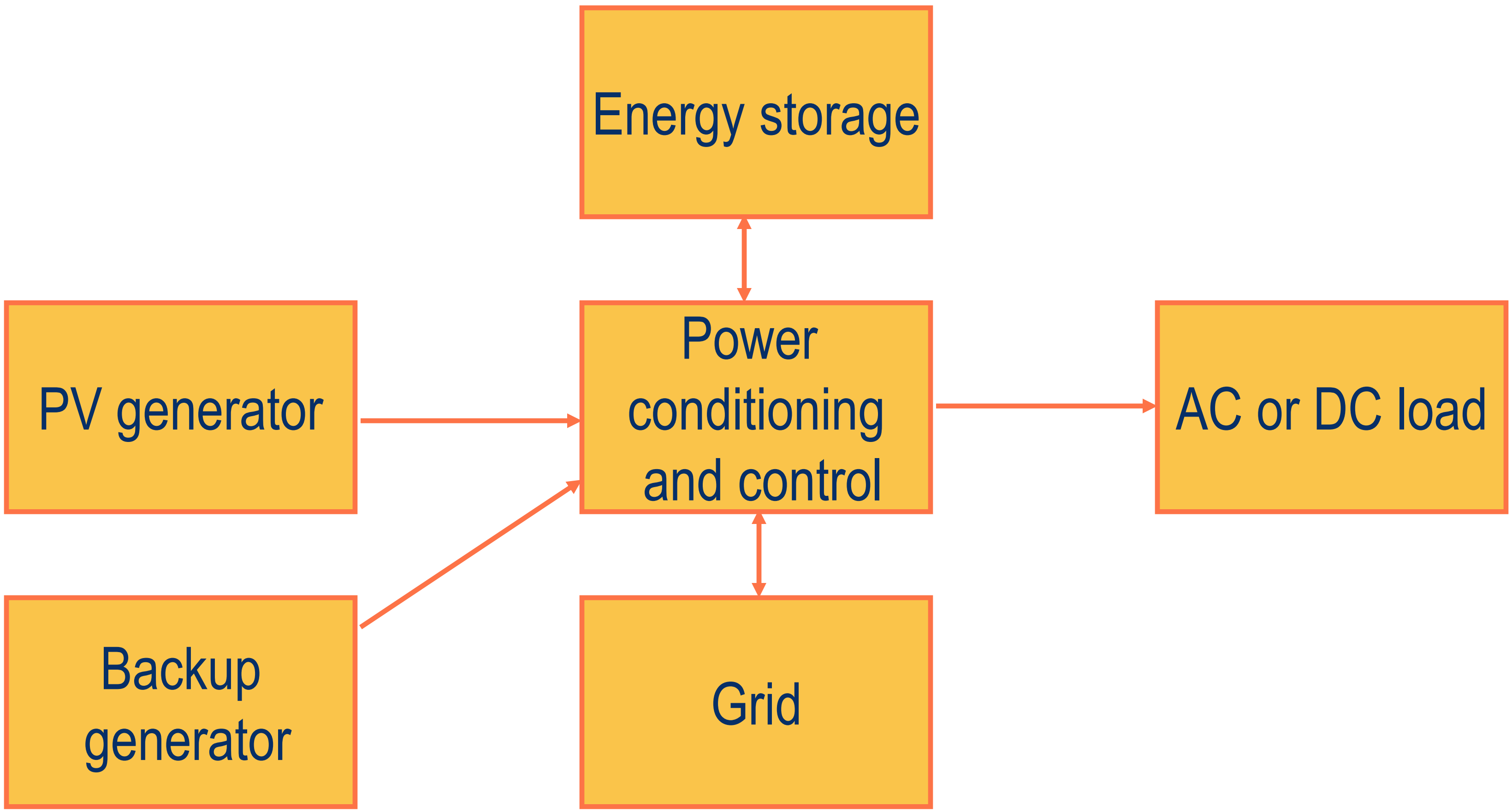
Solar energy systems

Overview

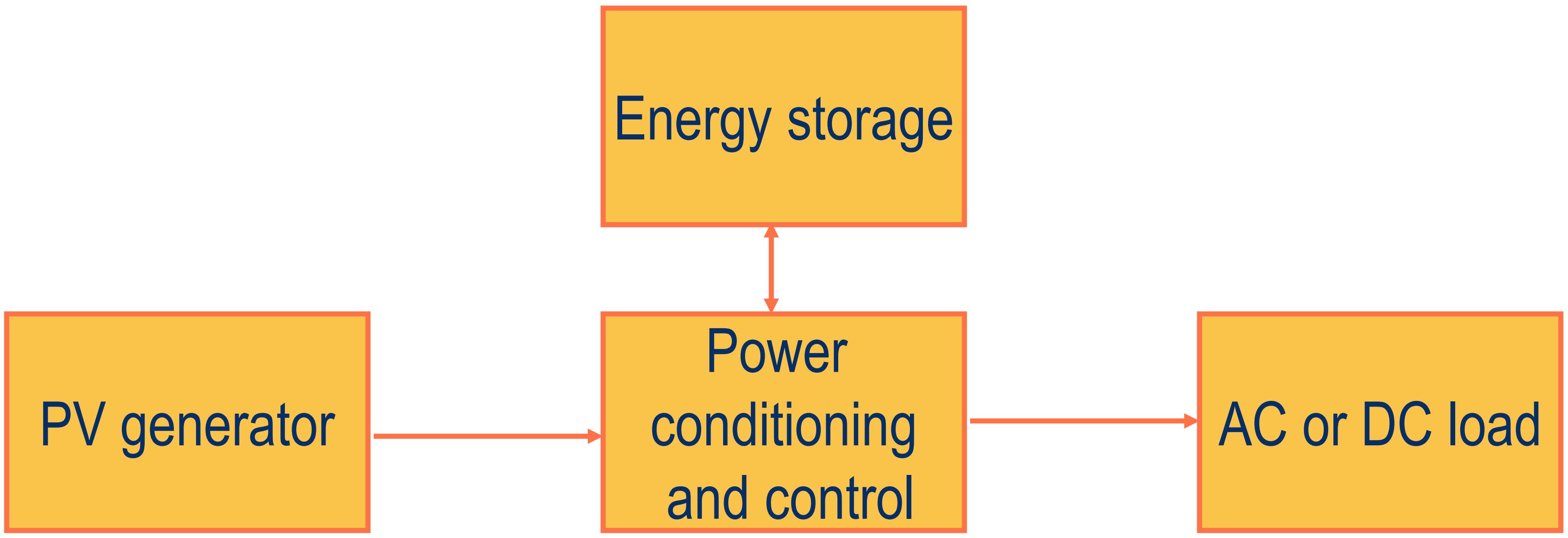
- Structure of a PV energy system
- The PV generator
- Energy storage
  - Batteries
- Power conditioning and control
- Sizing off-grid PV energy systems
- Example applications of PV energy systems
  - Off-grid systems
  - Grid connected systems
- Economics of PV energy systems
- Environmental impact of PV energy

