"Solar Energy" WS 2021/2022

PV Technology:

Lecture 11: PV System Components

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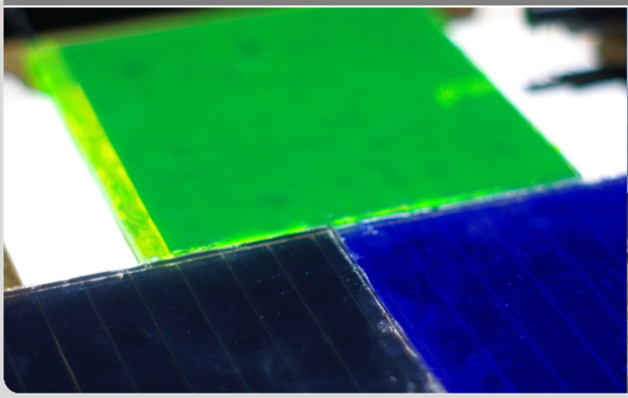


Types of PV Systems

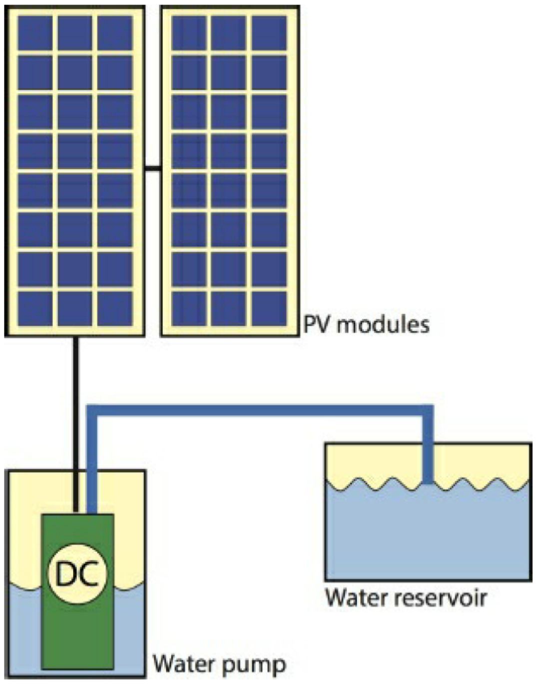
- Some PV systems small and simple ⇒ just a PV module and load, e.g. a directly powering the motor of water pump
  ⇒ only needs to operate when Sun shines
- Large power plants (solar farms)
  ⇒ peak power > 1 GW connected to electricity grid
- PV systems on residential rooftop:
  - If house is "off grid" (not connected to electricity grid)
    ⇒ PV system supply energy day and night
  - May have to feed both AC and DC loads
  - Energy storage ⇒ batteries
  - Reserve power ⇒ backup generator
  - If house is "on grid" ⇒ export solar electricity to grid during day, import electricity back at night

Stand-Alone PV Systems

- Stand-alone or "off grid" system ⇒ rely on solar power only

Simplest example:

- PV directly-connected to load
- No electronics & no batteries
- Pumps water when sun shines ⇒ good match between demand and supply (e.g. more water needed when hot & sunny)



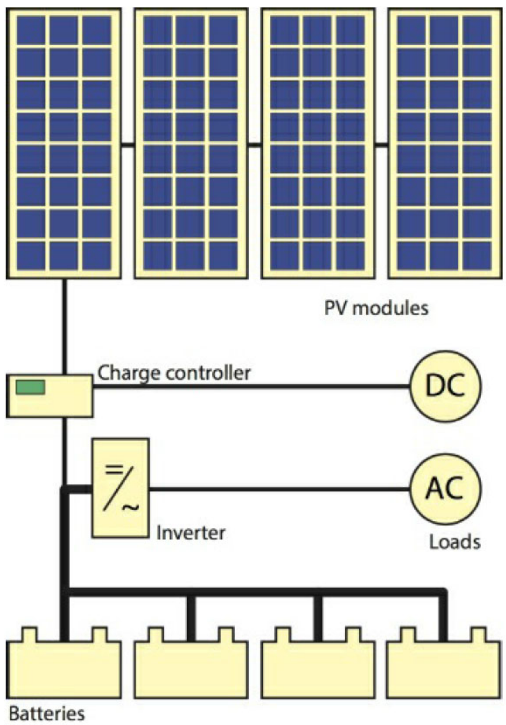
Source: textbook
http://www.climatesamurai.com/solar/solar-powered-pumps-water-treatment-solutions-have-huge-potential-in-india-grundfos/

Stand-Alone PV Systems

More complex example:

- Batteries ⇒ supply solar electricity during cloudy periods or night
- Electronics needed to i) charge batteries & ii) produce AC electricity

Europe:



Source: textbook
https://www.sma.de/en/home-systems/solar-system-off-grid.html

Stand-Alone PV Systems

Less complex example:

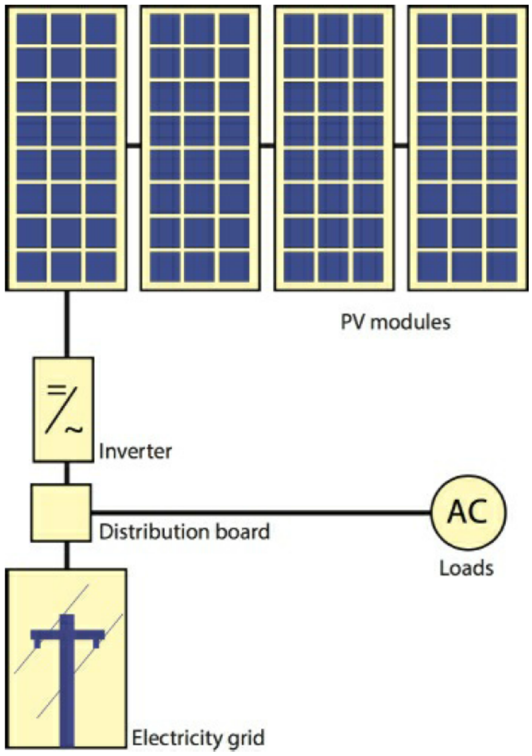
- Batteries ⇒ supply solar electricity during cloudy periods or night
- Electronics needed to charge batteries ⇒ DC system only
- Main load is LED lighting

Africa:

Source: https://www.pv-magazine.com/2019/10/31/pay-as-you-go-solar-systems-worth-216-million-shipped-in-h1-2019/

Grid-Connected PV Systems

- Connected to grid via inverter ⇒ ~99% of EU and ~90% of U.S. PV systems are grid connected
- Residential systems: inverter is connected to distribution board ⇒ solar power is transferred into electricity grid or AC appliances
- No batteries ⇒ grid acts as a buffer (virtual storage) for oversupply of solar power ⇒ provides power to house when solar insufficient
- Increasing grid-connected systems also have batteries ⇒ to increase fraction of own solar power



Source: textbook

Grid-Connected PV Systems

KIT Karlsruher Institut für Technologie

- Large PV systems act as power stations ("solar farms") ⇒ all PV-generated electricity is directly transported to grid
- Solarpark Meuro (2012, Germany) 166 MWp ⇒ built on former lignite (brown coal) mine ☺

Source: https://en.wikipedia.org/wiki/Solarpark_Meuro

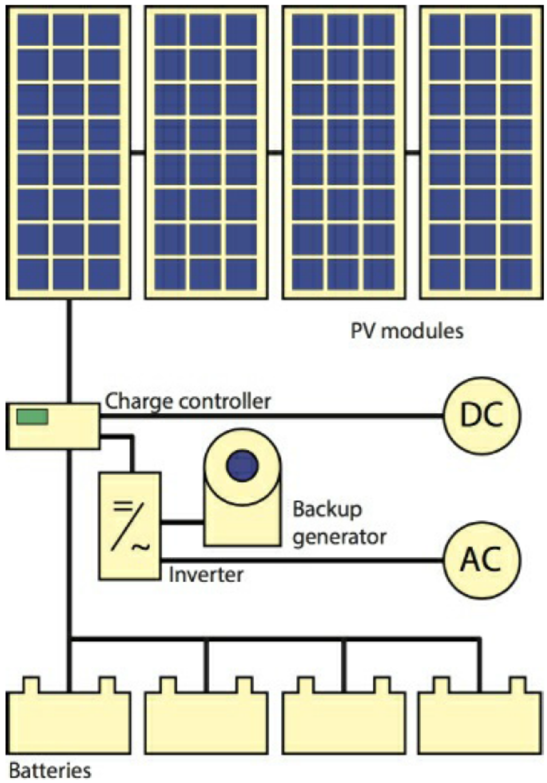
Grid-Connected PV Systems

- Tengger Desert Solar Park (2016, China):
  1.55 GWp
  43 km²
  ~6.2 million PV modules
  (assuming 250 W)

