Photovoltaic System Components

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Comparison with Gensets

- Fossil fuel generator sets (gensets) are the main competitor of PV systems in remote areas.
- Gensets are widely distributed and well-known, but so are their drawbacks, e.g. high costs, difficult and unreliable fuel supply as well as intensive operating and maintenance requirements.

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System and Components

- A typical solar PV system for electric power supply consists of:
  - A solar generator for power generation
  - A battery to store this energy
  - A charge controller to operate the battery in a suitable way
  - Appliances and sometimes a power conditioning unit such as an inverter.

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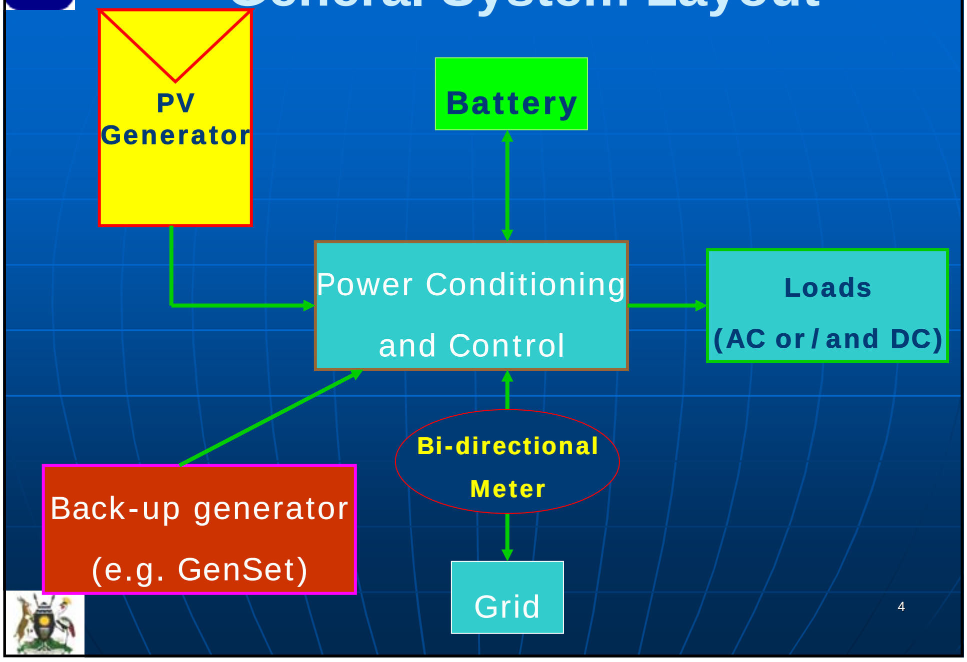
General System Layout



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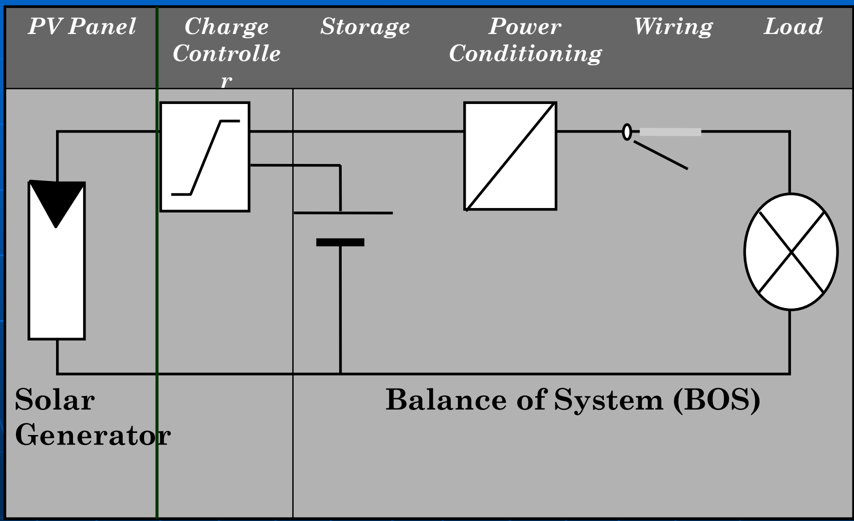
Basic Solar Home System (SHS)



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Entire System

- ***Solar panel*:** The heart of a solar PV system made of solar cells which convert solar radiation directly into electricity **(PV** conversion).
- During the day, the generated electricity by PV generator is immediately channelled to the **load** *(if available)*. Electricity not used by the load during the sunshine hours is stored in the ***battery*** for night time and over cast use.
- The ***charge controller***, referred to as the battery control unit (BCU), regulates the battery current flow. The BCU automatically reduces the charging from the solar panel if the battery is full and interrupts the flow of current to the load when the battery is too much discharged.