Based on T. Markvart's book "Solar electricity – 2nd edition", Wiley 2005

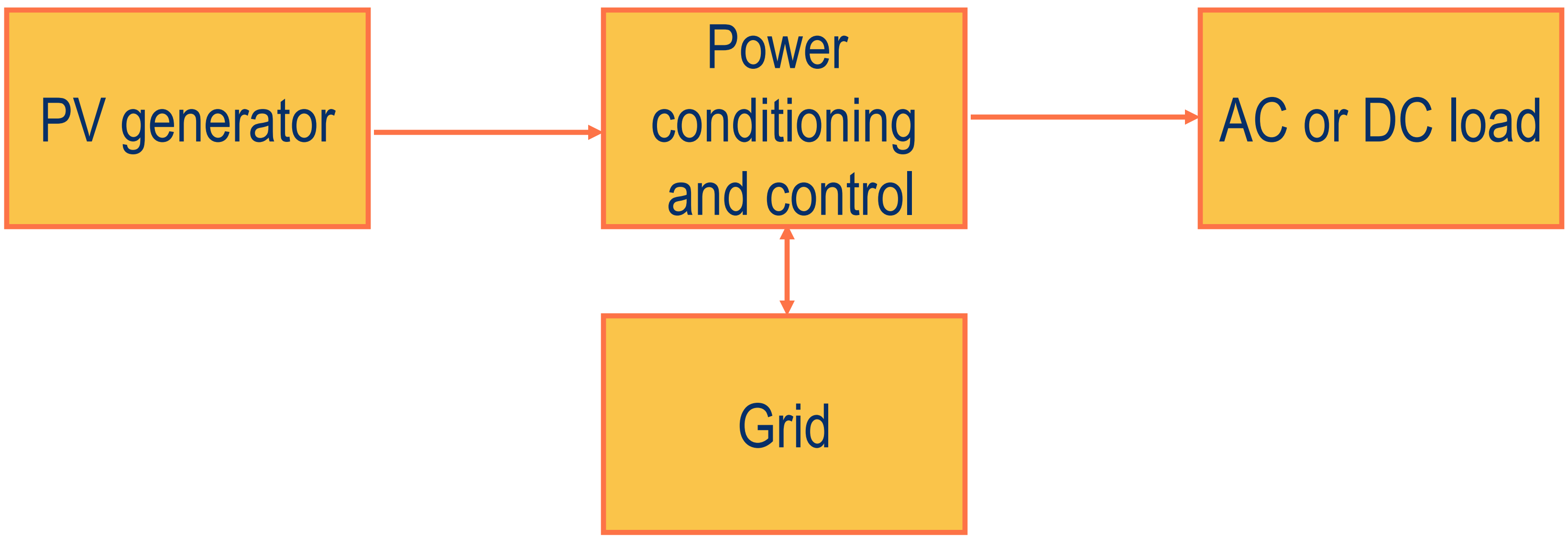
Structure of a PV energy system



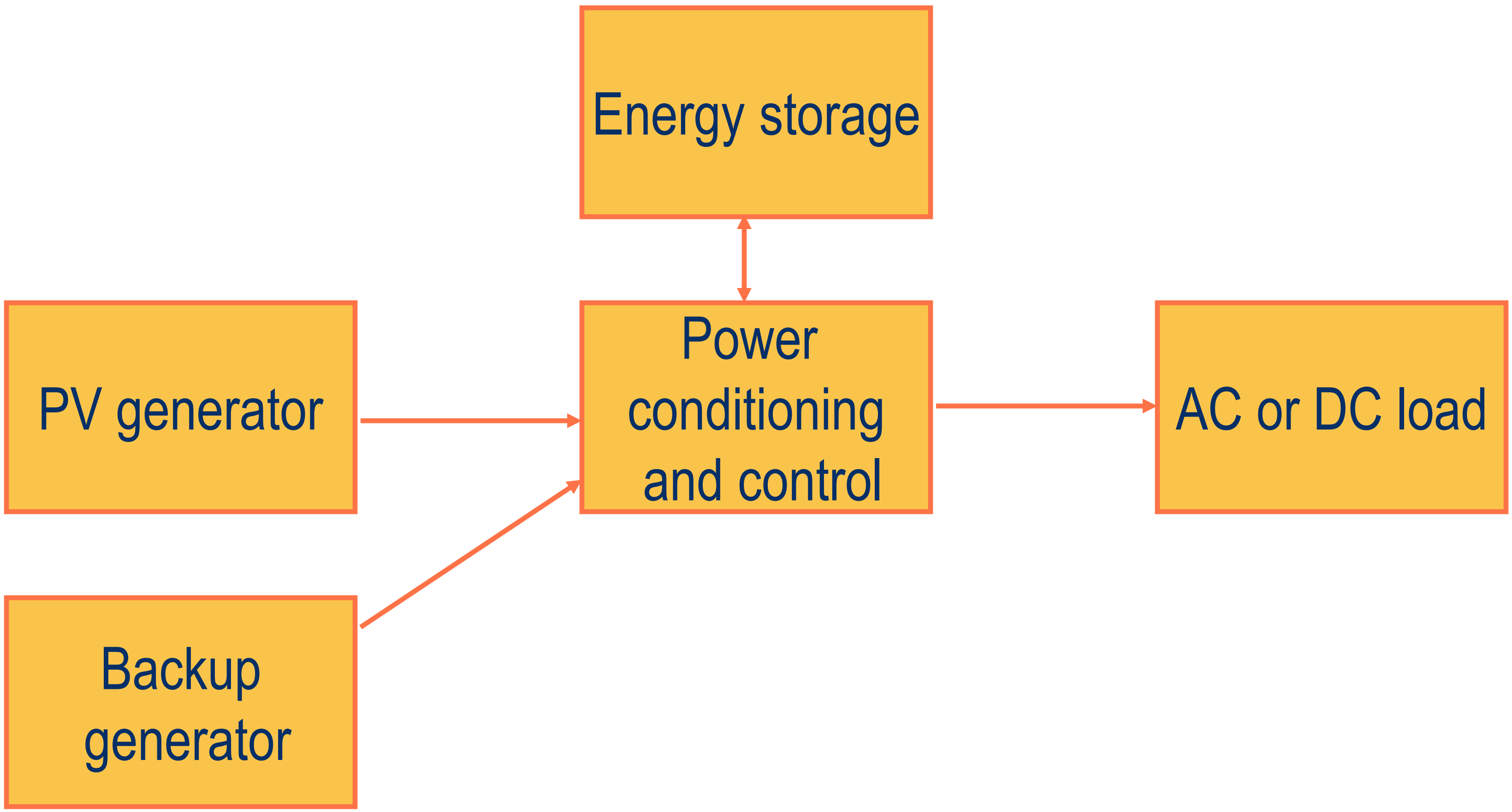
Stand alone PV energy system



Grid connected PV energy system



Hybrid PV energy system



The PV generator

- The solar module
  - Most PV modules are designed to work with 12 V batteries
    - Typical configuration: 36 cells in series
      - 36 * 0.5 V = 18 V
      - Some over-voltage allowed
      - Will give at least 12 V under non-ideal irradiation
  - From several tens to more than 100 W modules available
    - Output measured under STC
      - AM1.5 @ 1 kW/m^2
      - 25 ^oC
    - Nominal output often called W_p

Performance of the PV generator

- Effect of irradiance (G)

$$I_{SC}(G) \sim (I_{SC,STC}/G_{STC}) \cdot G$$

- Effect of temperature (T)

$$V_{OC}(T_c) = V_{OC,STC} + (T_{cell} - T_{cell,STC}) \cdot (dV_{OC}(T)/dT)$$

  - For Si solar modules: $dV_{OC}(T)/dT = -2.3 * N_{cells}$ [mV/K]
  - T_{cell} for a given G is given by the NOCT of the module

Nominal operating T_{cell} (NOCT)

- Nominal operating cell temperature (NOCT)

$$T_{cell} - T_{ambient} = (NOCT - 20\ ^{o}C/0.8) \cdot G$$

- Defined for a set of standard testing conditions (STC)
  - $G_{ref} = 0.8\ kW/m^2$
  - Wind speed 1 m/s
  - Ambient temperature = 20 ^{o}C
  - Mounting: open back side
- Typical NOCT values: 42 – 46 ^{o}C

Output power of a PV generator

- Example calculation
  - Module spec': $I_{SC,STC}$ = 3A, $V_{OC,STC}$ = 20.4 V, P_{max} = 45,9 W, NOCT = 43 ^oC
  - Operating conditions: G = 0.7 kW/m^2, $T_{ambient}$ = 34 ^oC

  - $I_{SC}(G) = I_{SC,STC} \cdot (G/G_{STC}) = 2.1\ A$
  - $T_{cell} = T_{ambient} + (NOCT - 20\ ^oC/0.8) \cdot G = 54.1\ ^oC$
  - $V_{OC}(T) = V_{OC,STC} + (T_{cell} - T_{cell,STC}) \cdot (dV_{OC}(T)/dT) = 18.1\ V$

- Assuming a FF independent of T and G:
  - $FF = P_{max} / I_{SC,STC} \cdot V_{OC,STC} = 0.75$
  - $P_{max}(G,T) = I_{SC}(G) \cdot V_{OC}(T) \cdot FF = 28.5\ W$

  - Under these conditions, this module operates at 62 % of nominal rating

