to be charged by the PV power.

[1] As defined by the IEC 60364 (<120 V_{dc})
[2] Includes costs of charge controllers, PV junction boxes, protections and cables.
[3] Includes costs of PV inverters, protections and cables.

5. GENERATION

5.1. SOLAR PHOTOVOLTAIC

CURRENT TRENDS AND EFFICIENCY OF SOLAR MODULES



Passivated Emitter and Rear Contact (PERC):

Have an extra layer within the back side of the cell, allowing some of the sun's rays to reflect back into the solar cell, giving them another opportunity to be turned into energy.

Increases the surface reflection reducing heat absorption and increasing efficiency.

Interdigitated Back Contact (IBC):

Place the conductors on the back of the cell, leaving the frontal surface entirely exposed to the sun (no busbars losses)

Bifacial Solar Cell (BSC):

Can generate electricity from both sides of the panel, using the albedo light.

Key Specs for Solar PV Modules in the Pacific

- Front load resistance ≥ 5400 Pa uplift.
- Compliance with IEC 61701 (testing standard for salt mist resistance for solar panels).

String configuration

PV panels are normally wired together to increase the total output voltage and current. Panels can be stringed in a series or parallel, which is better depends on the situation.

Basics of stringing

1. Ensure the minimum and maximum voltage are within the inverter/charge controller range
2. Ensure strings have similar conditions (Same tilt & same azimuth) — or connect strings with different conditions to different MPPT ports of the inverter.
3. Group together in same string(s) and MPPT panels exposed to shading

SOLAR INVERTER

- Electrical converter which changes the direct current (DC) electricity produced by solar panels, into alternating current (AC).
- Inverter efficiency use to be between 90 and 98%, depending on quality and operation conditions
- Lifespan is between 10 and 15 years

String inverter / central inverter

- String or array connected to the same inverter
- Most common, mature and economic technology
- If performance of one panel is reduced (damage, shadow…) the performance of the string is reduced.

Micro inverter

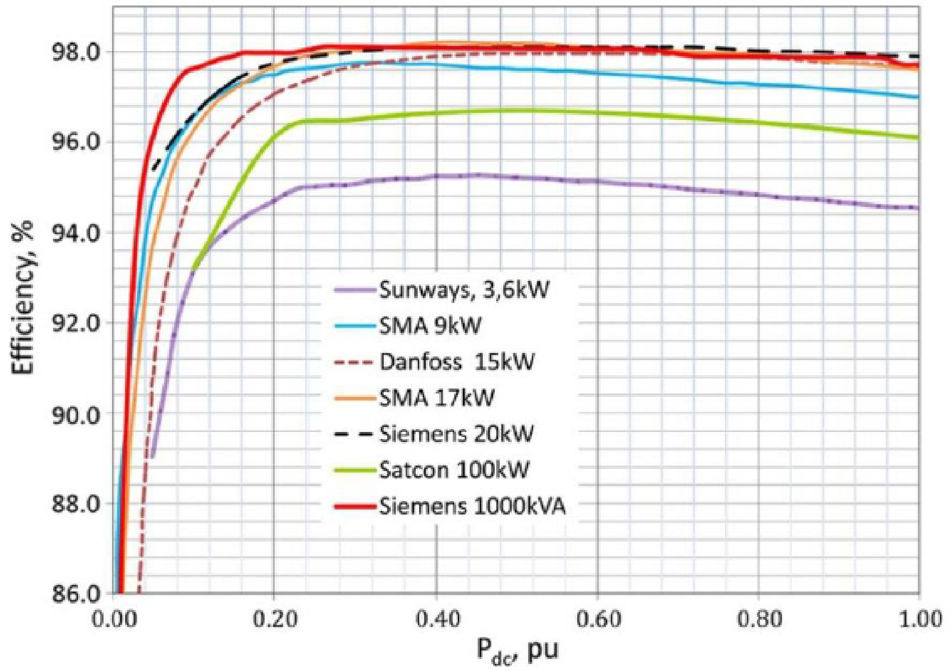
- Each solar panels has its own inverter
- Getting popular in solar home systems, but more expensive.
- Suitable in case that solar panels are affected by shades or the same string has different orientations.

Power optimizer

- Each solar panel has a power optimizer, that move the DC current to a string inverter.
- Same benefits that microinverters but cheaper

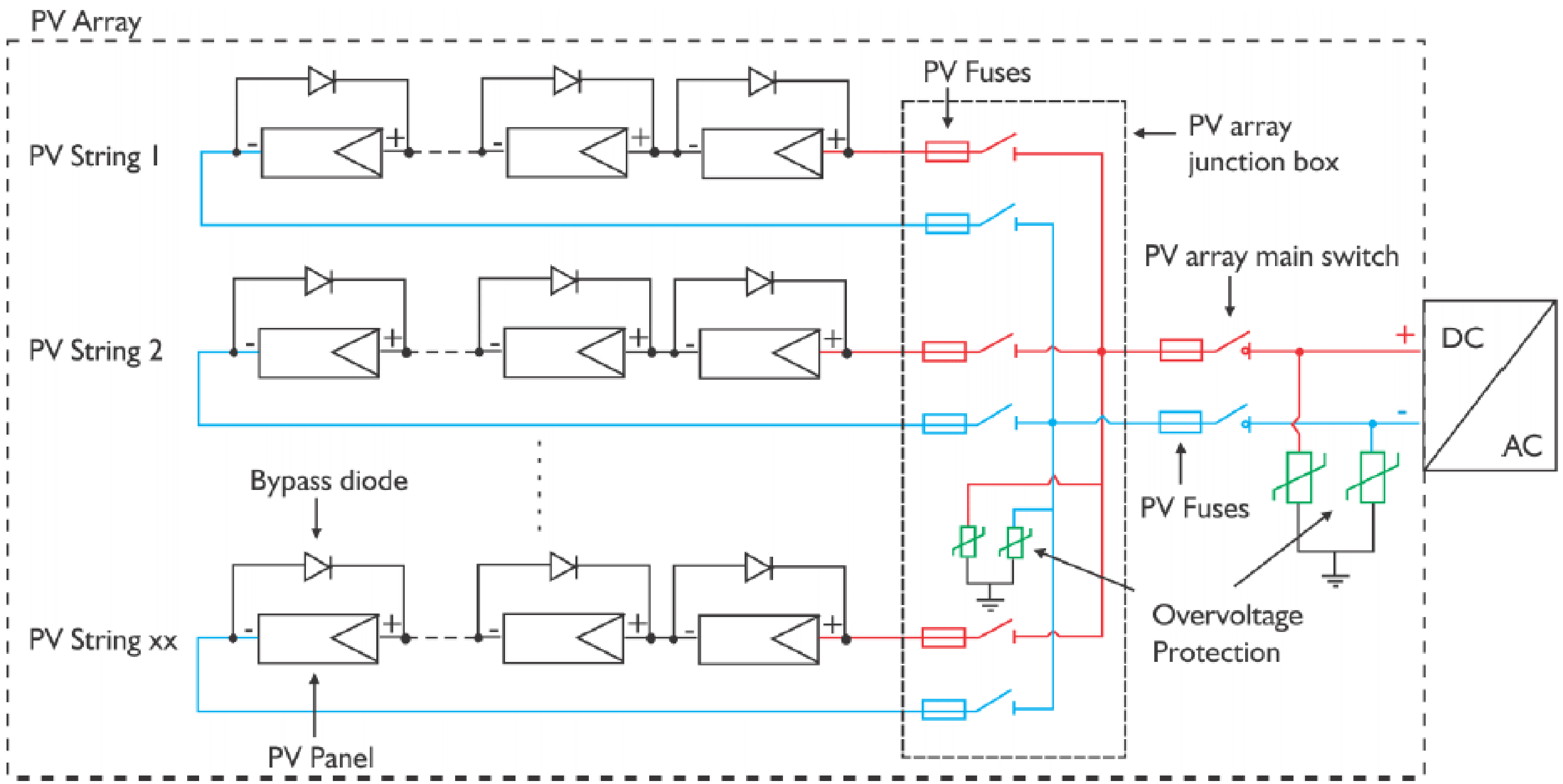
SOLAR INVERTER SPECIFICATIONS

- **Efficiency:** how much DC power is converted to AC power. It is affected by the operating conditions.
- **Rated output power:** how much power the solar inverters can produce to a load on a steady basis.
- **Peak Output Power/Surge Power:** maximum power output an inverter can deliver for a short time. In stand-alone systems, important to consider the power to start-up of some appliances (for example fridges) and for periods with many appliances connected.



- **Nominal input voltage:** optimal operation DC voltage
- **Input voltage range:** minimum and maximum DC operation voltage
- **Maximum input current:** how much electricity can absorb from the solar array. Higher currents can cause overheating and damage to the inverters.
- **AC output voltage:** utility voltage (Nauru should be 240 V).
- **Maximum output current:** how much current can produce the inverter. Important to determine the breaker and fuses size to protect appliances from overloading.