Sources: http://www.escn.com.cn/news/show-310093.html
https://twitter.com/copernicuseu/status/1024888969664835584

Hybrid Systems

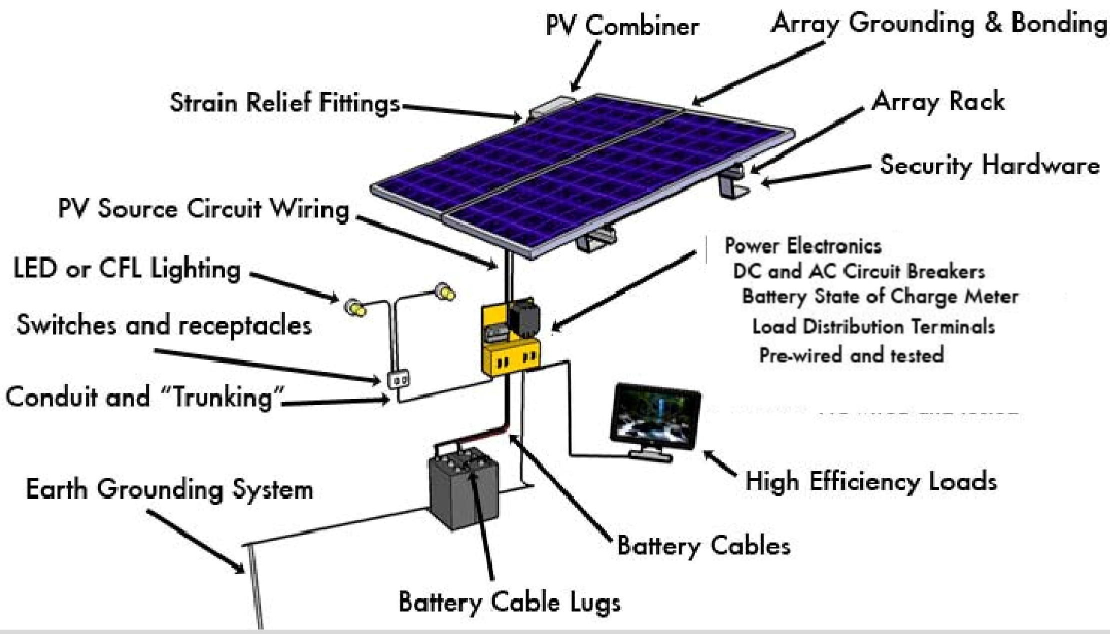
- Hybrid systems combine PV modules with other methods of electricity generation, e.g. diesel generator or wind turbine
- Charge controller in PV/diesel system ⇒ start diesel engine when battery state-of-charge is low ⇒ stop when the battery is fully charged
- While running, backup generator can also supply the load as well ⇒ e.g. including high power loads that could not normally run of PV, e.g. welding (20 kW!)



Source: textbook

Balance-of-System Components

- PV modules are heart of PV system, but many other components are required for a working system ⇒ together referred to as balance-of-system (BOS) components



Source: Youngren, *2011 IEEE Global Humanitarian Technology Conference*. IEEE, 2011

Balance-of-System Components

- Which BOS components are needed depends on whether system is grid-connected or stand-alone

BOS components include:

- Mounting structure – fix the modules so they face the sun
- Energy storage – typically batteries –vital part of stand-alone system to enable system to deliver electricity during night and in periods of bad weather
- DC-DC converters – PV module output voltage variable ⇒ depends on time of day and weather conditions ⇒ convert to a compatible output voltage to match input required for i) inverter or ii) batteries

Sources: textbook

Balance-of-System Components

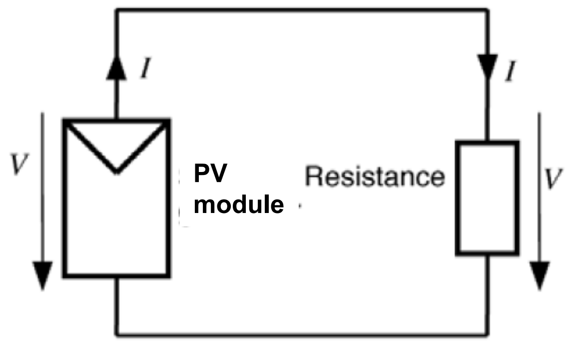
- Maximum power point tracker (MPPT) – to extract the maximum power out of the PV module at any one time
- Inverters – used to convert DC electricity from PV module to AC electricity. Many inverters have a DC-DC converter and MPPT included.
- Charge controller – used in stand-alone systems to control charging / discharging of batteries ⇒ also prevent batteries from being discharged via PV array during night. Some charge controllers contain a DC-DC converter and MPPT
- Cables – to connect different components of the PV system together and to electrical load ⇒ important to choose cables of sufficient thickness in order to minimize resistive losses
- Loads – are they AC or DC?

Sources: textbook

PV Module with Load

- The simplest load is an electric resistance *R*
- Ohm's law describes linear relationship between *I* and *V*:

$$I = \frac{V}{R}$$

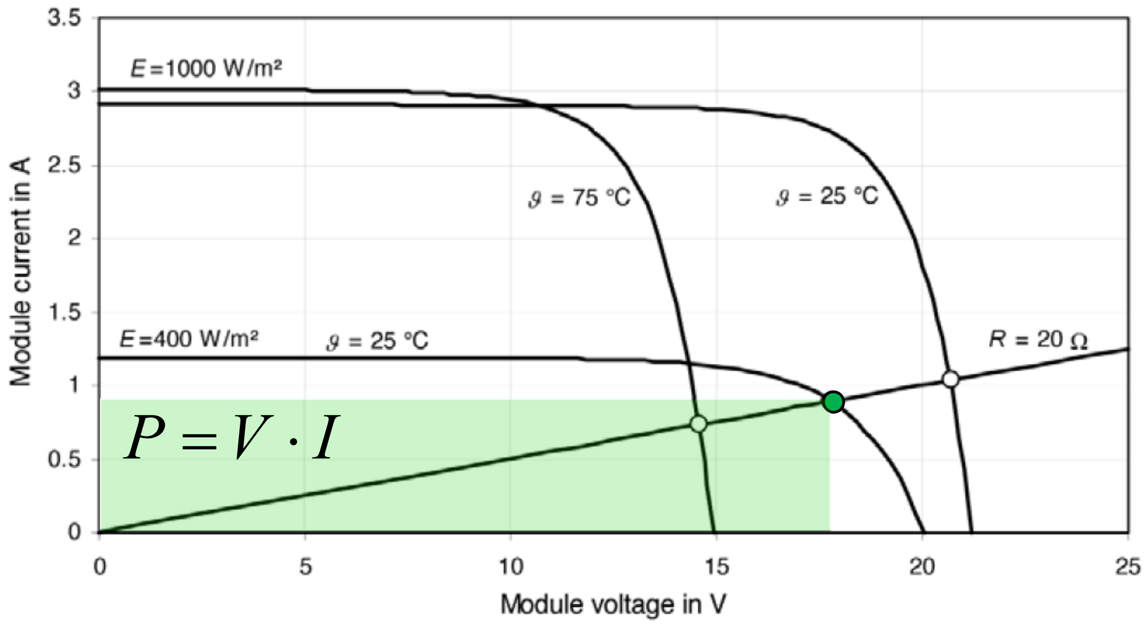


- Current flowing through load resistor = current of PV module $\Rightarrow$ common voltage $\Rightarrow$ find operating point on I-V curve

Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

PV Module with Load

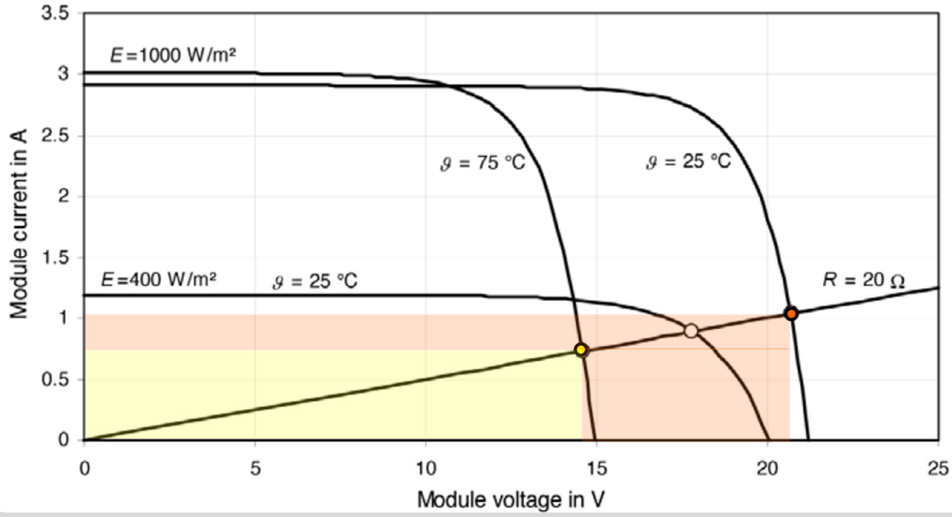
- Shown graphically below, with intersection of both characteristics then providing the operating point
  $\Rightarrow$ ● at 400 W/m² and 25°C, module operates close to MPP



Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

PV Module with Load

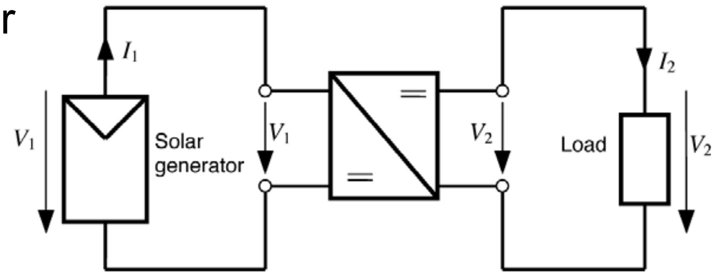
- But operating point of PV module can vary!
- Previously (400 W/m² and T = 25°C) module operated at close to MPP ⇒ but at other irradiances (●) and temperatures (●), module is operated sub-optimally ⇒ output power is much less than maximum



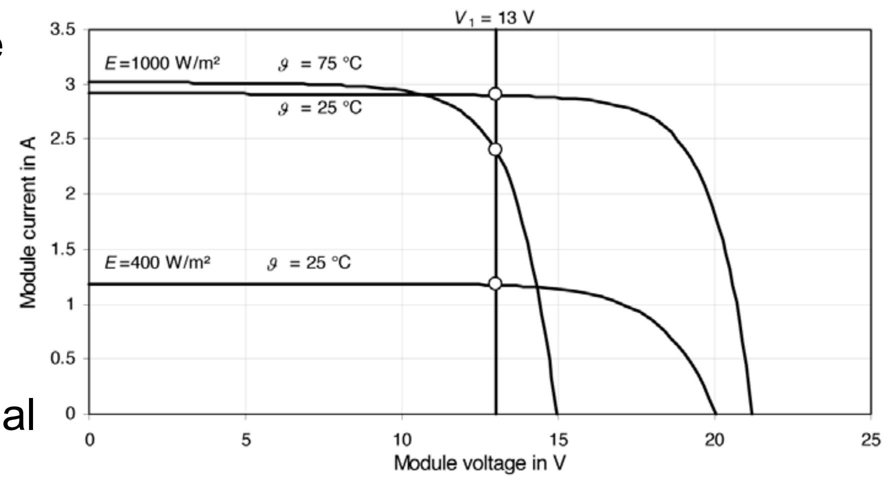
Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

DC-DC Converters

- Solution: DC-DC converter allows generation of a voltage at the load that is different from that of PV module



- E.g. can increase power output of PV module if it is operated at constant *V* instead…
- … but still not ideal



Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

DC-DC Converters

- PV module power output could be increased even more if both variations with illumination & temperature could be handled
- With DC-DC converter, input power P_1 and output power P_2 are identical (ideal converter with an efficiency of 100%)

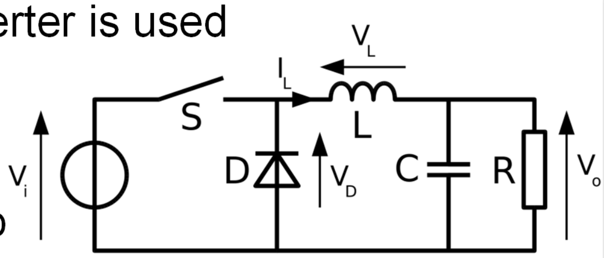
$$P_1 = V_1 \cdot I_1 = V_2 \cdot I_2 = P_2$$

- In practice, good DC–DC converter has efficiency of ~95% ⇒ only a small part of the generated power lost as heat
- Achieved in the following way…

DC-DC Converters

- If load voltage always lower than PV module voltage ⇒ "step-down" (or "buck") converter is used

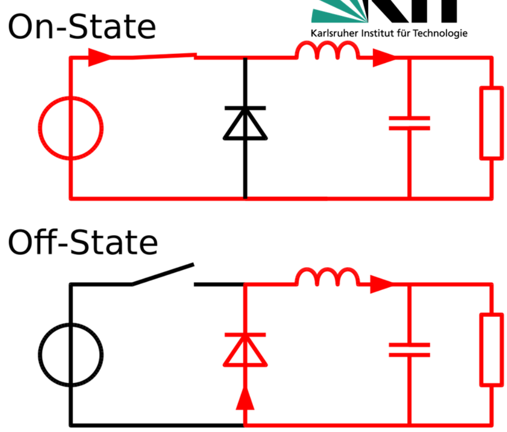
Operation:



- Begin with switch S open (off-state) ⇒ current in circuit is zero
- When switch is first closed (on-state) ⇒ current I_L starts flowing ⇒ inductor L builds up a magnetic field ⇒ produces an opposing voltage V_L across its terminals (in response to changing current)
- Voltage drop V_L counteracts the voltage of source V_i ⇒ reduces net voltage V_o across load
- Over time, magnetic field is established ⇒ rate of change of current decreases ⇒ V_L decreases ⇒ V_o increases

Sources: https://en.wikipedia.org/wiki/Buck_converter
https://electronics.howstuffworks.com/inductor.htm

DC-DC Converters



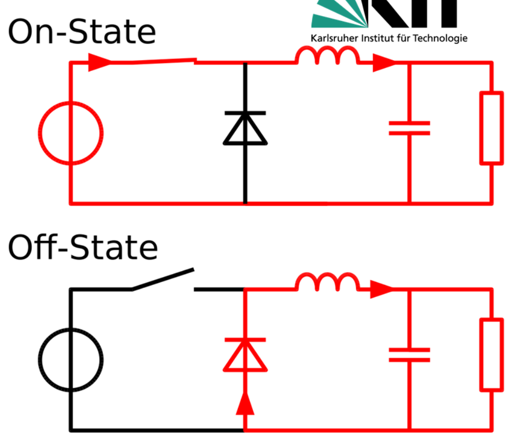
- During on-state, inductor stores energy in the form of magnetic field

$$V_L = L\frac{dI_L}{dt} \qquad E = \frac{1}{2}\, L\, {I_L}^2$$

- If switch is opened while current is still changing ⇒ will always be voltage drop across inductor
  ⇒ net voltage at load will be less than input voltage
- When switch is opened again (off-state) ⇒ voltage source removed from circuit ⇒ current will decrease ⇒ produces a voltage drop across inductor (opposite to the drop at on-state) ⇒ now inductor behaves like current source (due to energy stored in magnetic field)

Source: https://en.wikipedia.org/wiki/Buck_converter

DC-DC Converters

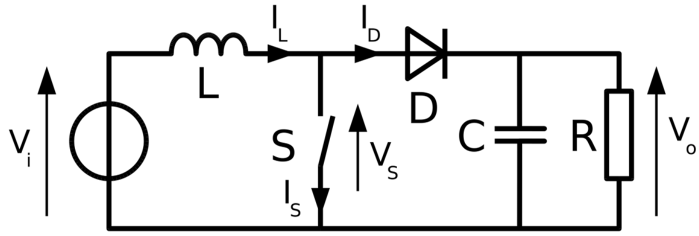


- Stored energy in inductor's magnetic field
- During off-state ⇒ inductor is discharging its stored energy through circuit
- This current can be greater than average input current
- Increased average current makes up for reduction in voltage ⇒ no loss of power
- Change voltage via ratio of T_{on} to T_{off} ⇒ duty cycle
- Fast switching frequency 20 – 200 kHz