Output power of a PV generator

- Any given situation with any given T and G has a corresponding maximum power point (MPP)
  - If possible, it is important to ensure operation of a PV generator as close to the MPP as possible

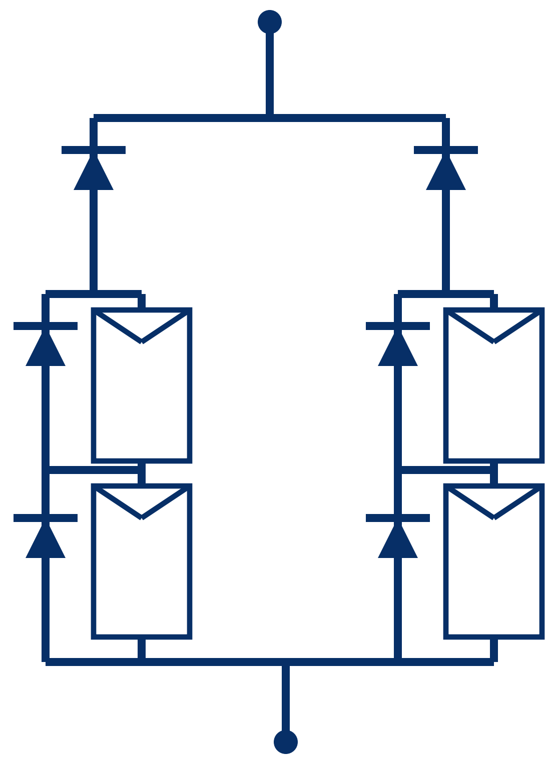
- If connected to a 12 V battery
  - $P = I_{SC}(G) \cdot V_{bat} \quad = I_{SC,STC} \cdot V_{bat} \cdot G \quad \equiv P_{eff} \cdot G$

Interconnection of PV generators

- Quite analogous to the interconnection of cells in a module
  - Number of modules in a string gives desired DC bus voltage
  - Number of strings gives current required from PV generator
- In practice, not all modules perform equally well
  - Variation in cell and module manufacturing quality
    - Typically results in higher dispersion in current than in voltage
  - Different operating conditions in different parts of PV generator system
    - Cleanliness
    - Partial shading and cloud cover
  - This leads to mismatch losses
    - Such losses minimized by sorting modules prior to interconnection

Interconnection of PV generators

- There is a possibility that the poorest module and/or string can be driven into reverse operation
  - Hot-spot formation
  - Can degrade or destroy modules
- Care can be taken to avoid this
  - Including a bypass diode for each module
  - Include a blocking diode for each string



Capturing the Sunlight

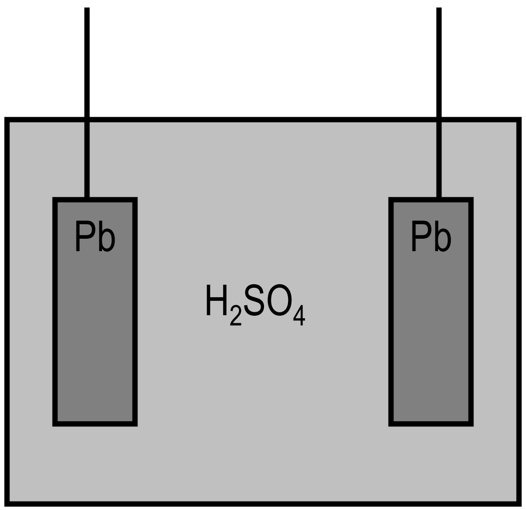
- A PV generator can be mounted in different configurations
  - Flat / horizontal
  - Inclined
    - Most common
    - Angle chosen commonly equal to latitude angle, as this maximizes the yearly average irradiation
    - In PV energy systems with summer peak loads (e.g. crop irrigation), a smaller angle gives better performance
    - In PV energy systems where the daily irradiance in the days with the least irradiance is critical (winter), a larger angle is more suitable
  - Tracking
    - Gives better performance, but moving parts increase need for maintenance and repair
    - Necessary in PV energy systems using concentrators