PROTECTION SYSTEMS



- PV systems that have three or more strings connected in parallel need to have each string protected
- A fuse link or circuit breaker on each sub-array will protect the conductors from current faults and help minimize any safety hazards. It will also isolate the faulted sub-array so that the rest of the PV system can continue to generate electricity.
- If a number of sub-arrays are subsequently combined then a further fuse link or circuit breaker should be incorporated.
- DC and AC cables need to be properly sized to have voltage drop below allowable levels (< 2%) and avoid fire hazards.

Foundations

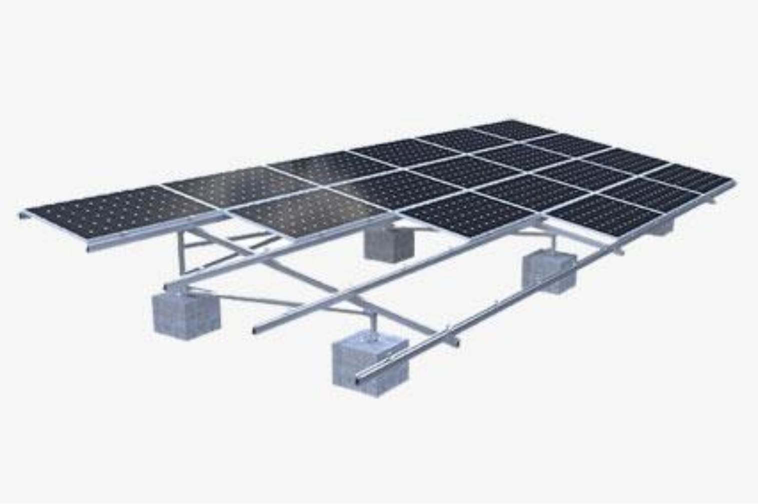
In remote locations where the access of heavy machinery is not possible, typically **concrete footings** or **ground screws foundations** are utilised.

Ground screw foundations offer some advantages over concrete foundations:

- Considered a more environmental solution as it does not require earthworks, pouring of concrete, sourcing of beach aggregate sand.
- They allow for an easy decommission and recycling of the foundations.
- They also provide time and cost benefits.

Therefore, ground screw foundations should be prioritized in sites where the soil conditions are favorable and access to heavy machinery is not possible.

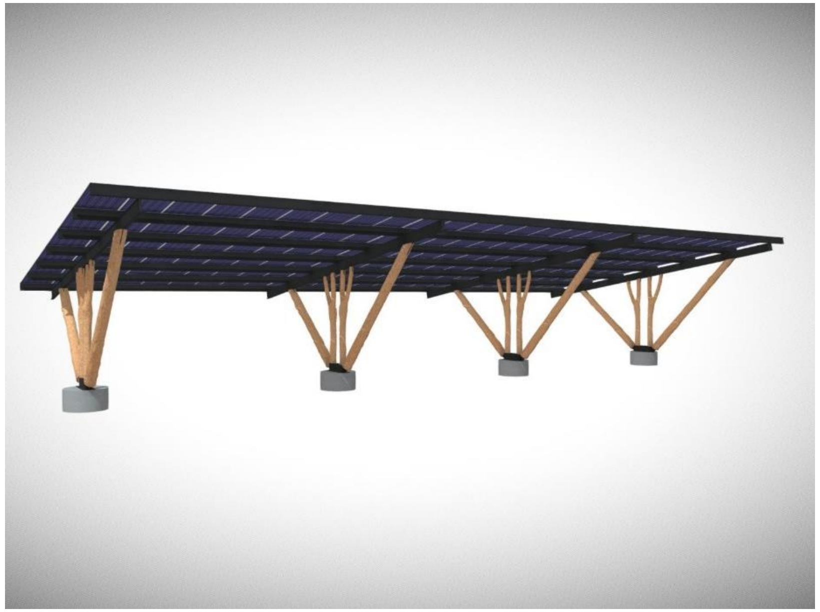
To determine the design and right type of foundations to be used in each site, a **geotechnical survey should** ideally be conducted.



Concrete footings – Mibet energy

Ground screws

Mounting structure



Ground mounted

Canopies/carports

Rooftops

Preferred options when land is scarce and/or often under dispute

Suitability to local environmental conditions

Design to withstand extreme weather conditions

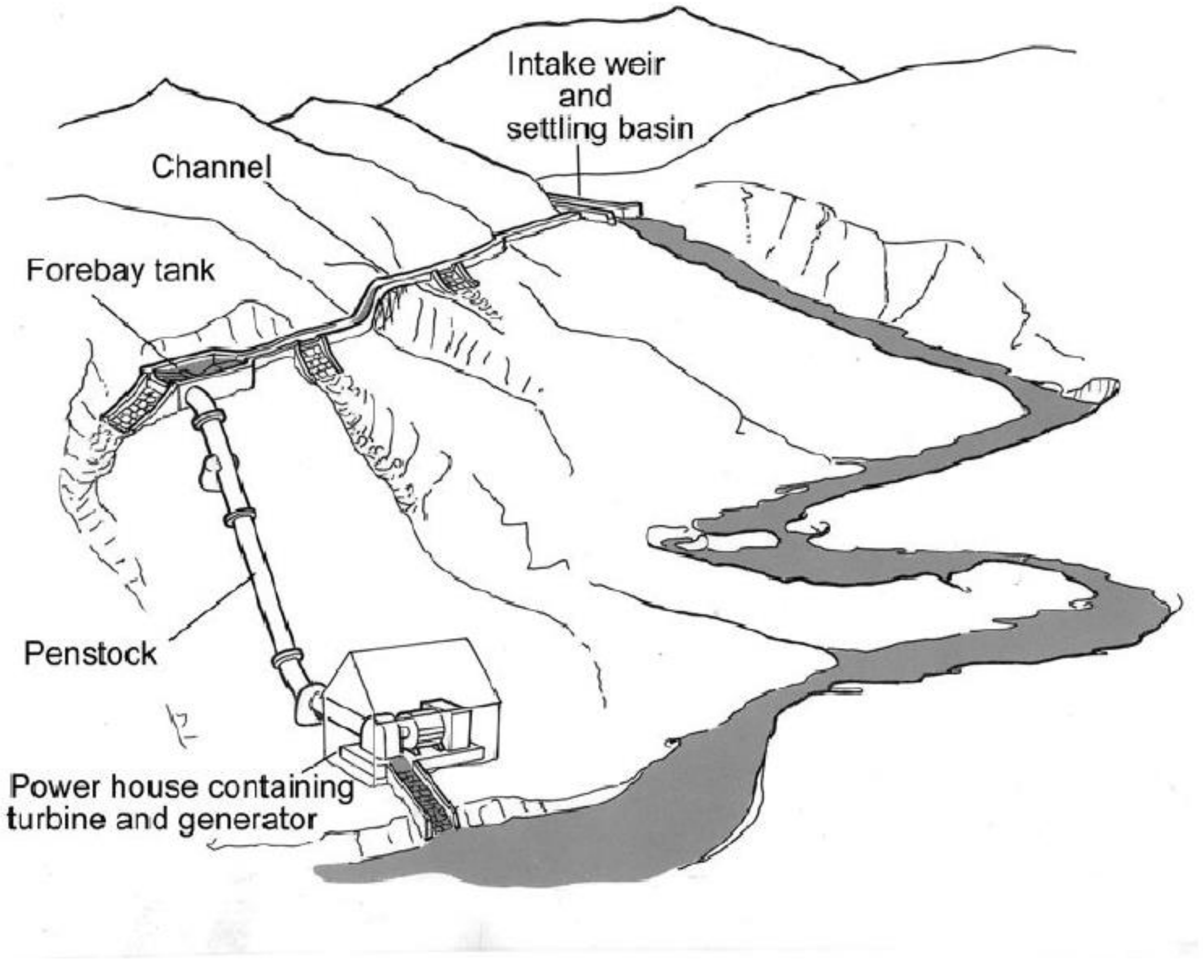
Rocky Mountain Institute publication: «**Solar Under Storm**» (https://rmi.org/insight/solar-under-storm/)

Design for highly corrosive conditions:

- Profiles material: hot-dip galvanized steel with a minimum Zinc coating thickness of 85µm or anodized aluminium with a minimum coating thickness of 20µm (AA20).
- Bolts and fastenings material: Stainless steel SS316.