Source: https://en.wikipedia.org/wiki/Buck_converter

DC-DC Converters

- A “boost” or “step-up” converter is a DC-DC converter that steps up voltage (while stepping down current) from its input (supply) to its output (load)
- Similar to buck converter except diode, switch and inductor change positions

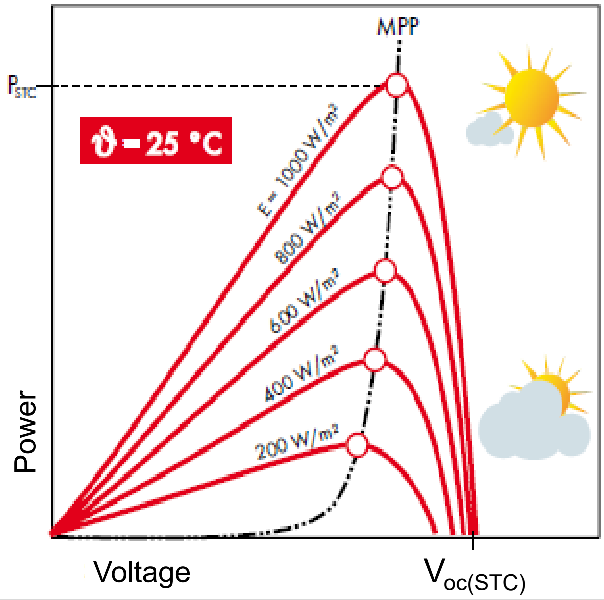


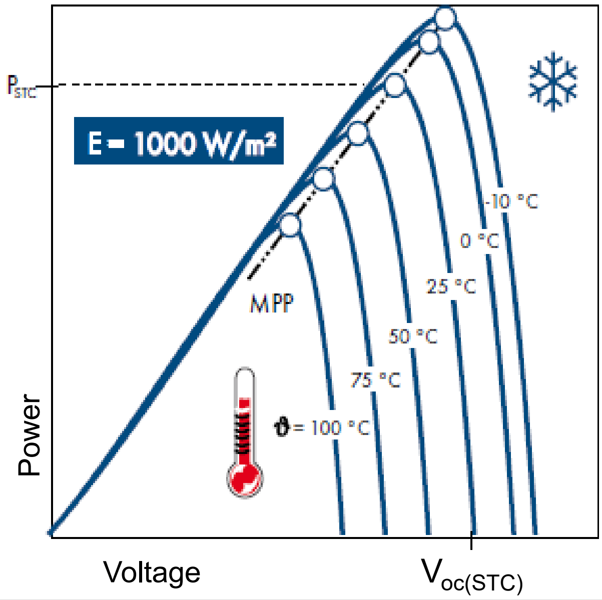
- *Not covered in more detail here – more detail can be found in textbook and Wikipedia (reference below)*

Source: https://en.wikipedia.org/wiki/Boost_converter

Maximum Power-Point Trackers

- Voltage converters can maintain different voltages at PV module and at load
- Optimal operating V depends on irradiance and temperature

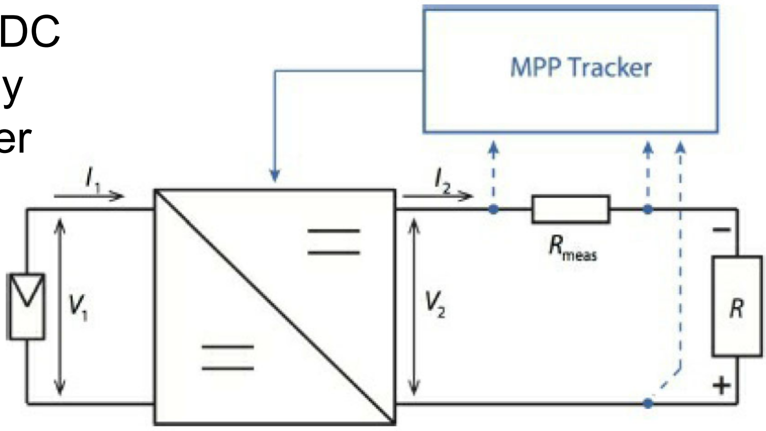




Source: www.sma.de

Maximum Power-Point Trackers

- MPPT concept: at variable temperatures and irradiances, greatest amount of power is extracted from PV module <u>not</u> with a fixed voltage (= fixed duty cycle), but via varying the duty cycle of DC-DC converter to realise operation at V_{MPP}
- The duty cycle of DC-DC converter can be varied to account for changes PV module MPP
- Thus, a MPPT ≡ a DC–DC converter that constantly varies duty cycle in order to operate PV module at MPP ⇒ improves energy yield



Source: textbook

Maximum Power-Point Trackers

- Three examples for implementing MPPT control:

1. <u>Sensor-controlled regulator</u>: the maximum power point (MPP) voltage is calculated as a function of the inputs from
   i) an irradiance sensor and
   ii) temperature sensor (on back of PV module)

2. <u>Zero transit method</u>: here, the measured voltages and currents are multiplied and the derivative dP/dV determined. The voltage is then increased or decreased depending whether the derivative is positive or negative

Maximum Power-Point Trackers:

3. Oscillating search control – a.k.a. hill climbing or perturb-and-observe (P&O):

   Voltage & current are measured at PV module ⇒ power is calculated and stored

   Small changes in duty cycle cause a voltage change. Then power is estimated again. If power increases, duty cycle is changed again in same direction. Otherwise, duty cycle is changed in the opposite direction.

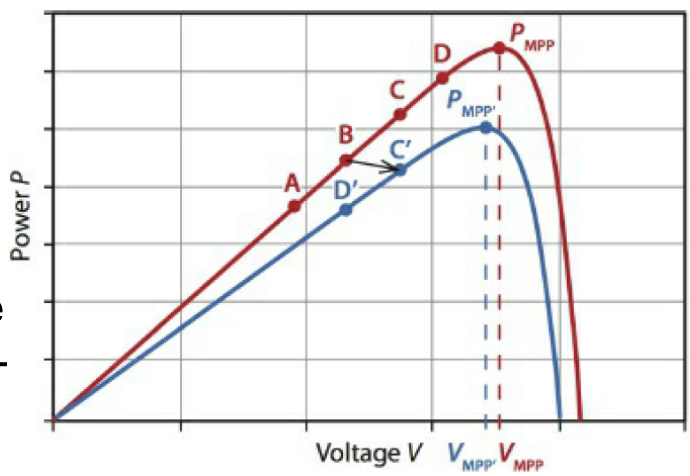
MPPT algorithm can have difficulty in finding the optimal operating point:

i. under rapidly changing conditions (esp. illumination);

ii. when PV module is partially shaded

Maximum Power-Point Trackers:

- If P&O algorithm determined that MPP lies at higher V than point **B** ⇒ next step is perturbation to move towards MPP
- If illumination constant ⇒ end up at **C** ⇒ algorithm conclude that MPP is still higher voltage ⇒ correct
- But if illumination changes rapidly before next perturbation ⇒ shifts operating point to **C'** instead of **C** ⇒ algorithm thinks MPP is now to left of **C'** ⇒ moves to point **D'**
- Wrong assumption slows down speed of convergence of algorithm ⇒ key figure-of-merit for MPPT techniques



Source: textbook

Maximum Power-Point Trackers:

- Shading of PV module = lost electricity
- Can happen quickly (leaf falls on module)
- Good MPPT should cope under irregular operating conditions, where local maxima can occur in I-V curve
- Important to scan through <u>whole voltage range</u> to find true MPP

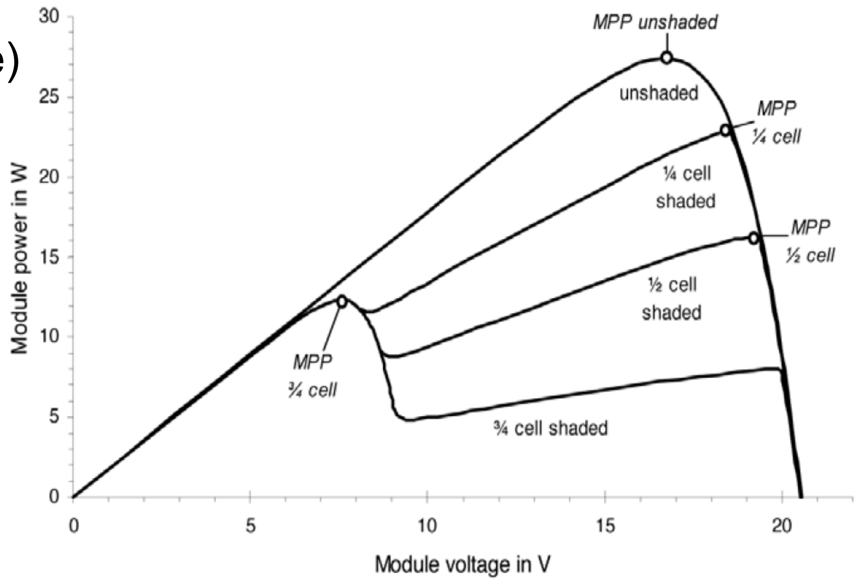


Figure 4.28 *P-V Characteristic of a Module with 36 Cells and Two Bypass Diodes. A Single Cell is Shaded to Different Degrees; All Other Cells Are Fully Irradiated (E = 574 W/m², T = 300 K)*

Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

Electrical Energy Storage

- Loads rarely ever <u>directly connected</u> to a PV system due to:
  1. fluctuations in power availability throughout the day (clouds), and
  2. night
- Two exceptions: PV-powered water pumping (left) and water treatment (right) – why?