Energy storage

- Solar energy supply varies with time
- Stand-alone PV energy systems must usually be able to store energy over time
- Most PV energy systems use battery storage
  - Notable exeption: water pumping systems
  - Most common batteries: lead-acid batteries
  - Other possibilities
    - Compressed air
    - Flywheels
    - Current in superconducting rings
    - Hydrogen

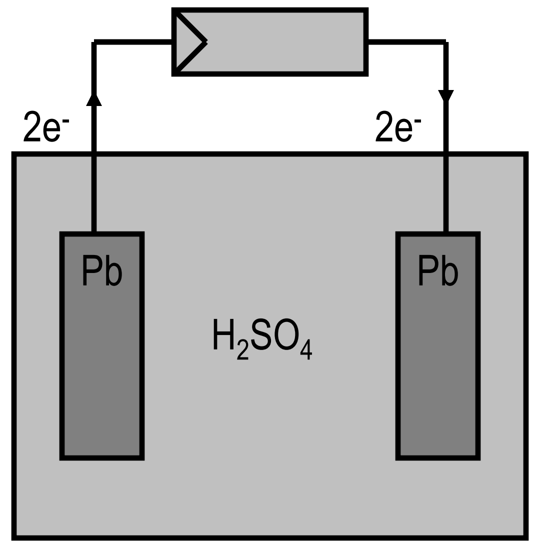
Batteries

- Example: a lead-acid battery
  - Lead electrodes
  - Sulphuric acid electrolyte



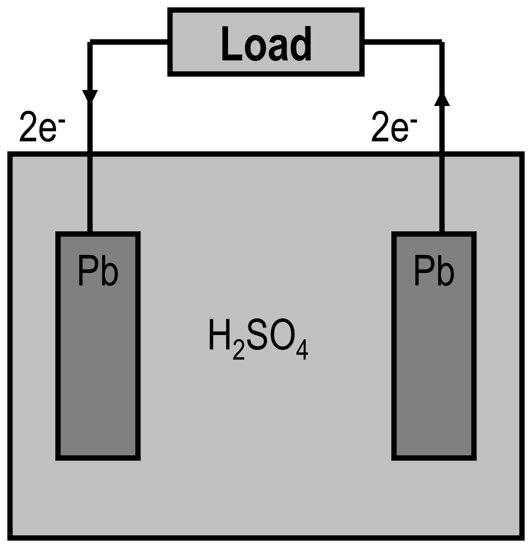
Battery charging

- Charging
  - Lead oxide forms at one electrode (anode)
  - Pure lead forms at other electrode (cathode)
  - Sulphuric acid liberated in electrolyte



Battery discharging

- Discharging
  - Lead sulphate formed at both electrodes
  - Acid removed from electrolyte



Batteries

- Cyclical operation
  - The battery is charged by the PV generator
  - The battery is discharged through the load
- Charging
  - If excessively charged, O_2 and H_2 gas is formed at the electrodes
    - Battery lifetime shortened
    - Increased maintenance requirements
    - Can be used to alleviate stratification
- Cycling leads to repeated growth and dissolution of lead, lead oxide and lead sulphide
  - Resulting mechanical stresses might lead to the shedding of active matter from the electrodes

Batteries

- Sulphation
  - Large lead sulphate crystals can form at electrodes hindering further chemical reactions
  - Mainly occurs if battery remains in low charge state for some time
- Stratification
  - During battery operation, the densest parts of the electrolyte sink to the bottom of the battery
    - Promotes corrosion and sulphation in lower part of battery
  - Can be avoided by regular overcharging and accompanying gassing

Batteries

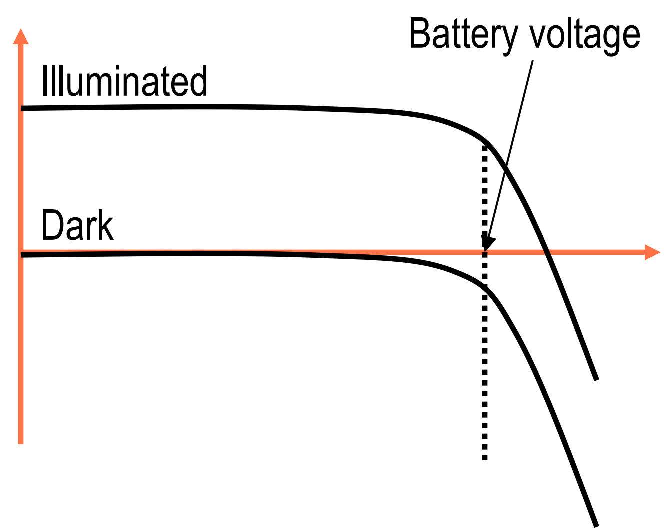
- Care must be taken when designing and calculating the cost of a stand-alone PV energy system based on batteries
  - Maintenance requirements
  - Typically shorter lifetime of battery than PV generator makes replacement(s) necessary under the lifetime of the system

Power conditioning and control

- The output from a PV generator varies with time
  - Position of Sun
  - Weather
  - Shading
  - …
- A range of different electronic devices are used to condition the output power
  - System malfunction must be avoided
  - DC/AC conversion
  - …

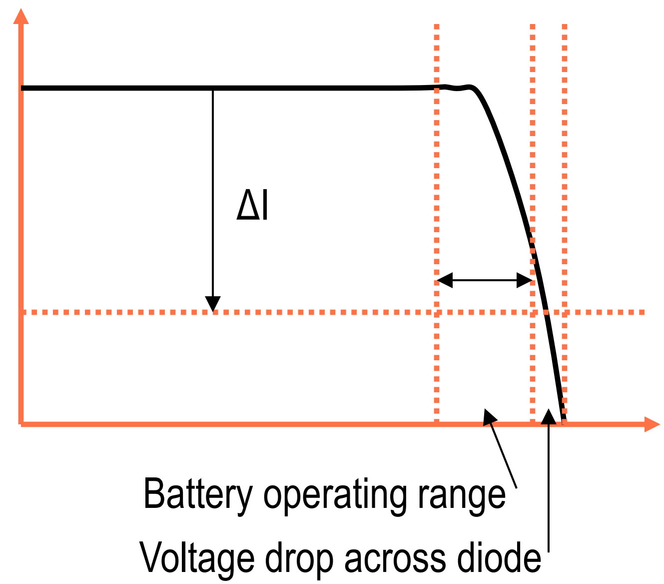
Power conditioning and control

- Blocking diodes
  - A PV generator in the dark will become a discharge path
    - Night
    - Shading
  - When the voltage at the battery exceeds the voltage of the generator, the diode becomes reverse-biased
  - Will cause voltage drop during daytime operation, and is sometimes omitted