5.2. HYDROPOWER

Typical arrangement of a micro-hydro site



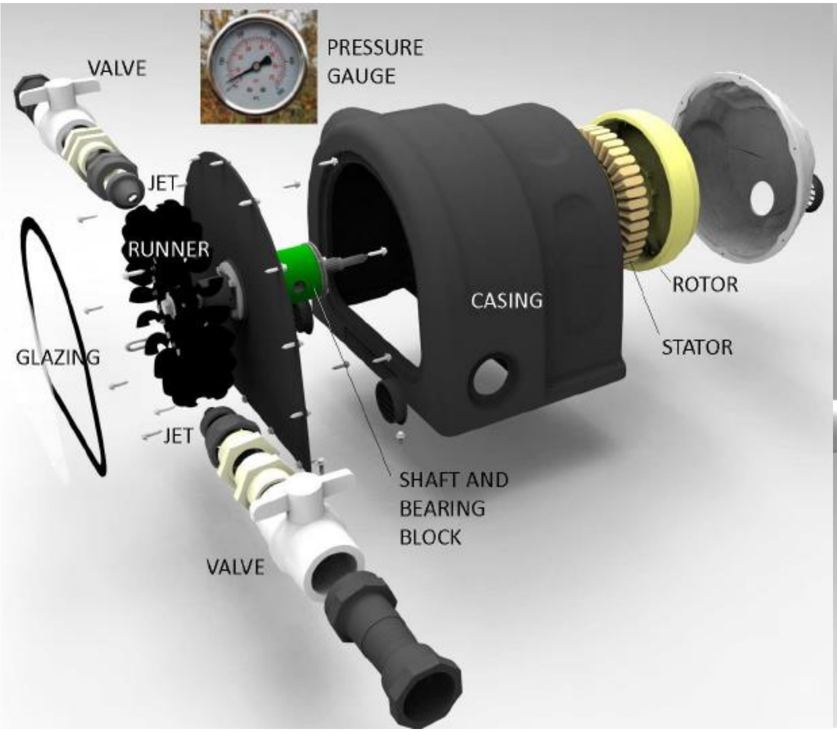
Type of hydro turbine based on head

High head: +100m
Medium head: 30 to 100m
Low head: 1 to 30m

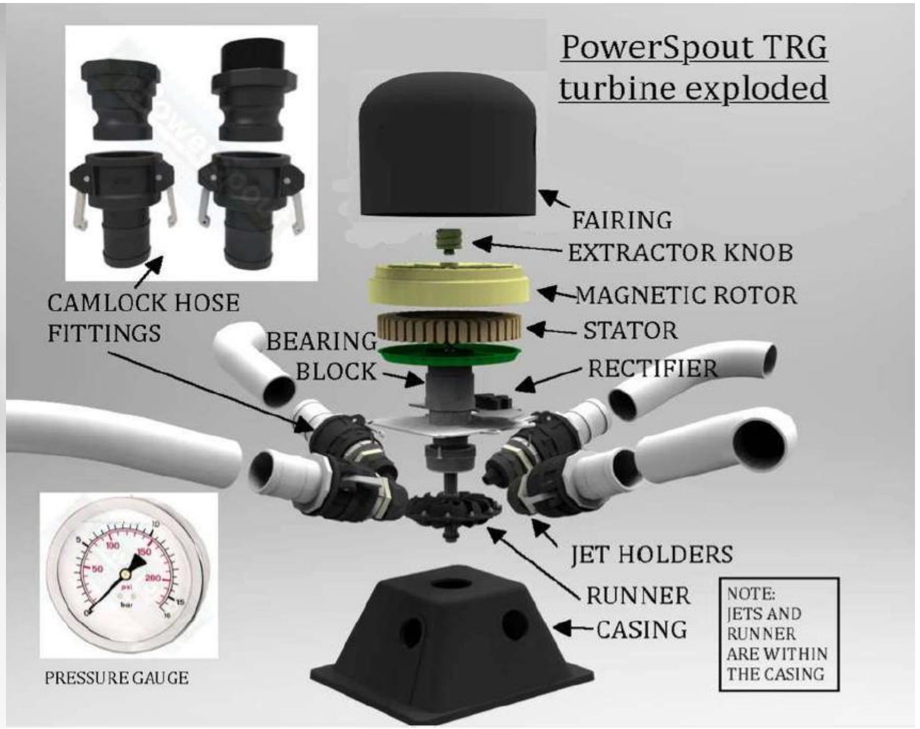
Turbine Runner	Head Pressure		
	High	**Medium**	**Low**
Impulse	Pelton	Crossflow	Crossflow
	Turgo	Turgo	
	Multi-jet	Multi-jet Pelton	
Reaction		Francis	Propeller
		Pump-as-turbine (PAT)	Kaplan