Sources: <u>http://www.dowdens.com.au/cases/agricultural_solar_pumping_systems_26_09_2016.asp</u>
Schäfer, Broeckmann, Richards, Environ. Sci. Technol. 41 (2007) 998-1003

Electrical Energy Storage

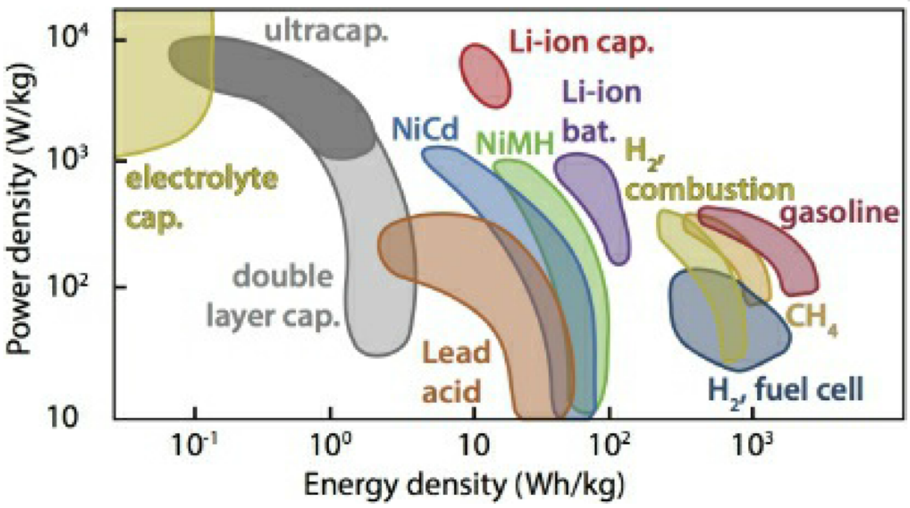
- Storage of electrical energy broadly classified into:
  i. <u>short-term storage</u> for a few hours or days to cover periods of bad weather and night-time darkness
  ii. <u>long-term storage</u> over several months ⇒ compensate for seasonal variations in solar irradiation in summer and winter
- And how <u>critical</u> is the load?
  If the house lights go out during the night one can use candles or torches for a couple of hours.

  However, if the lighthouse doesn't shine any more…?

Source: https://teara.govt.nz/en/photograph/6678/solar-power

Electrical Energy Storage

- Ragone plot compares energy density to peak power density
- For PV, typically require a high energy density and (depend-ing on application) also reasonably high power density
- For short- to medium-term storage, best choice batteries
- Seasonal storage at large scale still to be solved ⇒ hydrogen?



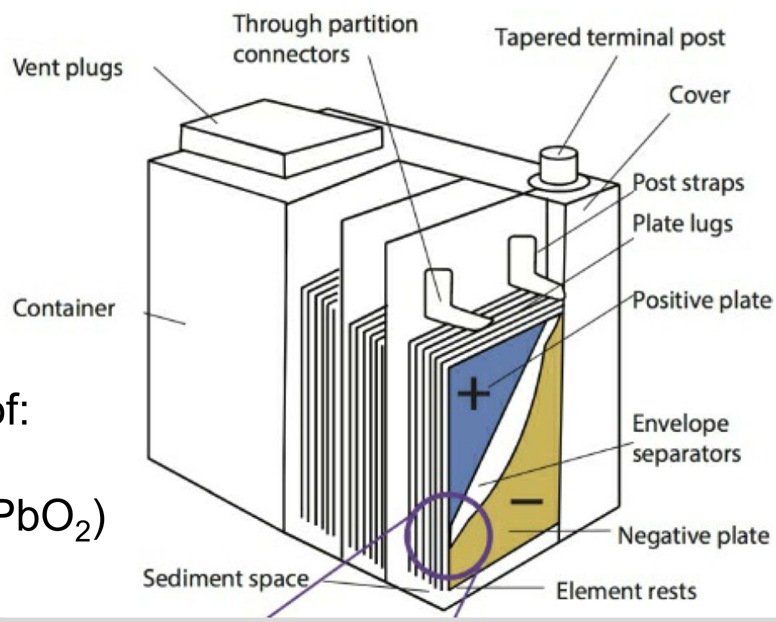
Source: textbook

Lead-acid Battery

- For economic reasons, the lead–acid (LA) battery is still the dominant technology for energy storage in PV systems
- Rechargeable LA battery builds on expertise from automotive industry, however so-called “solar batteries” have modified design compared to car batteries ⇒ longer lifetimes and don’t need a few hundred amps starting current!
- Lithium ion batteries decreasing significantly in price over last decade but currently remain more expensive than LA batteries

Lead-acid Battery

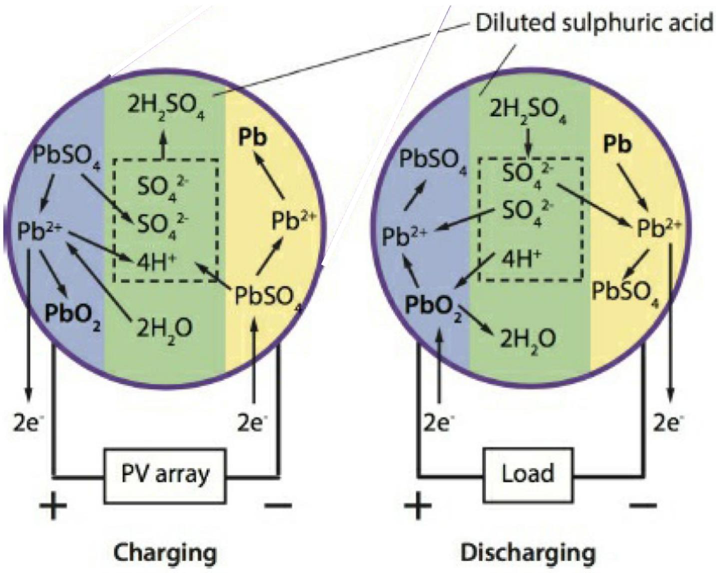
- Typical LA battery typical battery composed of several individual cells, each with cell voltage ~2 V
- Individual cells can share housing ⇒ interconnected internally
- To achieve 12 V ⇒ six cells connected in series
- LA batteries use acidic electrolyte (dilute sulphuric acid H_2SO_4)
- Two electrodes made of: negative: lead (Pb) positive: lead dioxide (PbO_2)



Source: textbook

Lead-acid Battery

- When battery being discharged ⇒ electrons flow from negative to positive electrode via external circuit ⇒ causes chemical reaction between the plates and the electrolyte
- This forward reaction also depletes the electrolyte ⇒ affects state-of-charge (SoC)
- When source with voltage higher than actual battery voltage is connected ⇒ reverse reaction is enabled ⇒ flow of electrons is reversed ⇒ battery is recharged



Source: textbook

Lead-acid Battery

- Reversible chemical reactions inside LA battery:

$$\text{Negative electrode: } Pb + SO_4^{2-} \underset{\leftarrow \text{Charge}}{\overset{\text{Discharge}\rightarrow}{\longleftrightarrow}} PbSO_4 + 2e^-$$

$$\text{Positive electrode: } PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \underset{\leftarrow \text{Charge}}{\overset{\text{Discharge}\rightarrow}{\longleftrightarrow}} PbSO_4 + 2H_2O$$

$$\text{Net reaction: } PbO_2 + Pb + 2H_2SO_4 \underset{\leftarrow \text{Charge}}{\overset{\text{Discharge}\rightarrow}{\longleftrightarrow}} 2PbSO_4 + 2H_2O$$