Power conditioning and control

- Self-regulating systems
  - If output voltage from PV generator becomes too low, the blocking diode becomes reverse-biased and no longer conducts
  - Simple design
  - Temperature dependent system
  - Can often result in poor performance of the PV energy system
  - Mostly used in small, very low-cost systems



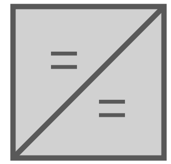
Power conditioning and control

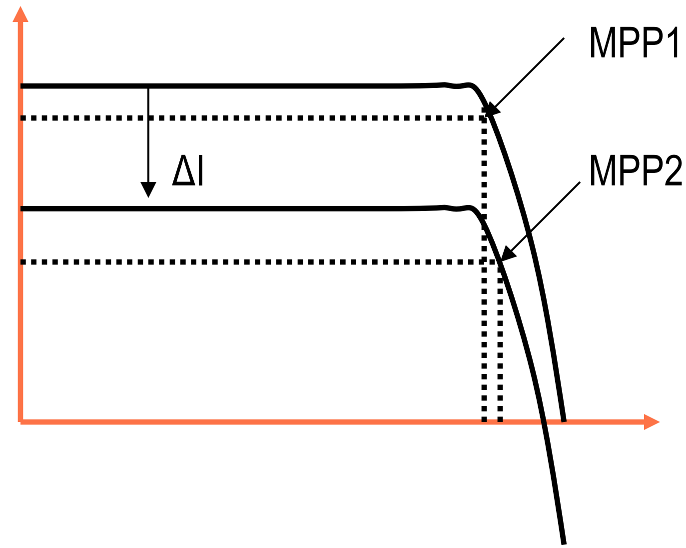
- Charge regulators
  - Variable resistors or switches
    - Series or shunt configurations
  - Disconnects load from battery if battery voltage becomes too small
  - Limits over-voltage
  - Can be tuned in order to prolong battery lifetimes
    - Controlled gassing

Charge regulator

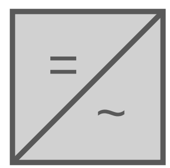
Power conditioning and control

- DC/DC converters
  - Will allow the PV generator to operate closer to the MPP
    - MPP tracking

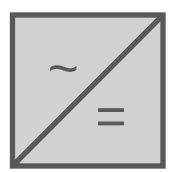




- DC/AC converters / inverters
  - Grid connection
  - AC appliances



- AC/DC converters
  - Useful in energy systems

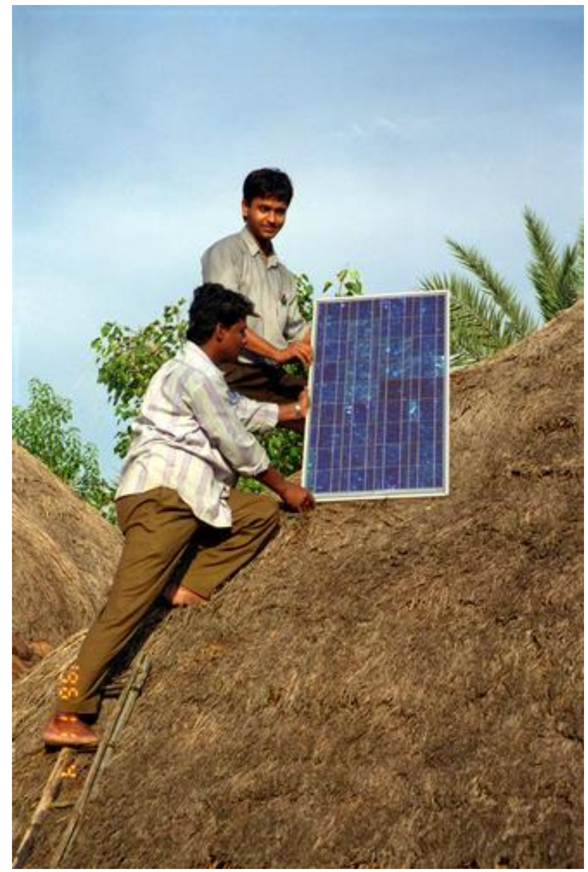


PV energy systems – examples

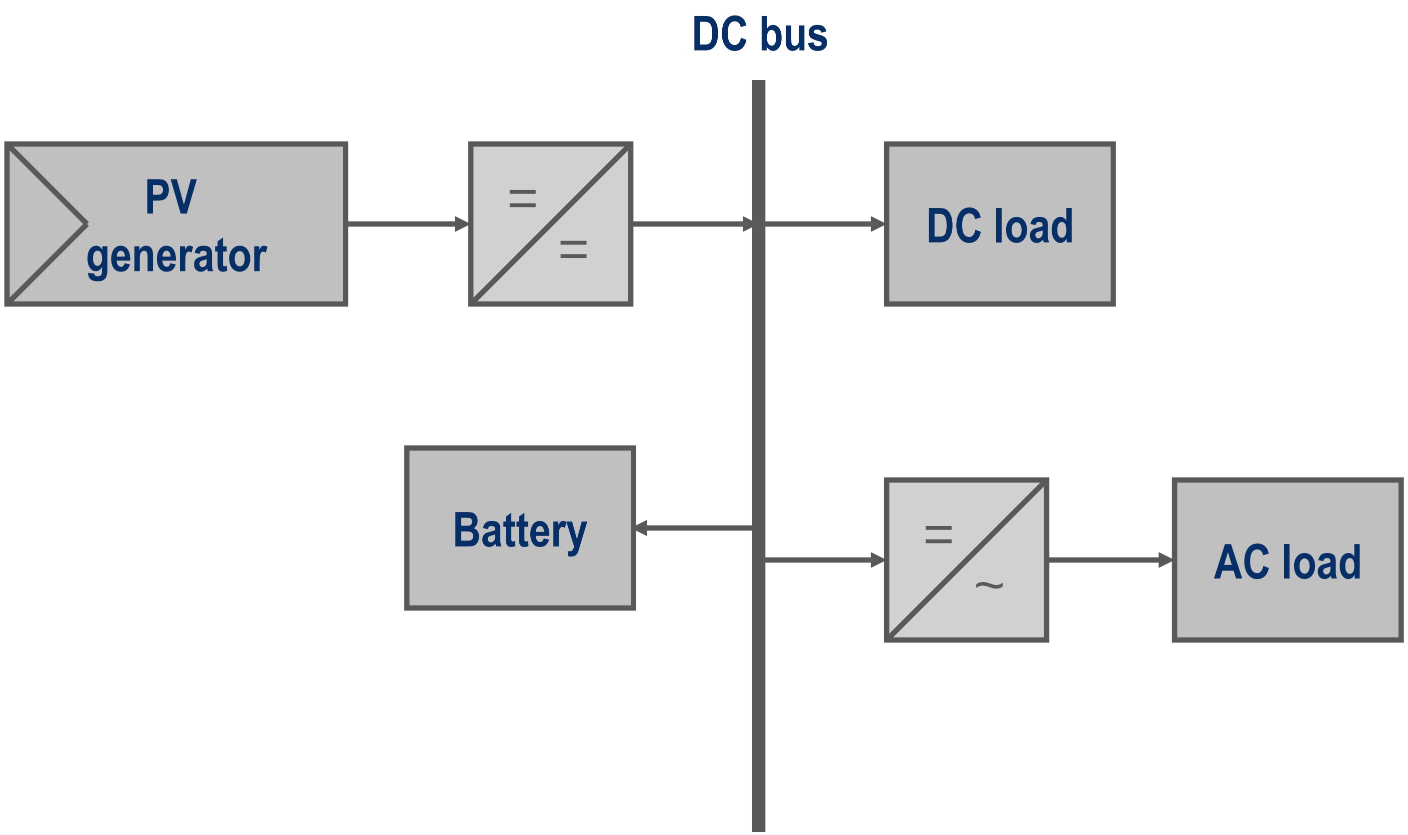
- Off-grid PV energy systems
- Grid-connected PV energy systems