Typical arrangement of a micro-hydro site

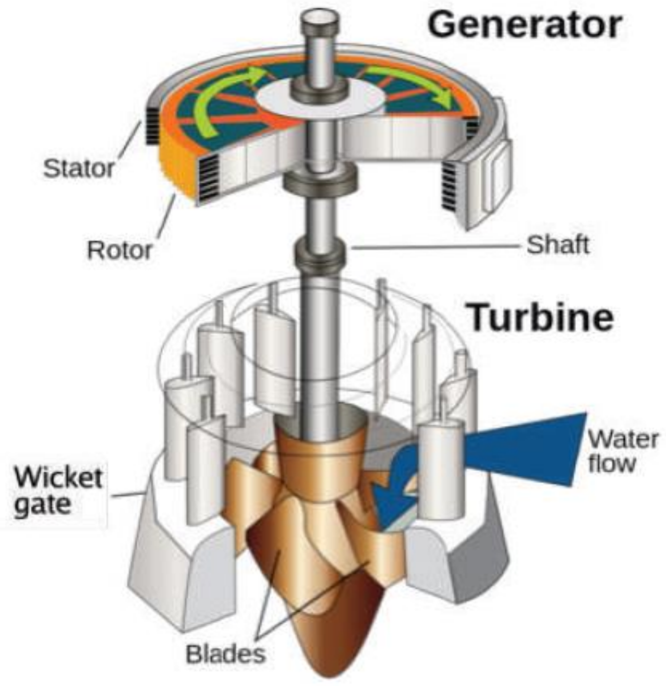
Pelton



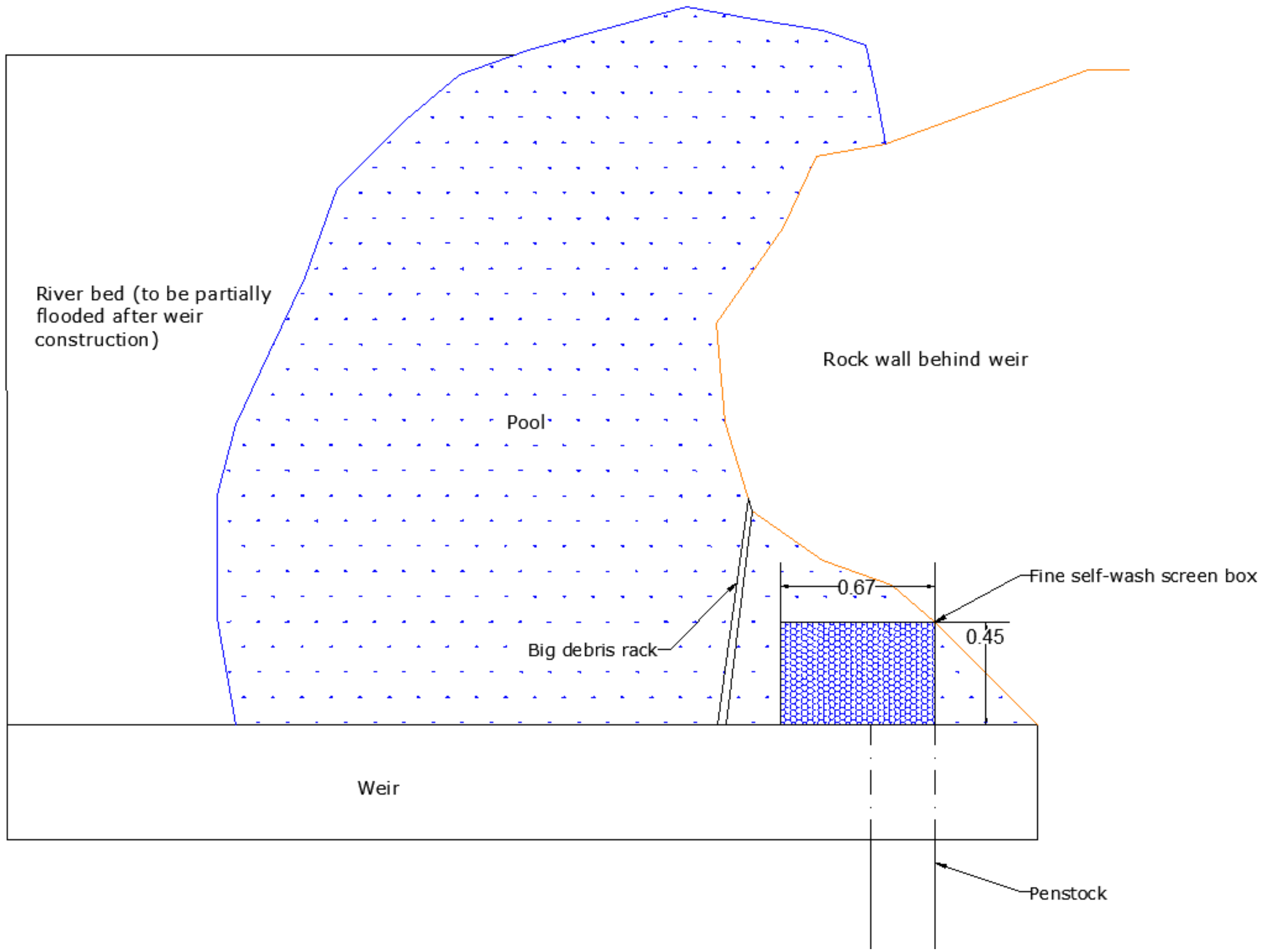
Turgo

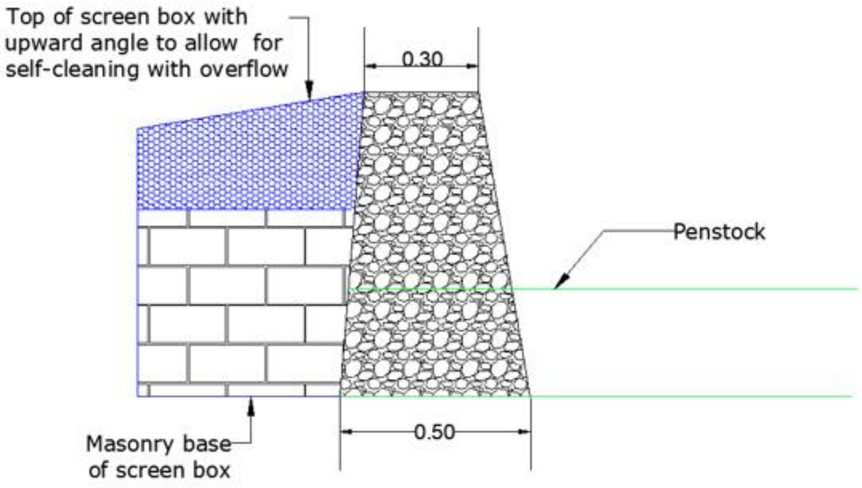


Kaplan

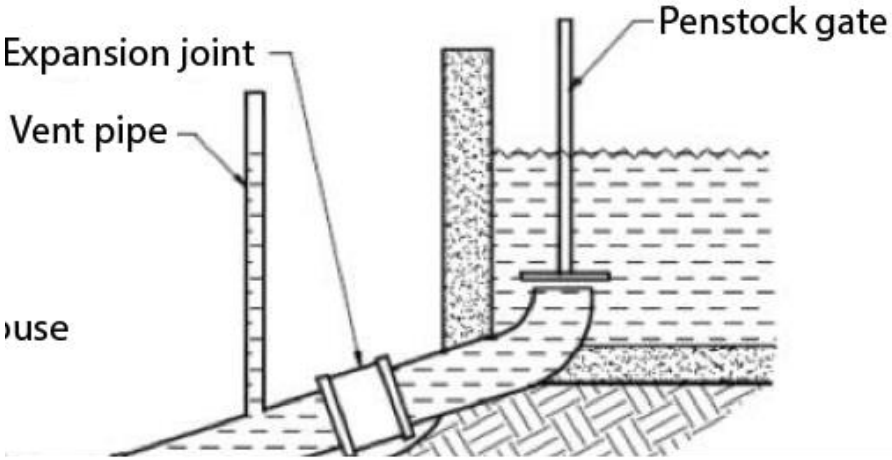


Typical arrangement of a micro-hydro site





Typical arrangement of a micro-hydro site

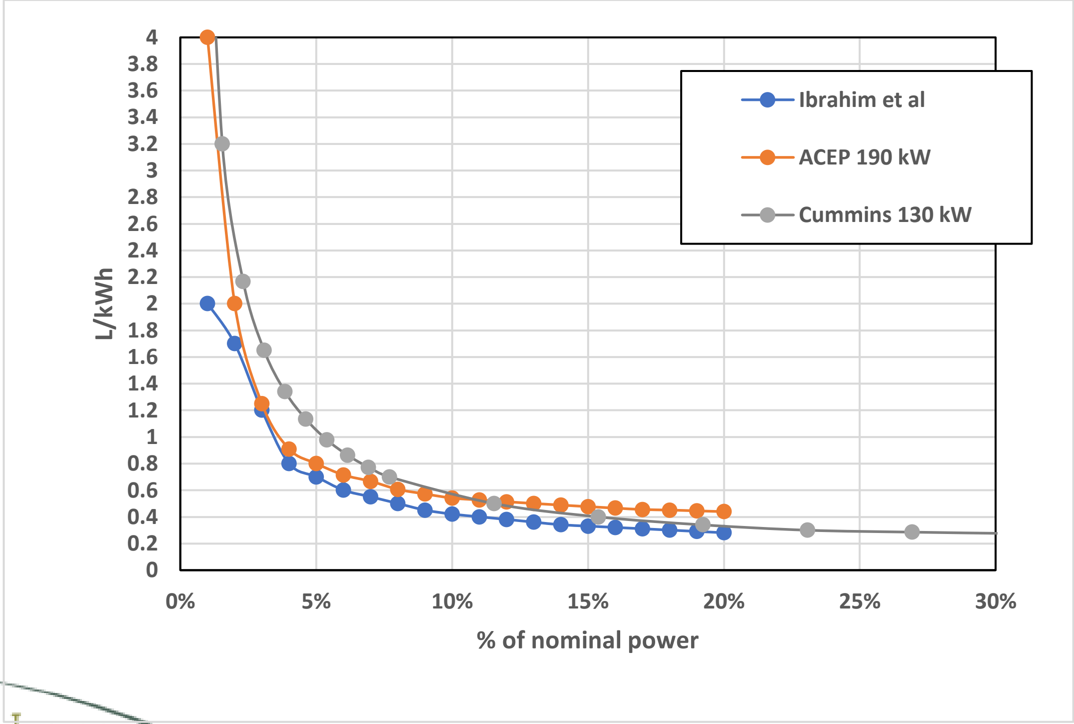


5.3. DIESEL GENERATOR

Diesel generators

The diesel generator is used as back-up to ensure quality of service when solar power generation and the state of charge of the battery are low or when demand is especially high.

- *Allows to reduce the size of the battery storage*
- *Increase operational expenses*
- *Re-introduce dependence on fossil fuels*



It can be noticed that the generators have a lower efficiency at a low load. **Normally, manufacturers recommend to use the generators at least at 25-30% of their capacity.**

This should be taken into consideration when sizing the back-up generator.

5.4. BATTERIES

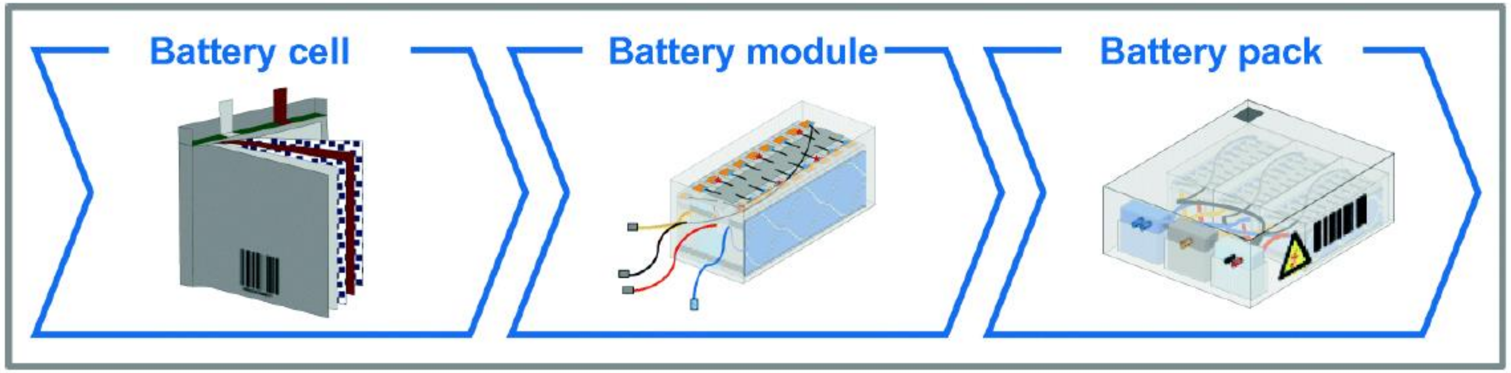
Batteries

Batteries play a key role in renewable energy off-grid systems:

- Allowing to store intermittent or fluctuating production from renewable energy sources, such as PV and Wind. This energy is stored and dispatched when the demand exceeds generation.
- Form the grid in off-grid systems with high renewable fraction. Diesel gensets are not essential anymore.