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…. Entire System

- **Power conditioning** can transform the direct current of a solar system (usually 12 V) into other voltages and frequencies, e.g. as required for 240 V, 50 Hz ac appliances, i.e., 3-phase pumps and fluorescent tubes.
- In order to function properly, all the components have to be matched and work harmoniously with each other.
- Note, that a complete PV system includes the loads.
- Thus, the selection of the suitable loads or appliances plays a central role in the design procedure

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PV Generator

- A solar panel is an assembly of solar cells which aims to protect the very delicate cells against ambient influences and to interconnect them to produce a handy voltage / current rating. PV panels today come typically in 12 V and in sizes up to 80 W_p (in case of Uganda).
- Photovoltaic panels are distinguished by their cell material. There are three main types of silicon solar cells commercially available - the ***monocrystalline***, ***polycrystalline*** and ***amorphous*** PV cells.

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…. PV Generator

- **Monocrystalline** cells have the highest efficiency among the three types. Made from solid crystals of silicon.
- **Polycrystalline** cells show several large silicon crystals. Their manufacture is generally less expensive and their efficiencies are less.
- The **amorphous** thin film cell is the one commonly known from calculators and other small solar devices. It has no crystal structure and the lowest efficiency.

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…. PV Generator

- The performance of a solar cell is characterized by an I-V curve with the following points:
- Short-Circuit Current (I_{SC}): the maximum current produced by the solar generator under given conditions of irradiation and temperature, corresponding to zero output voltage, the power at this point is zero.
- Open-Circuit Voltage (V_{OC}): the maximum voltage under given conditions of light and temperature, corresponding to maximum voltage but zero current flow, the power at this point is zero.

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…. PV Generator

- Maximum Power $P_{MAX} = I_{MPP} * V_{MPP}$ [W_P]: the point on the I-V curve where under STC (radiation 1 kW/m^2, 25°C, AM1.5) the power is a maximum. PV panels are quoted by their maximum power, rated in Watt peak [W_P]
- Fill Factor, $FF = P_{MPP} / \mathbf{I_{SC}} * \mathbf{V_{OC}}$: Solar cell I-V curves have maximum curve factors of about 0.8.
- Conversion Efficiency, $\eta_{sc} = P_{MPP} / P_{Ph}$ Efficiency in relation to the incident irradiation power is the most important parameter of a solar cell. Silicon cells could theoretically achieve 24% efficiency and today practically reach 18 %.

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NOCT

- NOCT = Normal Operating Cell Temperature. Is defined as the cell temperature when the module operates under the following conditions at open circuit, irradiance 0.8 kW/m^2, spectral distribution AM1.5, Ambient Temperature 20^{0}C and wind speed < 1 m/s
- NOCT for modules is usually between 42^0 C and 46^0 C
- It is used to determine cell temperature T_C from Ambient temperature T_A, NOCT and irradiance G (kW/m^2) as follow:

$$T_C = T_A + \frac{(NOCT - 20)}{0.8} G\left(kW / m^2\right)$$

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Impact of Temperature

- It is an important parameter of the PV system operation
- Solar cells are characterised by the temperature coefficient for open circuit voltage (-α [mV/^{0}C])
- For silicon cells α ≈ 2.3 mV/^{0}C for individual cell
- The current coefficient, β [μA/^{0}C] is very small and positive, for silicon β ≈ +6 μA/^{0}C (usually negligible)
- Only voltage variation with temperature is considered in practical calculations. Consider a module with n_c solar cells, then α is calculated as:

$$\frac{dV_{OC}}{dT} = -2.3xn_C\left(mV/^0 C\right)$$

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Impact of Irradiance

- I_{SC} of the module is proportional to irradiance
- In the design of solar PV generator it is customary to neglect the voltage variation, but to set the I_{SC} proportional to irradiance

$$I_{SC}(G) = I_{SC}(at\_STC)xG(kW/m^2)$$

- The operation of the module should lie as close as possible to the maximum power point
- Thus I_{MPP} depends on G roughly independent of temperature and V_{MPP} depends on temperature and roughly independent of G

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Storage (Batteries)

- As the sun does not always shine as much and when needed for a particular load, the PV system requires a storage device.
- The most frequent storage used for PV systems is a chemical battery.
- The common battery used in solar systems is the lead-acid battery.
- Readily available all over the world, however, a solar battery should be selected with care. Otherwise it may become the most expensive

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Features of Solar Batteries

- Batteries can be manufactured to match solar conditions, which impose low-current charging / discharging and frequent, deep cycles:
- Deep cycle proof and should survive frequent discharges for long time.
- They have a high charging and discharging efficiency.
- Low maintenance requirements e.g. need less refills with distilled water.
- They have low self-discharge rate.
- Reliable and ability to survive complete discharge
- Minimum change in performance over temperature range of operation

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Features of Solar Batteries

- Deep cycle batteries are highly recommended for use in a solar system for they last longer and give more power.
- In Solar Home System cheap ordinary automotive batteries are used, but it is not as efficient as deep cycle battery.

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The Lead – Acid Battery (Pb –H_2SO_4)

- A Pb-Acid storage battery is an electrochemical device which stores and converts chemical energy into electrical energy. When the battery is connected to an electrical load, the chemical energy is converted into electrical energy and current flows through the circuit.