Off-grid PV energy systems

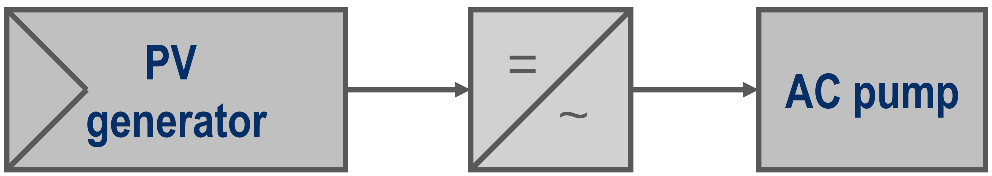
- Off-grid PV energy systems
  - Rural electrification
  - Water pumping
  - Consumer electronics
  - Space applications
  - Telecommunications
  - Navigation
  - Vaccine cooling
  - Education
    - Illumination
    - Information technology
  - …
- PV-diesel hybrid energy systems
- Sizing off-grid PV energy systems



Off-grid PV energy system



Water pumping system

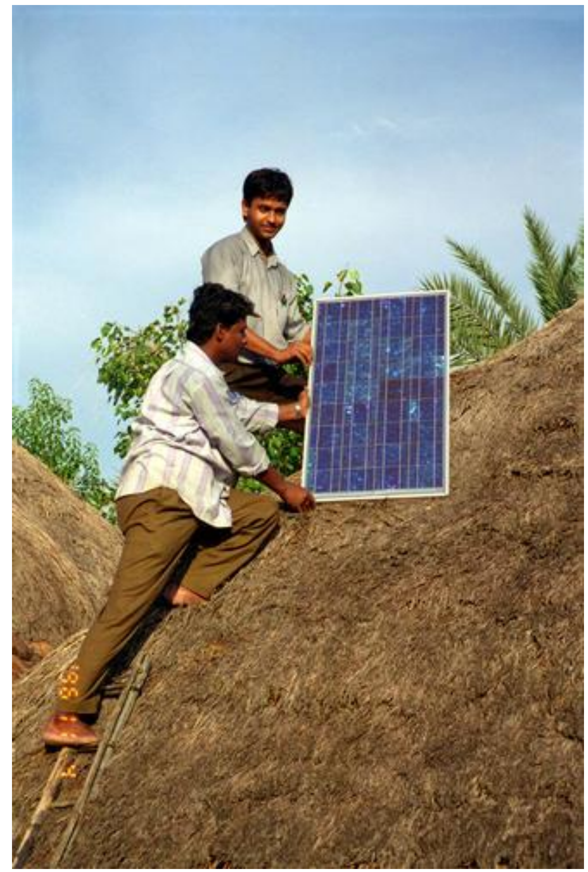


Sizing off-grid PV energy systems

Sizing off-grid PV energy systems

1. Determine energy input
   - Daily solar radiation data
   - Panel inclination
   - Calculate available daily solar energy
     - Average
     - Seasonal (winter / worst case)