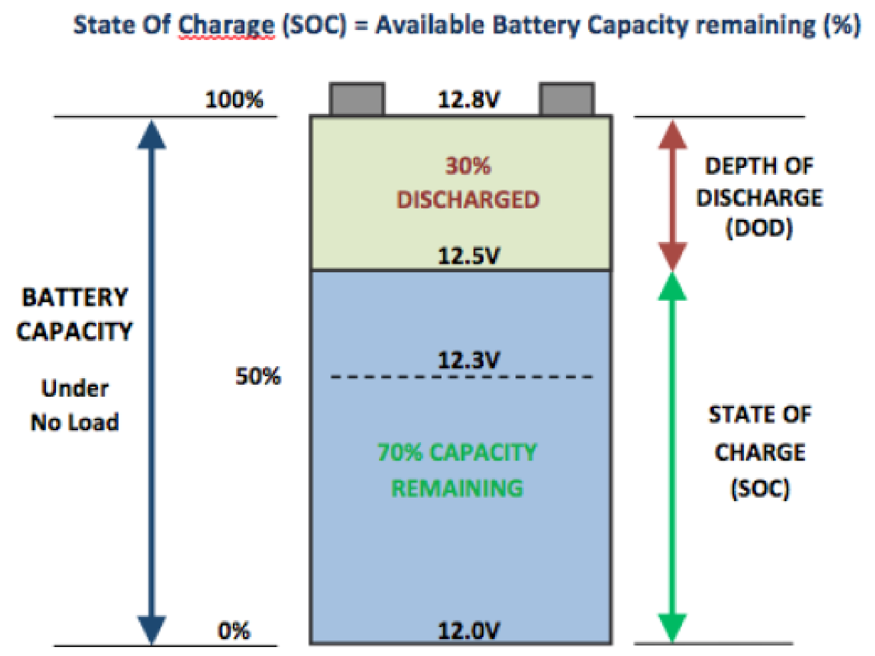
3 main types of batteries:

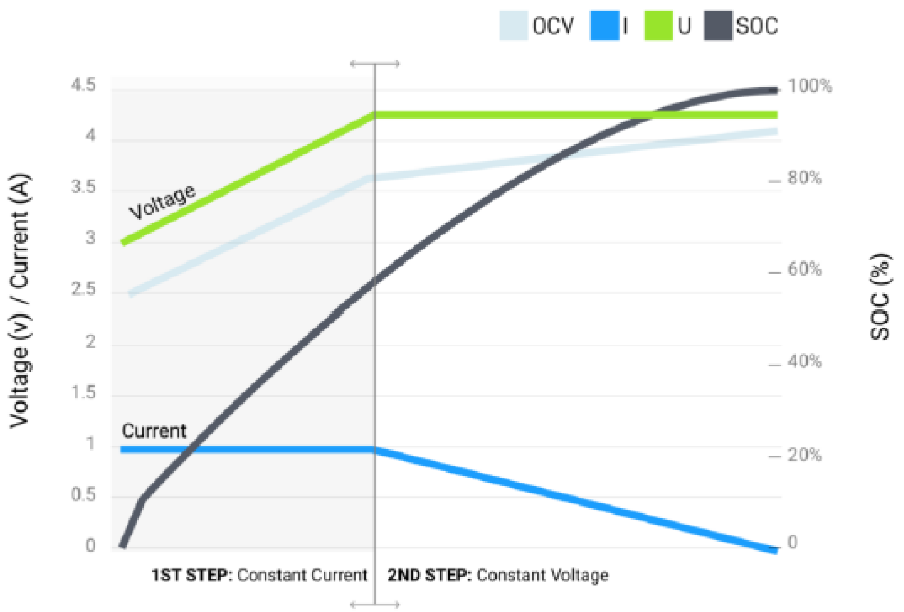
- **Lead-acid batteries**-Traditionally used for off-grid power systems but are not widely used today
- **Lithium-ion batteries**-Now the most common type of battery
- **Flow batteries**-Generally used for larger energy storage applications and gradually evolving



BATTERIES: BASIC CONCEPTS

- **Depth of discharge (DoD):** amount of battery power used/discharged as a percentage of maximum capacity.
- **State of charge (SoC):** amount of energy available as a percentage of maximum capacity.
- **Nominal Voltage (V):** The reported or reference voltage of the battery, also sometimes thought of as the “normal” voltage of the battery.
- **Cut-off Voltage:** The minimum allowable voltage. It is this voltage that generally defines the “empty” state of the battery.
- **Charge Voltage:** The voltage that the battery is charged to when charged to full capacity (usually 15% higher than nominal voltage). Charging schemes generally consist of a constant current charging until the battery voltage reaching the charge voltage, then constant voltage charging, allowing the charge current to taper until it is very small.
- **Float Voltage:** The voltage at which the battery is maintained after being charge to 100 percent SOC to maintain that capacity by compensating for self-discharge of the battery.





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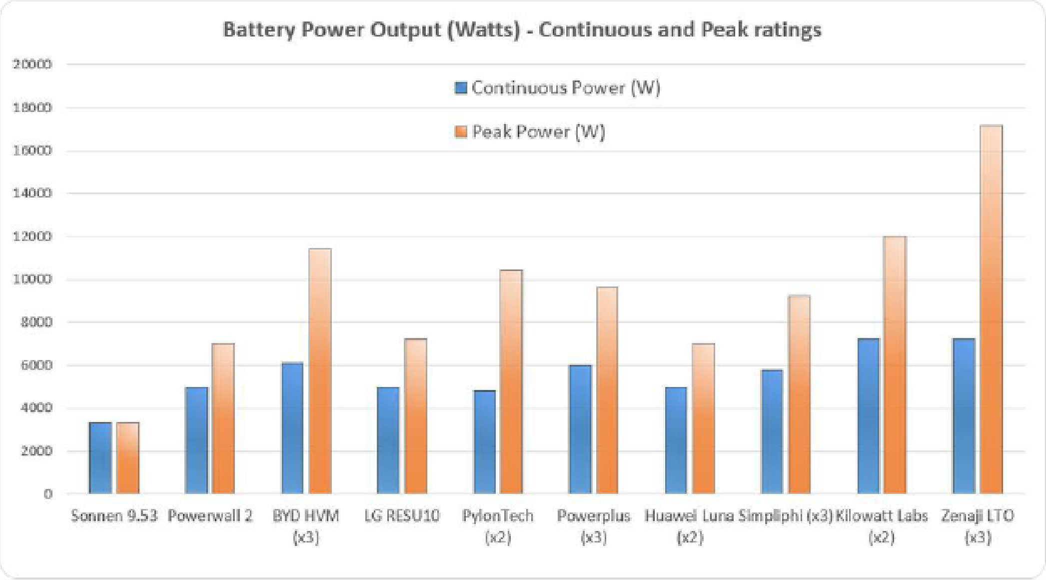
BATTERIES BASICS

- **Round trip efficiency:** is the charging and discharging efficiency or loss during cycle use.
- **Capacity (C):** is measured in either Amp Hours (Ah) or kWh. To convert Ah to kWh multiply the battery Ah rating by the total battery bank voltage.
- **C-rate:** speed at which the battery is fully charged or discharged. Is measured in A/Ah or W/Wh. It can be represented in 2 different ways:
    - Number in front of the C → Example: 10C with 100 Ah, can be charged/discharged at 10 x 100 Ah = 1000 A → 6 minutes
    - Number after the C → Example: C10 with 100 Ah, can be charged/discharged at 100 Ah / 10 = 10 A → 10 hours

- **Maximum Continuous Discharge Current/power:** The maximum current (A)/power (W) at which the battery can be discharged continuously.
- **Maximum 30-sec Discharge Pulse Current (peak power):** The maximum current (A)/power (W) at which the battery can be discharged for pulses of up to 30 seconds.