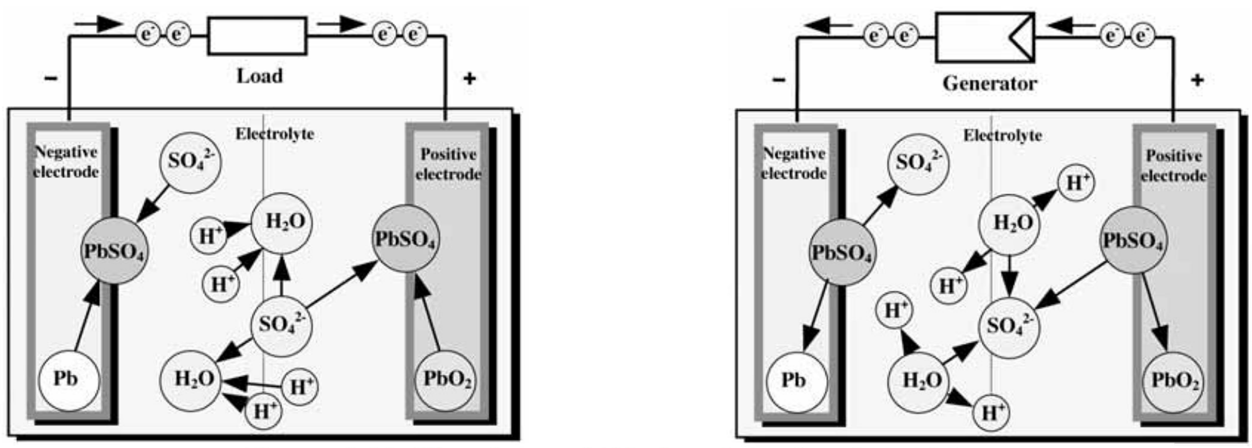
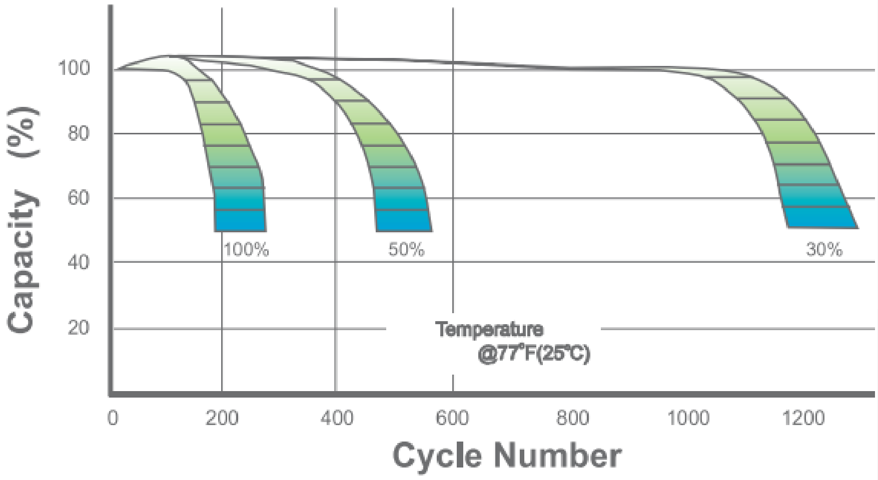


Figure 4.41 *Charging and Discharging a Lead–Acid Battery*

Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

Lead-acid Battery

- Self-discharge ⇒ leakage current results in losses of ~0.3% / day (at *T* = 25°C, increases with T)
- Lifetime of battery – defined by number of charge/discharge cycles achievable (typically ~1000-1500 cycles)
- Lifetime decreases with increasing *T* and depth-of-discharge (DoD)
- Maximum recommended DoD is ~70%, with DoD's of >50% avoided if at all possible



Source: https://www.sunwize.com/gel-vs-agm-batteries/

Lead-acid Battery

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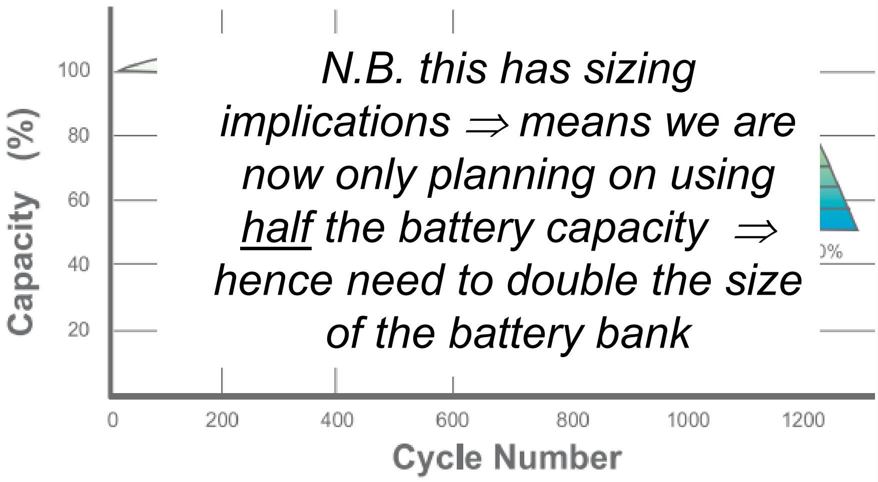


N.B. this has sizing implications ⇒ means we are now only planning on using <u>half</u> the battery capacity ⇒ hence need to double the size of the battery bank

Source: https://www.sunwize.com/gel-vs-agm-batteries/

Lead-acid Battery

- Rechargeable batteries need to be protected against both deep discharge and overcharging
- If the battery is totally empty, crystalline lead sulphate is created ⇒ much more difficult to reconvert than normal amorphous material ⇒ damages the battery permanently
- Deep discharge avoided by switching off the load at ~30% SoC (i.e. 70% DoD)

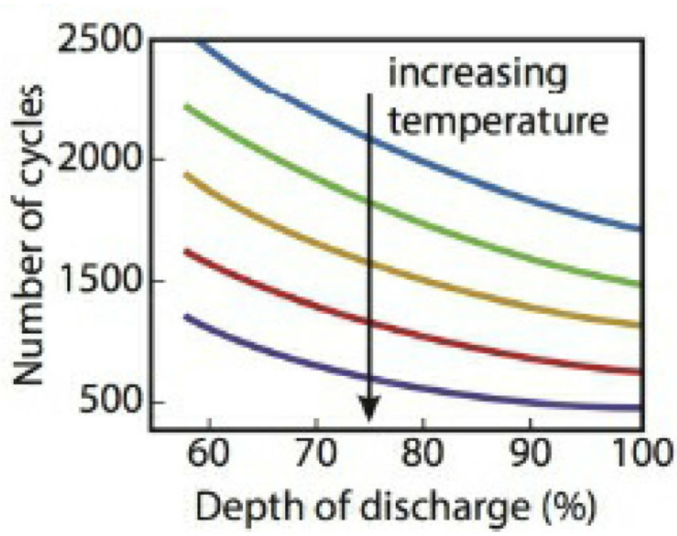
Table 4.8 *Dependence of the Open Circuit Voltage and the Charge Density on the State of Charge of a 12-V Lead–Acid battery*

State of charge (SOC)	*100%*	*75%*	*50%*	*25%*	*0%*
Voltage in V	12.7	12.4	12.2	12.0	11.9
Acid density in kg/l	1.265	1.225	1.190	1.115	1.120

Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

Lead-acid Battery

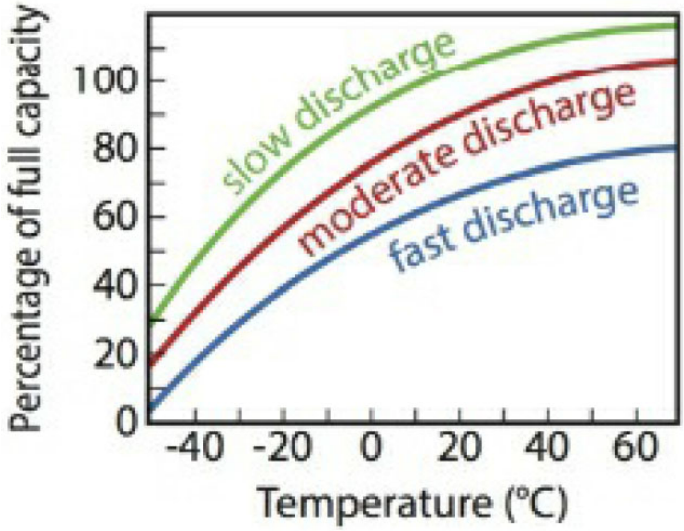
- Cycle lifetime not fixed ⇒ actually very dependent on DoD and temperature
- Colder operating temperatures ⇒ longer cycle lifetime
- Lower DoD ⇒ longer cycle lifetime