2. Determine load demand
   - Load specifications
   - Daily load profile
   - Calculate load power demand



Sizing off-grid PV energy systems

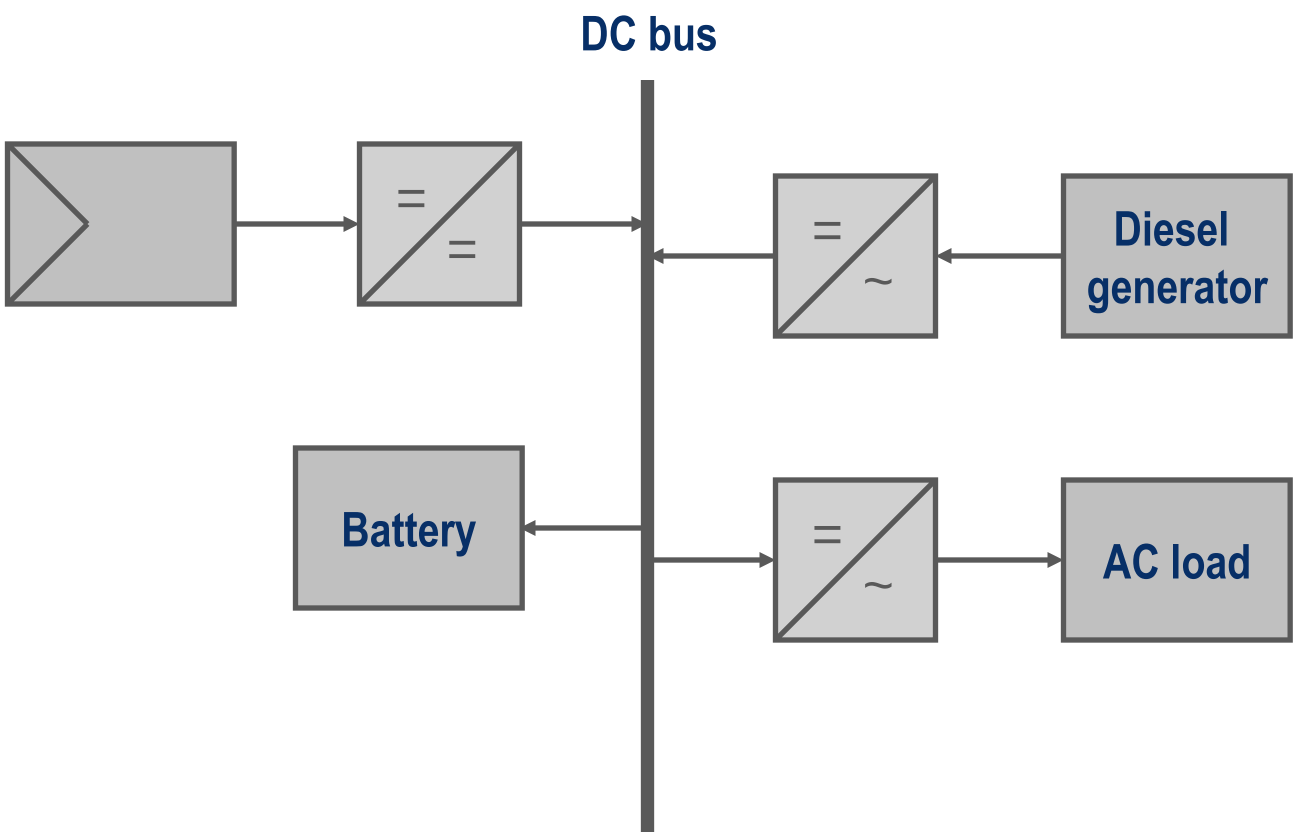
3. Determine number of modules connected in series
   - Required DC operating voltage
     - Usually a multiple of 12 V

4. Determine number of parallel strings
   - Calculate average load currents
     - Use average load power demand and operating voltage
   - Using the average available solar energy, the number of parallel strings is calculated
   - Usually an oversize factor is used

Sizing off-grid PV energy systems

5. Sizing the required energy storage
   - Calculate daily charge deficit
     - Gives allowed daily discharge limit for safe system operation
   - Calculate seasonal (winter) charge deficit
   - If properly sized, excess charge generation in the summer should cover the winter charge deficit

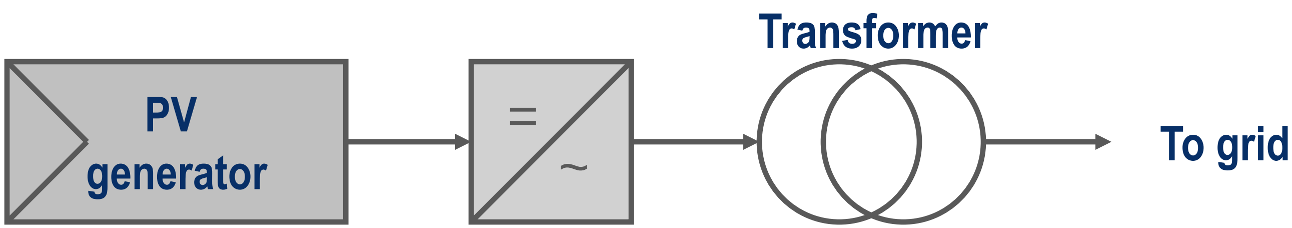
PV-diesel hybrid energy system



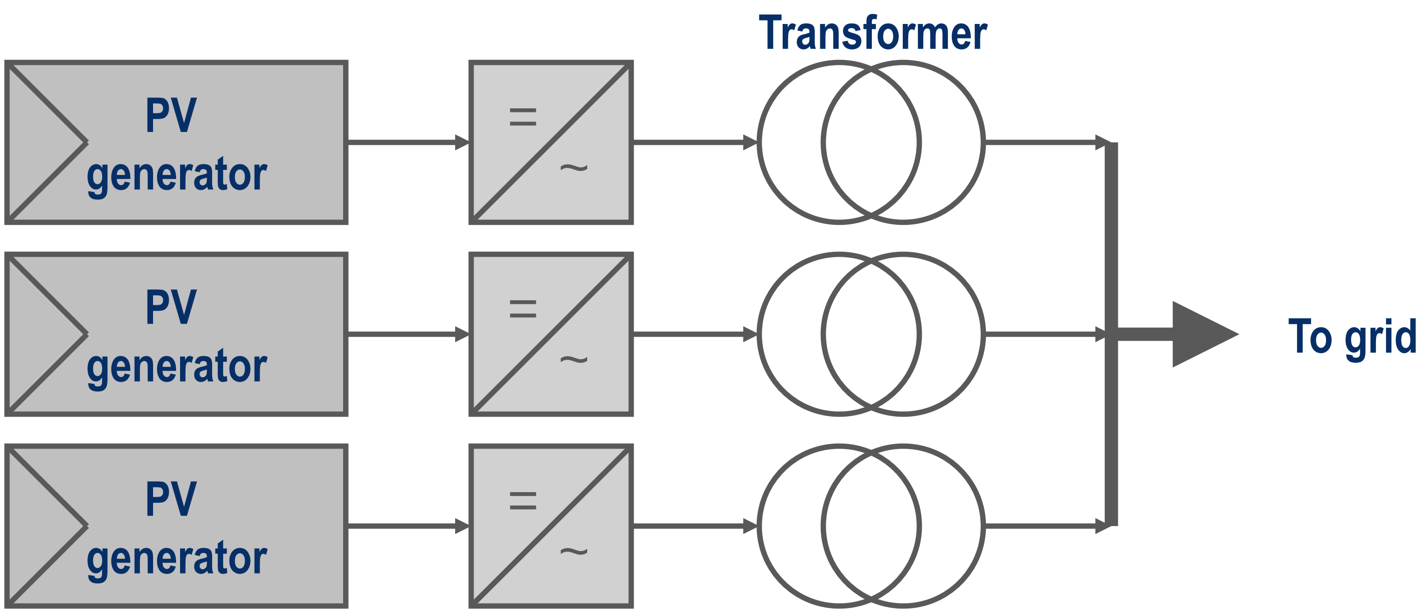
Grid-connected PV energy systems

- Grid-connected PV energy systems
  - Building-integrated PV (BIPV)
  - PV power stations