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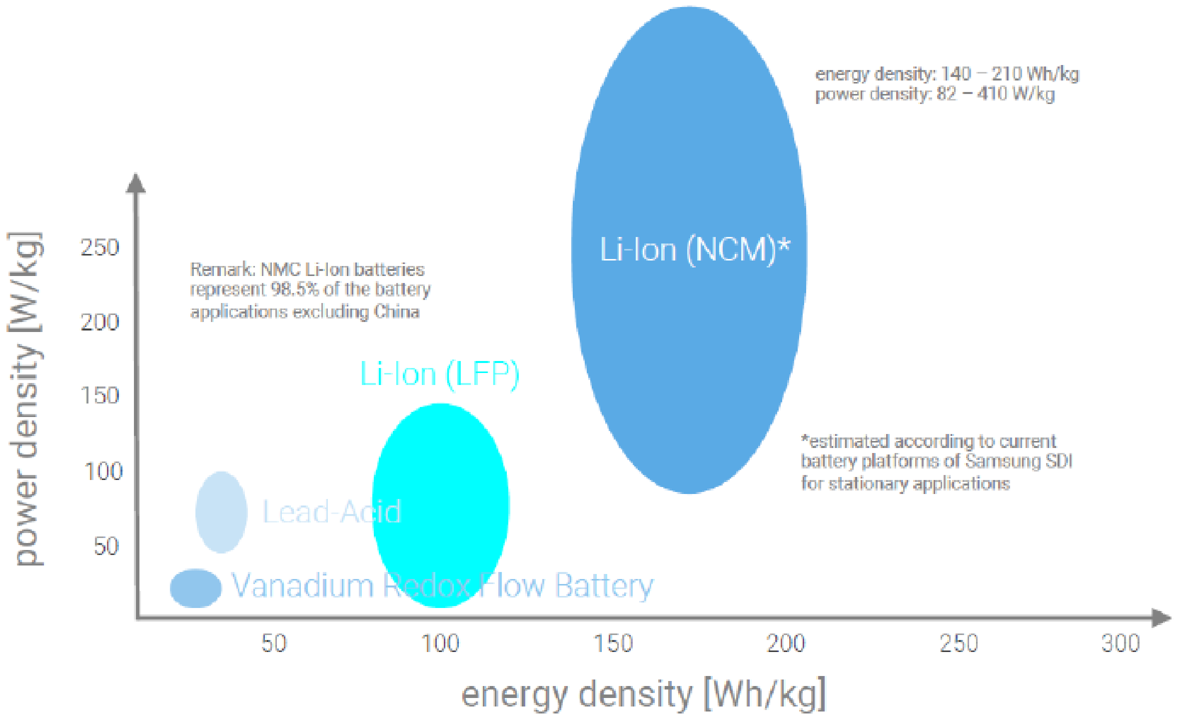
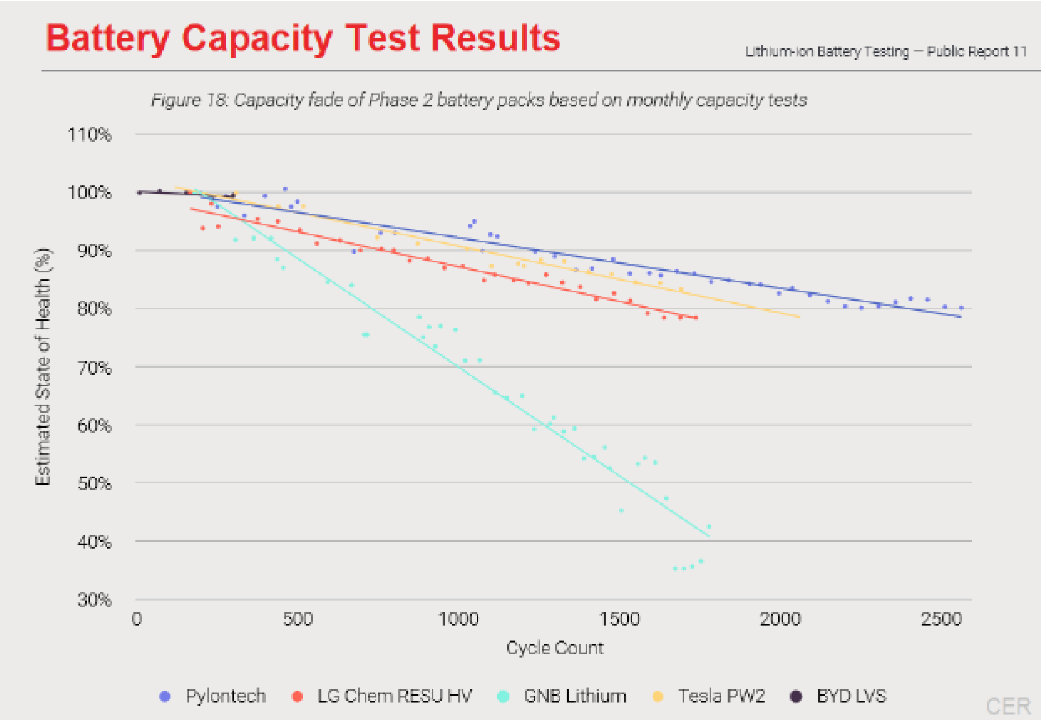
BATTERIES BASICS

- **Specific Energy (Wh/kg):** The nominal battery energy per unit mass, sometimes referred to as the gravimetric energy density. Specific energy is a characteristic of the battery chemistry and packaging.
- **Specific Power (W/kg):** The maximum available power per unit mass. Specific power is a characteristic of the battery chemistry and packaging.
- **Energy Density (Wh/L):** The nominal battery energy per unit volume, sometimes referred to as the volumetric energy density. Specific energy is a characteristic of the battery chemistry and packaging.
- **Power Density (W/L):** The maximum available power per unit volume. Specific power is a characteristic of the battery chemistry and packaging.



BATTERIES BASICS

- **Cycle Life:** The number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. The actual operating life of the battery is affected by the rate and depth of cycles and by other conditions such as temperature and humidity.
- **Warranty:** may be void if operating conditions are different than the manufacturer's warranty conditions.
- **Throughput warranty:** is the total energy a manufacturer expects the battery to deliver throughout its lifetime, usually expressed in MWh.
- **State of Health (SoH):** relation between the maximum charge available in the battery and the rated capacity.
- **End of life (EOL):** Almost all battery technologies slowly lose capacity over time. Industry standard establish a EOL once battery capacity has dropped to 80% of original capacity. (more recent lithium manufacturers are warranting their batteries to lower EOL values of 60 or 70%).
- **Operating temperature:** It has a significant effect on SOC (lower battery temperatures will reduce the SOC and amount of energy available), SoH, EoL…

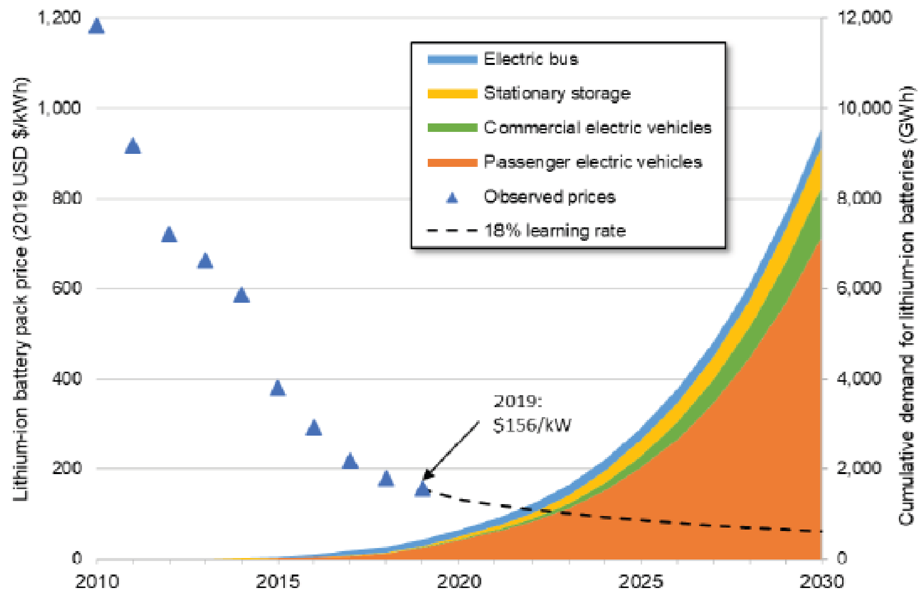


BATTERIES: LEAD-ACID

- Lead-acid batteries are the oldest type of storage battery and for a long time, they were considered the battery of choice for off-grid power systems due to their reliability and long service life.
- Are available in a huge variety of different types and sizes and can be anything from a single cell (2V) battery or be made up of a number of cells linked together in series to operate at a required voltage (usually 6V, 12 V or 24 V).
- There are several different types:
  - **Flooded lead-acid:** oldest and most basic type. Until 10-12 years ago flooded batteries were the most common deep cycle battery available and are still used for some large off-grid systems. Long durability (up to 20 years) if regular maintenance is performed.
  - **Valve regulated lead-acid (VRLA):** sealed in a leak proof enclosure with the electrolyte in a non-liquid form. Are safer and easier to handle and transport. However, if the battery is exposed to overheating, excessive voltage or current, it will release gas.
    - **Absorbed glass mat (AGM):** It is most cost effective, however has a lower lifespan.
    - **Gel electrolyte (GEL): it** has a good performance under high discharge rates and longer durability, but it is more expensive.
  - **Lead-carbon:** are also sealed and typically use a gel electrolyte for improved safety and low maintenance. The carbon acts as a sort of 'supercapacitor' which allows faster charging and discharging, plus prolonged life at partial state of charge.
  - **Deep cycle OPzV tubular gel:** very high performance and high cycle life, but also more expensive.

BATTERIES: LITHIUM-ION

- Lithium-ion batteries have only been commercially available for 10-15 year. Lithium-ion battery pack costs have dropped by more than 80% over the past decade and are expected to continue to fall based on technological improvement and continued scale of production, driven largely by electric vehicle demand.
- There are many different types of Li-ion batteries available with the most common being lithium-ion phosphate (LiFePO4 or LFP), Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium polymer.
- There are now two main types available, the common low voltage (48V) systems and the higher voltage (300-500V) battery systems.