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Materials for a Pb –H_2SO_4 Battery

- Anode: Lead Oxide (PbO_2) as active material
- Cathode: Lead (Pb) as active material
- Electrolyte: Sulphuric Acid (**H_2SO_4**) solution

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Charging and discharging Pb –H_2SO_4 Battery

- Lead-acid batteries are called .secondary batteries. or accumulators since they are rechargeable.
- The electro-chemical reactions which take place during charge and discharge of a lead acid battery are:

charging:

$2PbSO_4 + 2H_2O \rightarrow PbO_2 + Pb + 2H_2SO_4$

discharging:

$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$

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Charging and discharging a Pb $-H_2SO_4$ Battery

- The electrolyte becomes pure water during discharge; a discharged battery therefore has the density of about 1 kg/liter.
- During charging, sulfuric acid is formed; a fully charged battery should have a density of about 1.24 kg/liter.

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Charging and discharging a Pb – H_2SO_4 Battery

- The voltage over a battery plate changes with the state of charge.
- The nominal voltage of one cell is 2 V. During discharge it can drop to 1.8 V which would be an undesirable deep-discharge.
- During charging the voltage may rise to 2.5 V which would be an equally undesirable overcharge. Oxygen can be released, visible by bubbling, and the electrolyte level decreases while the density is raised.
- Charge controllers have to maintain the voltage between 1.92 and 2.42 V per cell or 11.5 V and 14.5 V for a 12 V battery.

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Measuring state of charge

- Measuring density of the electrolyte is the good measure for state of charge.
- Hydrometer is used to measure relative density of the electrolyte
- Also a voltmeter can be used to measure voltage since voltage is related to density of the electrolyte

Battery Capacity

- Batteries are rated by their capacity and voltage.
- Capacity of the battery is measured in terms of the amount of current that can be discharged over a certain time. This is expressed as Ampere-hours (Ah). A battery discharged over 100 hours (C/100) will have higher capacity if it is discharged over 20 hours (C/20).

Battery Capacity

- The principal factors that affect the capacity of storage cells are:
  - quantity and concentration of electrolyte
  - cut-off or final voltage
  - rate of discharge
  - temperature
  - thickness of the plates
  - previous history of the plates

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Battery Capacity

Note that for the battery:

- Increasing the **depth of discharge** decreases cycle life.
- Increasing the **number of cycles** performed per year decreases life.
- Excessive **overcharging** leads to increasing positive grid corrosion, active material shedding, and shorter wet life.
- **Storing** wet cells in a discharged condition promotes sulphation (which is the formation of large grains on lead sulphate on the eletrodes)
- Sulphatation decreases capacity permanently and life.

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Types of Pb –H_2SO_4 Batteries

Type	*Application*	*Operation*	*Characteristics*
SLI	Vehicle starter batteries	Supply of high peak power for short time	Low resistance to cycling
Traction	Electric vehicles	Deep and frequent cycles	High water consumption, frequent maintenance
Stationary storage	Emergency power supply	Operation in high state of charge	moderate resistance to cycling, low water consumption

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Battery Control Unit (BCU)

- With the factors affecting the capacity of the battery, it is important, that the battery is designed to match the operating and life requirements of the application.
- Therefore there is a need for a control unit to control the discharging and charging processes
- The BCU sometimes is known as Charge Controller or simply Controller or regulator

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….. BCU

- The battery control unit or BCU is the central power management of a SHS and provides also information about the system status

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Types of Charge Controllers

- This is responsible for regulation of the charging voltage to prevent excessive gassing and overcharging
- Types of controllers are:
    - Shunt Regulator
    - Series Regulator

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Shunt Regulator

- Has a variable resistance element in parallel with the battery
- The current from PV is shunt when the resistance reduces & less current through the battery
- The variable resistance element is generally a transistor (MOSFET)
- Disadvantage: May dissipate large amount of power

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Series Regulator

- Variable resistance element is connected in series with the PV array and battery
- The resistance increases as the battery gets charged and voltage rises.
- The increase in resistance is to reduce the battery voltage and current

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DC/DC Converter

- Transform DC power between one voltage and another
- Switching power converters are widely used
- Different circuits used
- The Buck converter (reduces voltage)
- Boost converter (increases voltage)

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Inverters

- Solar modules and batteries operate with DC. The mains electricity, however, is AC. Many electrical appliances and accessories are only available for AC.
- An **inverter** transforms low-voltage DC supplied by a solar system into high-voltage AC. The input of an inverter is designed for 12 V (24 V, 48 V, etc.), depending on the type.
- At the output it produces 240 V AC. Inverters are designed for stand-alone as well as for grid-connected systems.

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… Inverters

- Inverters are designed for a maximum load. They provide a certain **overload capacity** for a short-term demand arising e.g. from the starting current of a motor.
- High-quality inverters have an efficiency of more than 90% between 10% and 100% rated power.

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… Inverters

- Inverters produce a **sinusoidal current** like the mains, a modified square or a square wave current. Square wave inverters are not suitable. Sinusoidal inverters are optimal. Modified square inverters are approx. 40% cheaper, but electronic and motor-equipped appliances (TVs, computers, pumps, fans, refrigerators, etc.) may run poorly or may even be damaged.

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… Inverters

- Safety measures include protection against short circuit, overload, high input and output voltage, high temperature and reverse polarity.

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