Grid-connected PV energy system



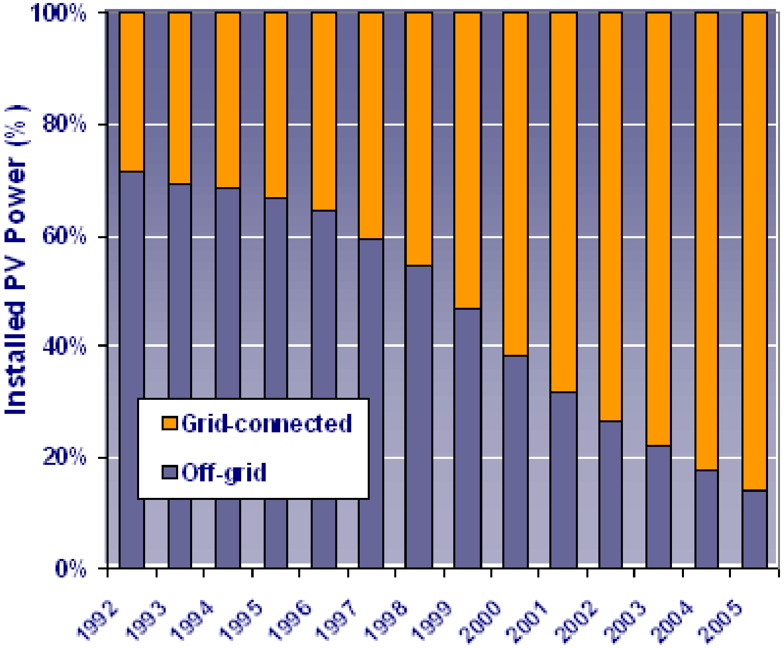
Grid-connected PV power station

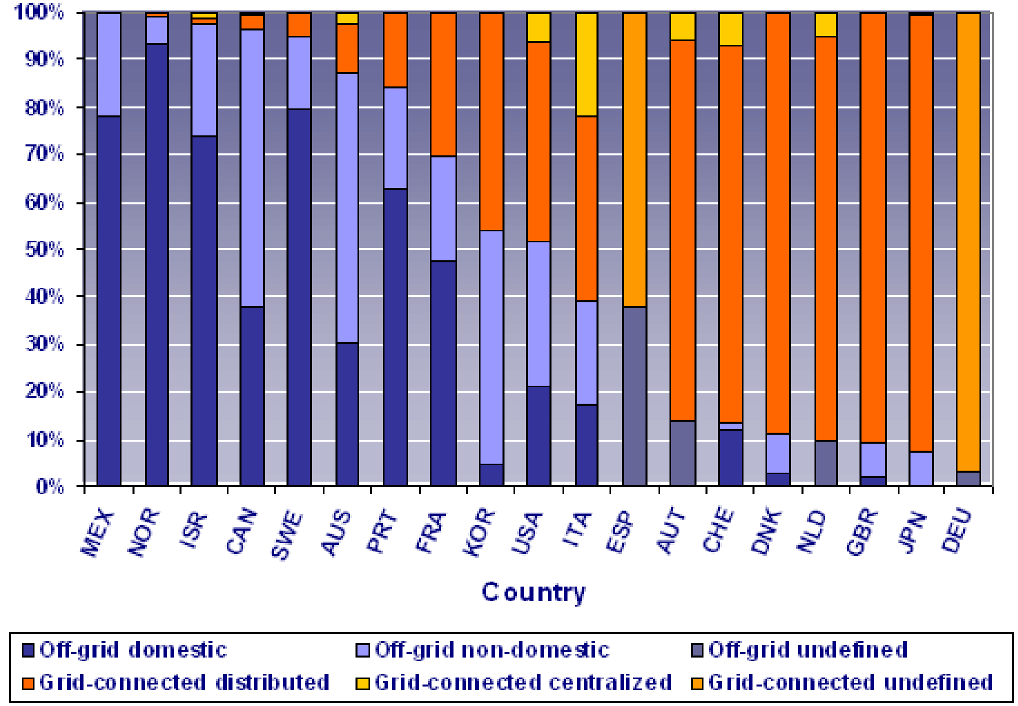


Solar energy statistics

Source: www.iea-pvps.org

On-grid or off grid?

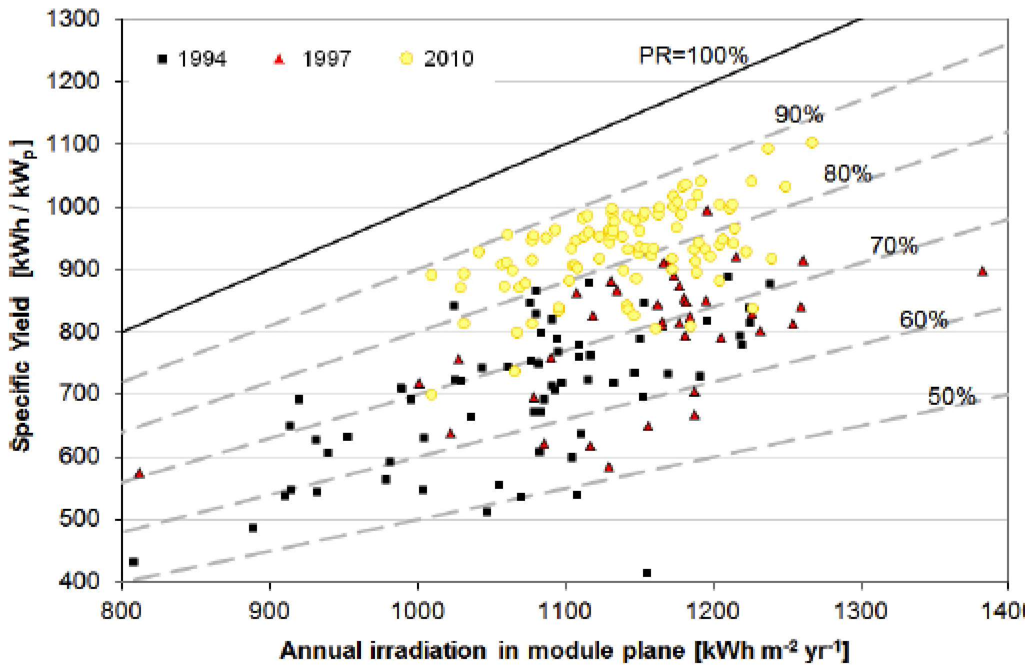




Source: www.iea-pvps.org

Performance Ratio Development for PV Systems

Germany



In the 1990's

- Typical PR ~70 %
- Widely ranging PR values

Today

- Typical PR ~80-90 %
- Less variance in PR as compared to 1990's

Source: Fraunhofer ISE "1000 Dächer Jahresbericht" 1994 and 1997; 2011 system evaluation

Fraunhofer ISE