Advantages

- Higher energy density and specific energy.
- Longer duration
- Are able to be deeply discharged 80-90% of total capacity without compromising the life of the battery.
- Can be charged faster
- Do not expel any volatile gases during charging & discharging unlike some lead-acid batteries and are safe to be installed inside a building without the need for complex venting systems.

Disadvantages

- Higher cost
- Individual lithium cells have a very high energy density and can heat up during use, thus they require sophisticated control systems known as a BMS (Battery Management System) to monitor cell temperatures and voltage so they are not over-charged and damaged.

BATTERIES: LITHIUM-ION VS LEAD-ACID

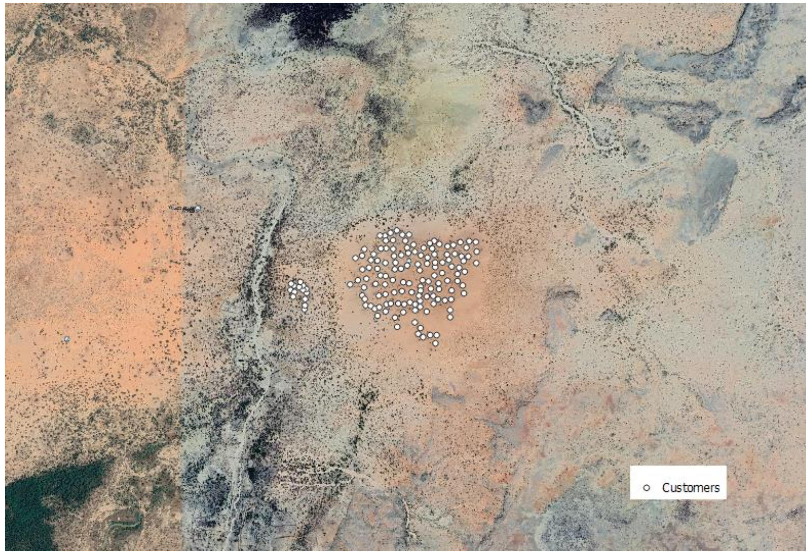
Parameter	Lithium-ion	Lead-acid
Round trip efficiency	92% - 98%	76% - 85%
Charge time	1 to 2 hours	2 to 4 hours
Depth of discharge	80-90%	AGM: 20-30% Gel: 20-40% Carbon: 20-50%
Cycle life	3,000-4,500 cycles	1,000-3,000 cycles
Lifespan	10-20 years	3-12 years
Warranty (1 cycle/day)	~10 years	~5 years
Energy density	110-160 Wh/kg	30-50 Wh/kg
Cost	~700-1000 US$/kWh	~400-6000 US$/kWh
Recycling	Complex	Easy

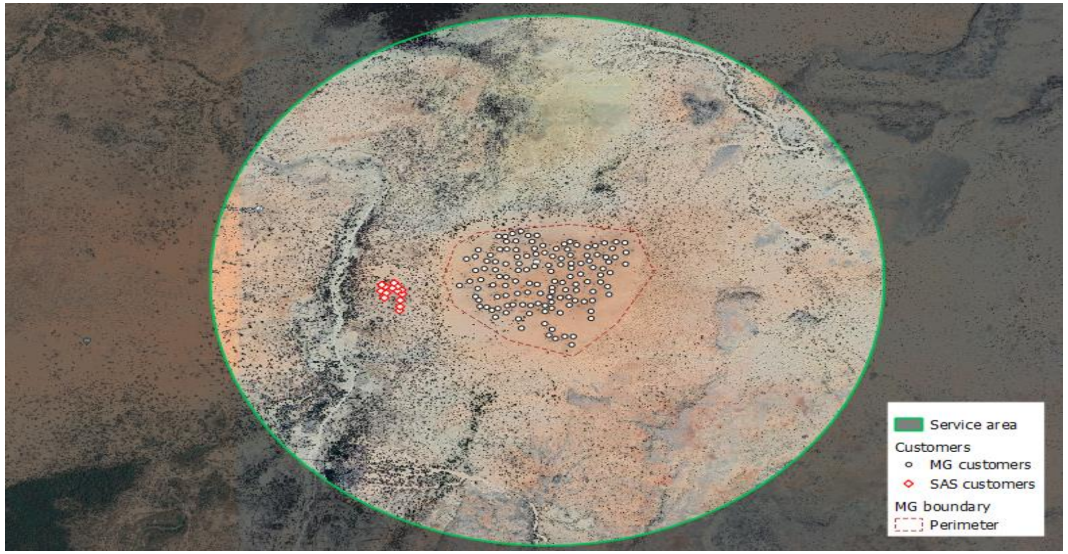
6. DISTRIBUTION NETWORK

Distribution network pre-design

Step 1 - Mapping out potential users
Identify connection points and categorize per consumer type. This step can be performed by collecting GPS coordinates during the site visits or through GIS tools able to identify different types of buildings.

Step 2 – Defining the service area
Understand the boundaries of the site and define the criteria to determine mini-grid customers versus standalone consumers. Definition of inner and outer boundaries can help during this task.





Distribution network - Example

Lamap, Malekula Island, Vanuatu

Distribution network - Example

Lamap, Malekula Island, Vanuatu

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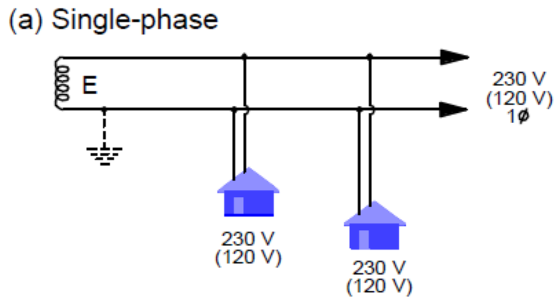
Line configuration

a) SINGLE-PHASE

Nº conductors: 2 wires
V = 230 V_{AC}



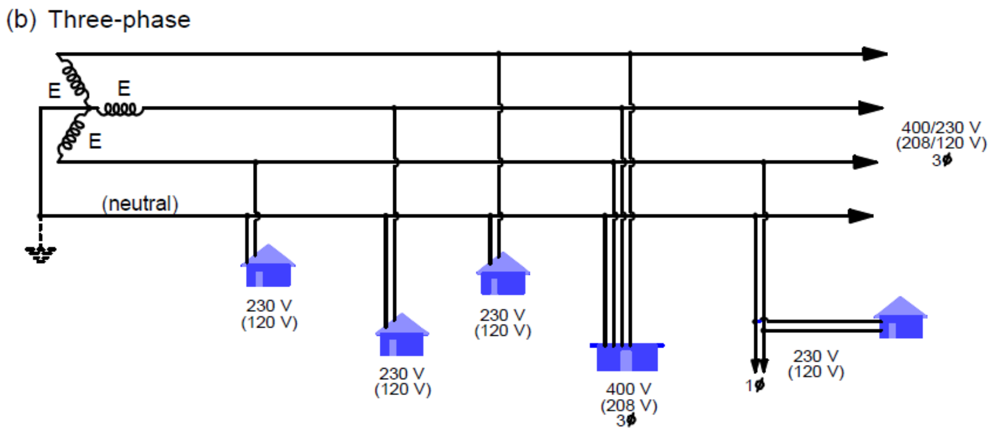
P = V x I

(V = 230V)

$$I = \frac{P}{230}$$

b) THREE-PHASE

Nº conductors: 4 wires
V = 400/230 V_{AC}



P = 1,73 x V x I

$$I = \frac{P}{1{,}73 \cdot 400}$$

Overhead VS Underground

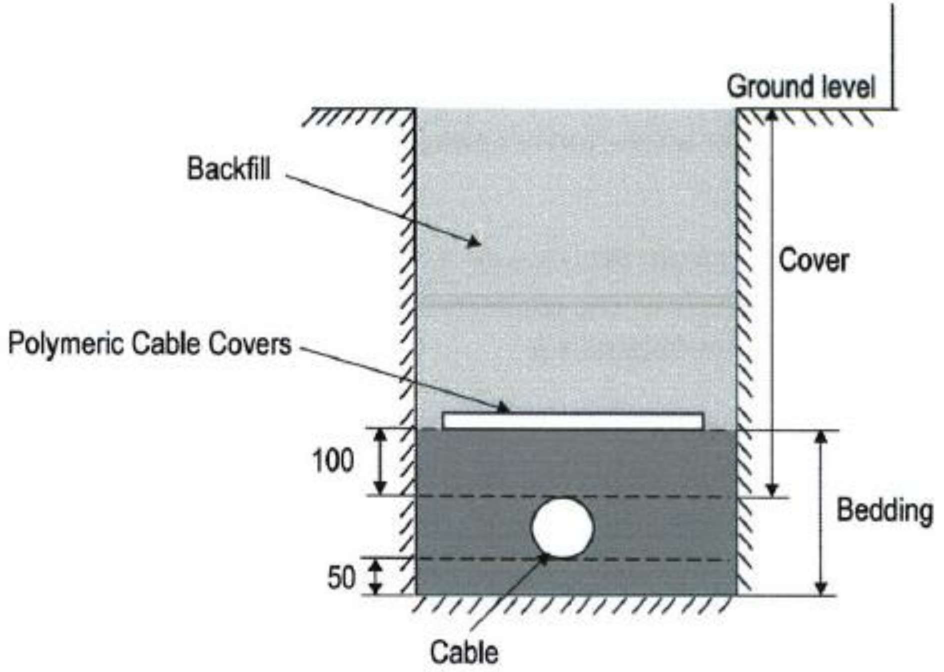
UNDERGROUND

Pros

- Not visual impact
- Resilient cyclones, etc.
- Less hazard to individuals (no direct contact)
- No need to remove trees
- Lower preventive maintenance

Cons

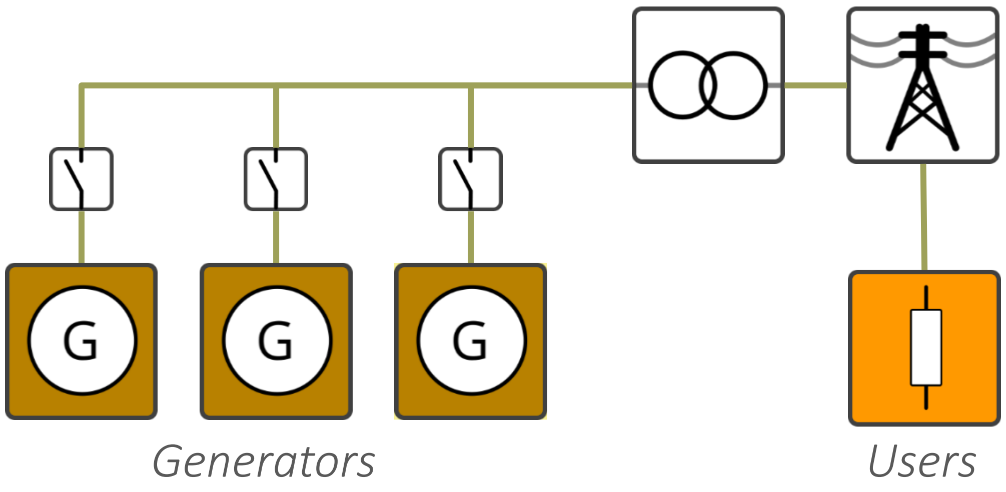
- Difficult locating and reparing faults
- If additional capacity is required in the future, not easy in increase
- Exposed to water, insects, rats
- Digging trenches can be difficult in locations with hard soil condition



7. HYBRIDIZING DIESEL MINI-GRIDS

Diesel mini-grids

The geographical configuration of most of the Pacific countries does not allow for a main grid, servicing all the population. Many places are already relying on isolated mini-grids, mostly powered by diesel generators.



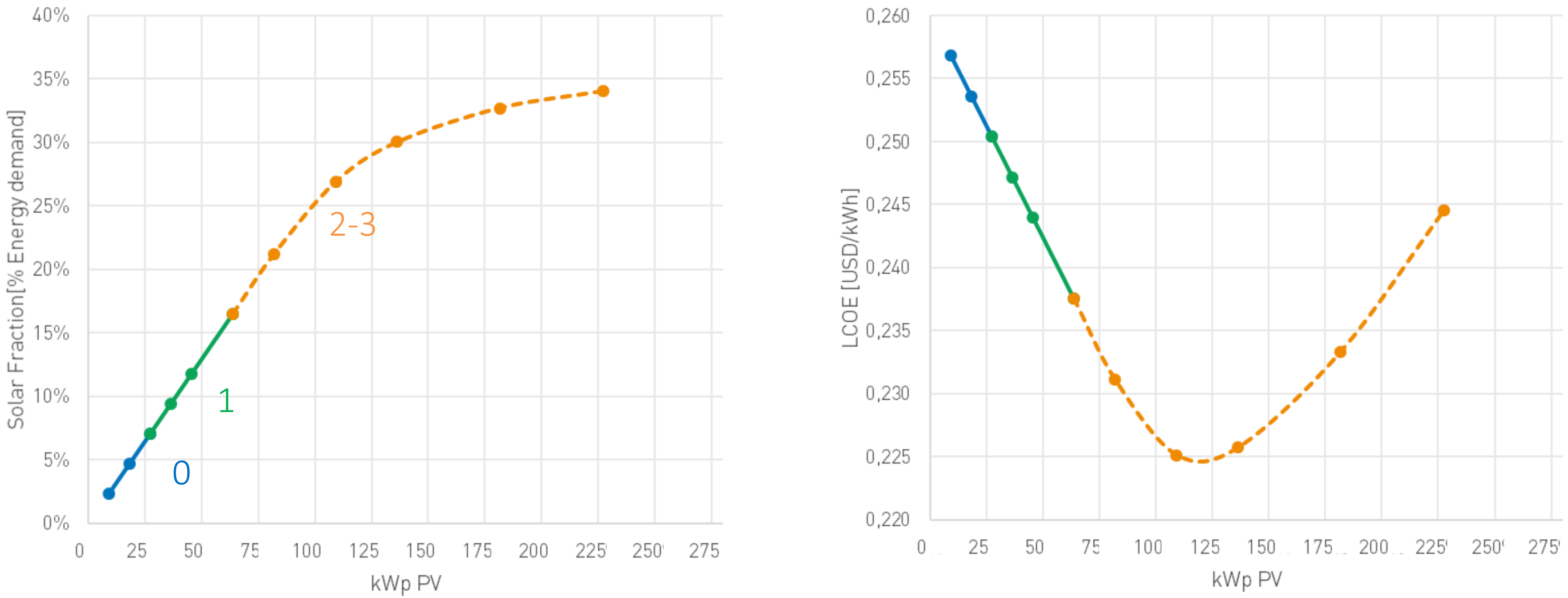
In the past years, with renewable technology cost going down and fuel price going up, **hybridazing the existing diesel mini-grids** has become more and more common.

Nevertheless, often it is not straightforward.

Sizing of PV in an hybrid system

Finding the **optimal size of the system** depends on the following factors:

- Load profile, grid configuration and operation and technology to be used



PV-Diesel Hybrid systems: How much storage is useful - Prof. A. Notholt - PV Days- Halle - 24.10..2017

Example calculation HS in Bolivia, Load 165MWh/dy, CAPEX PV: 1 250USD/kWp, CAPEX Battery: 1000USD/kWh, OPEX: 10% CAPEX/a, Diesel:production costs 0,26 USD/kWh (~1USD/l)

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Source: Prof. A. Notholt

Classification of hybrid systems

Type	Genset operation	Photovoltaic generator	Storage size	Controller	Fuel savings
0	24/7	No control necesary	N/A	N/A	+ (SF < 5%)
1	24/7	Controllable (limit)	N/A	PV (limiting)	++ (SF < 15%)
2a	24/7	Controllable (limit)	Small (Power application)	PV & Storage (ramp rate & reserve)	+++ (SF < 25%)
2b	24/7	Controllable (limit)	Medium (power/energy application)	PV & Storage (Ramp rate & peak shaving)	++++ (SF > 25%)
3	On demand	Controllable (limit)	Large (with grid forming capabilities)	PV, Storage & Diesel	+++++ (SF > 50%)

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Based on the classification per Fraunhofer ISE (Rogalla, et al. 03/2017 Bad Staffelstein)

For hybrid systems of type 2a, 2b and 3, an **analysis of the stability and power quality of the grid** must be conducted to make sure that the addition of the renewable energy plant does not affect the regular operation of the grid.

Source: Prof. A. Notholt

Design principles

- **The system should not let the diesel generators run under their minimum load**

- **The system must have enough spinning reserve to cope with load changes or PV production gradients**
  - Battery systems provide a great solution to this problem.

- **System stability must be guaranteed at all times**
  - In form of an N-1 online planning
  - If PV production would at some point negatively influence stability, it must be curtailed. This requires communication to the plant.

- **In some configurations** (systems type 2b-3) **it may be economically optimal to turn all generators off (Diesel-off mode)** when the battery has enough State of Charge. In this case:
  - The current protection system (circuit breakers, fuses) must be analysed and shall be compatible with the use of inverters (I_k'' between 1.5 and 2)
  - Grid-forming inverters to be specified.

Source: Prof. A. Notholt

3. ADDITIONAL RESOURCES

ADDITIONAL RESOURCES

- Rocky Mountain Institute: https://rmi.org/insight/solar-under-storm/
- PPA technical guidelines: https://www.ppa.org.fj/publications-2/
- Powerspout: https://www.powerspout.com/pages/document-index

Vinaka!

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