Source: textbook

Lead-acid Battery

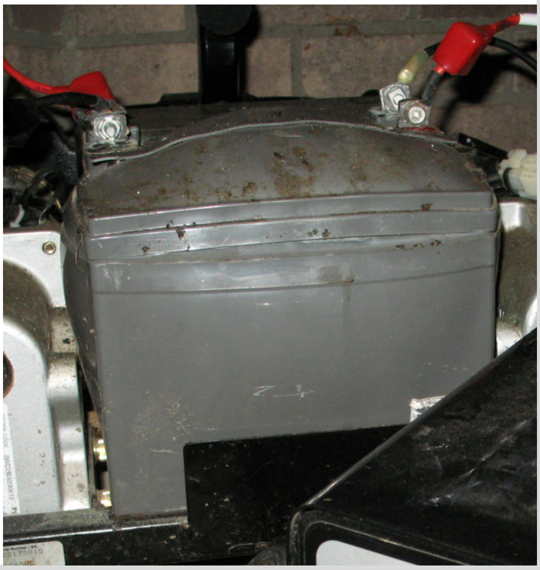
- Also, battery capacity increases when discharge current is lower
- Due to discharge process in battery being diffusion limited ⇒ thus if more time allowed, better exchange of chemical species between (porous) plate and electrolyte takes place



Source: textbook

Lead-acid Battery

- If LA battery is over-charged ⇒ starts to produce gas at 14.4 V ⇒ electrolysis decomposes water within the electrolyte into hydrogen and oxygen ⇒ gases escape from battery ⇒ therefore battery must be refilled with water occasionally
- Continuous strong outgassing (and associated temperature increase) can damage a battery ⇒ protected via stopping charging somewhere between 13.8 V and 14.4 V



Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

Lead-acid Battery

- SoC of LA battery can be estimated from voltage

Table 4.9 *State of Charge Estimation for a 12-V Lead–Acid Battery Based on Measured Operating Voltages*

Voltage range (V)	*State of charge (SOC)*
>14.4	Stop charging, battery is full
13.5–14.1	Normal voltage range during charging without load
12.0–14.1	Normal voltage range during charging with load
11.5–12.7	Normal voltage range during discharging
11.4	Disconnect load, start charging

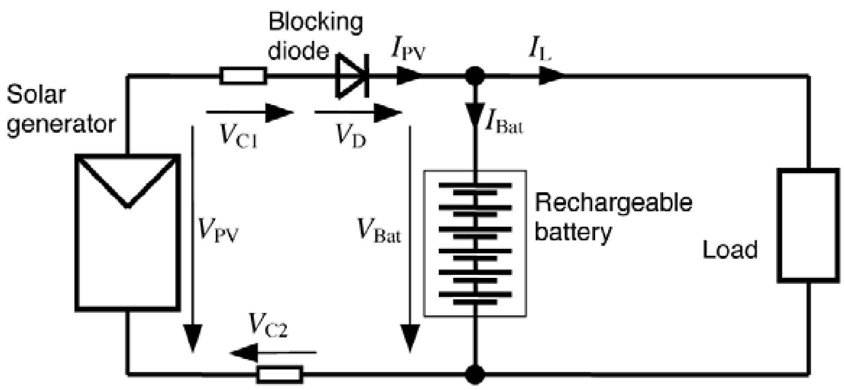
Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

PV Systems

- Simple system can consist of just PV module, battery and load
- Reminder: since internal resistance of PV module is low
  ⇒ battery can discharge through PV module ⇒ avoid such reverse currents by placing <u>blocking diode</u> between PV module and battery
  ⇒ stops discharge at night but this diode causes a loss

$$P_{\mathrm{L,diode}} = I_{\mathrm{PV}} \cdot V_{\mathrm{D}}$$

- Hence diodes with low forward voltages often used (e.g. Schottky diode, V_D ~ 0.15 – 0.45 V)



Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

PV Systems

- Cables cause further losses: a connection cable with cross-section A, specific resistance ρ and cable lengths l_1 and l_2 for the cables from PV module generator to battery and back, respectively, causes following losses:

$$P_{\mathrm{L,cable}} = I_{\mathrm{PV}} \cdot (V_{\mathrm{C1}} + V_{\mathrm{C2}}) = I_{\mathrm{PV}}^2 \cdot (R_{\mathrm{C1}} + R_{\mathrm{C2}}) = I_{\mathrm{PV}}^2 \cdot \frac{\rho}{A} \cdot (l_1 + l_2)$$

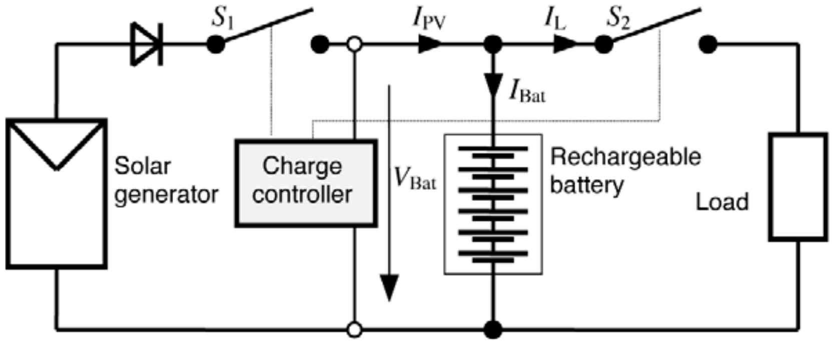
- Copper cable (ρ_{Cu}=0.0175 Ω.mm^2/m) with cable length $l_1 = l_2$ = 10m, cross-sectional area = 1.5 mm^2 and a current I_{PV} = 6 A causes cable losses of $P_{L,cable}$ = 8.4 W
- Assuming the PV module can produce 100 W ⇒ cable losses + blocking diode losses of 3.3 W are considerable at ~12%!

PV Systems

- To minimize losses, cables should:
  1. be as short as possible and,
  2. have large cable cross-sectional area
- For a 12V battery system, a voltage drop of 5%, or 0.6 V, is acceptable, e.g. this requires cable cross-section of ~6 mm^2
- For high power systems, losses can be reduced if batteries are connected in series ⇒ increases battery voltage and decreases current flow ⇒ thus losses reduced

Charge Controllers

- Charge controllers are needed in PV-battery systems to protect batteries: i) limiting discharge levels and ii) preventing overcharging
- Charge-controllers work on basis of voltage control:

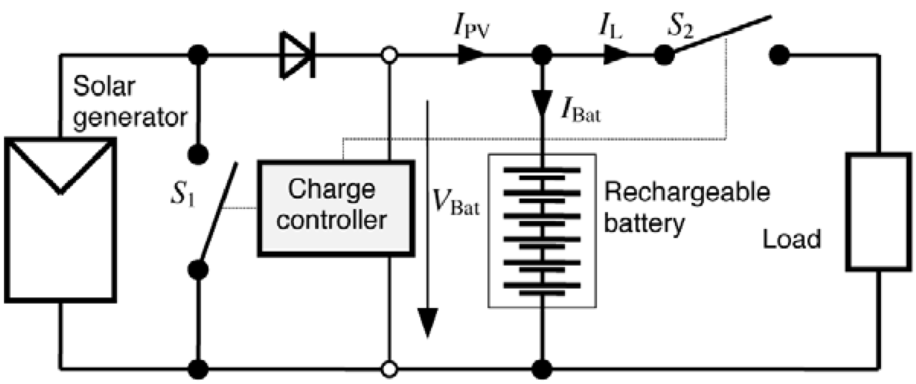


- Charge controller measures the battery voltage V_{Bat}. If it falls below the deep discharge voltage (11.4 V) ⇒ switch S_2 disconnects load from battery.

Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

Charge Controllers

- When battery is charged again (rising above an upper threshold voltage) ⇒ switch reconnects the load.
- If the battery voltage rises above the end of charge voltage (about 14.4 V for a 12-V lead–acid battery), the switch S_1 stops charging.
- The series charge controller (previous slide) and the parallel charge controller (below) are two main types

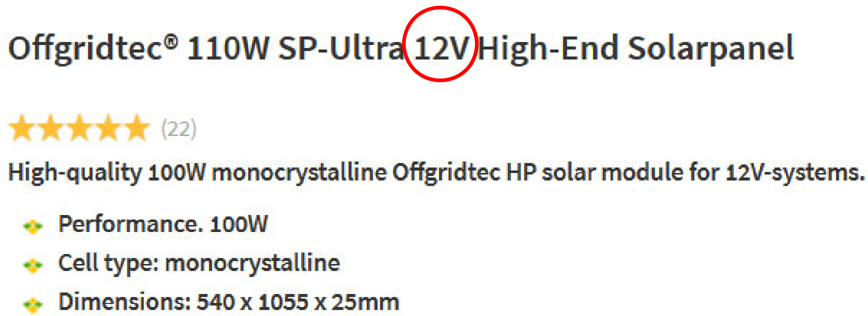


Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

Charge Controllers

- The parallel charge controller ⇒ most commonly used
- If battery is fully charged, the charge controller short-circuits the PV module across switch S_1. The PV module voltage falls to the voltage drop across the switch (<1 V). The blocking diode avoids reverse currents from the battery flowing back across the switch
- One advantage: consume little power when the load or battery is using only PV generated power
- Series charge controller - disadvantage: Continuous forward losses at switch S_1, e.g. a good MOSFET is ~0.04 Ω , but still with a current of 8 A, even this low forward resistance still causes losses of 2.5 W (I^2R)
- Advantage: if PV array voltage is also monitored (in addition to battery voltage) then blocking diode can be omitted ⇒ charge controller simply opens the switch S_1 ⇒ losses reduced

Typical 12V PV Module



Source: https://www.offgridtec.com/en/generators/solar-modules/12v-24v-high-performance-solar-modules/offgridtec-spr-50-60-w-12v-ultra-solarmodul.html

Typical 12V PV Module

Manufacturer:	Offgridtec
System Voltage:	12 V
Performance (Pmax):	100W
Generator Performance (Wp):	110W
Module Voltage (Vmp):	18,56 V
Max. Current (Imp):	5,97 A
No-Load Voltage (Voc):	21,9 V
Short-Circuit Current (ISC):	6,32 A
max. Systemspannung (V):	1000 V
Cell Type:	monokristallin
Degree of Efficiency Cell:	>21%
Tolerance:	+/- 3%
Temperatur Coefficiency:	-0,45%/°C
Ambient Temperature:	-40°C - +86°C
Dimensions (LxWxH)):	1055 x 540 x 35mm
Weight:	6,9 kg
Rahmenstärke:	1 mm

Source: https://www.offgridtec.com/en/generators/solar-modules/12v-24v-high-performance-solar-modules/offgridtec-spr-50-60-w-12v-ultra-solarmodul.html

Charge Controllers

- Question: so why is a PV module with V_{mp} ~ 18.5 V required to charge a 12 V lead-acid battery?
  (or why is a PV module with V_{mp} of ~18.5 V called a "12 V" module)
- Five contributing factors – what are they?

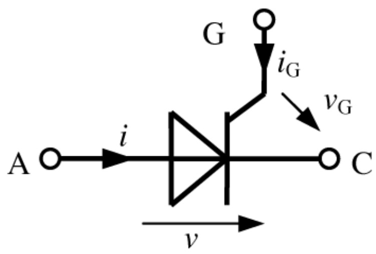
Charge Controllers

- Question: so why does a PV module with V_{mp} ~ 18.5 V required to charge a 12 V lead-acid battery?
  (or why is a PV module with V_{mp} of ~18.5 V called a "12 V" module)

- Five contributing factors:
  1. ~2.8 V lost when PV module operates at 60°C instead of at STC-rating of 25°C (-2.2mV/°C × 35°C × 36 cells)
  2. PV module voltage output is reduced at lower light intensities
  3. A drop of ~0.6 V occurs across the blocking diode
  4. A drop of 1.0 V typically occurs across the regulator
  5. A battery requires 14.4 V to reach full SoC

Inverters

- Most consumer applications use alternating current (AC) ⇒ need DC-AC converter, or inverter
- Different types of semiconductor elements that can switch very high voltages (>1000 V) and currents (>1000 A), e.g, gate turn-off (GTO) thyristors ⇒ "bistable switch"
- Thyristors has three contacts: A (anode), C (cathode) and G (gate).
- If control current i_G = 0, the thyristor blocks at negative and positive voltages *v*.



- If i_G positive (exceeds voltage *v*) then thyristor switched into forward mode ⇒ current *i* flows through thyristor
- While forward current *i* remains above the threshold ⇒ thyristor remains conductive.
- Thyristor is turned off via a negative control current

Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

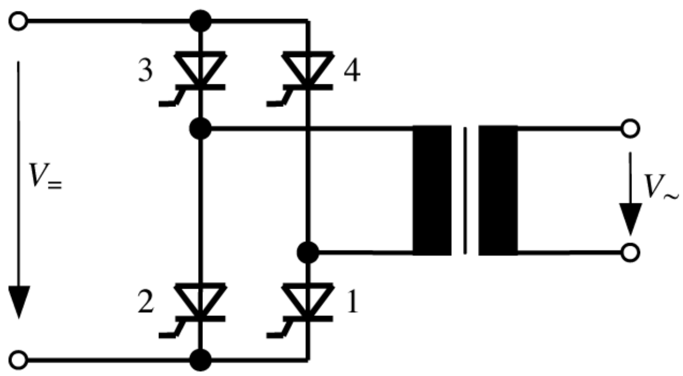
Inverters

- Two most common inverter technologies are:
  - square-wave inverters
  - pulse-width modulated (or sine-wave) inverters.
- Grid-connected inverters have to fulfil stringent criteria to maintain high power quality ⇒ amplitude, frequency and current shape must follow rules of grid operators ⇒ always sine-wave inverters
- Also, for grid-protection, the inverter must switch off immediately if the grid fails to prevent “islanding” ⇒ where a small arm of the grid remains active due to solar power being exported but the main generators have been disconnected
- Grid connected: the electricity grid provides the energy for switching the thyristors, called commutation. For off-grid, the circuit provides this signal itself.

Inverters

<u>Square-wave inverter</u>

- Simple circuit of two-pulse bridge connection shown
- Consists of 4 thyristors and a transformer
- Thyristors 1 and 3 work together, as do thyristors 2 and 4.
- If these two groups switch periodically, they generate a square-wave AC at the transformer



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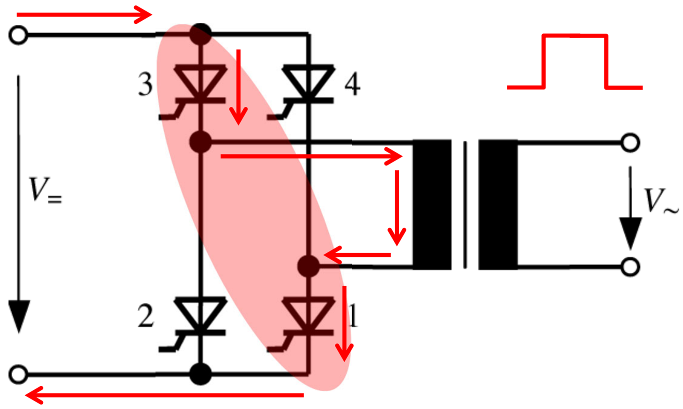

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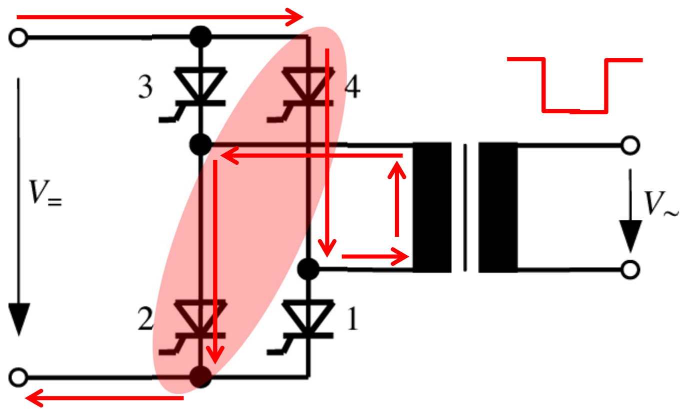
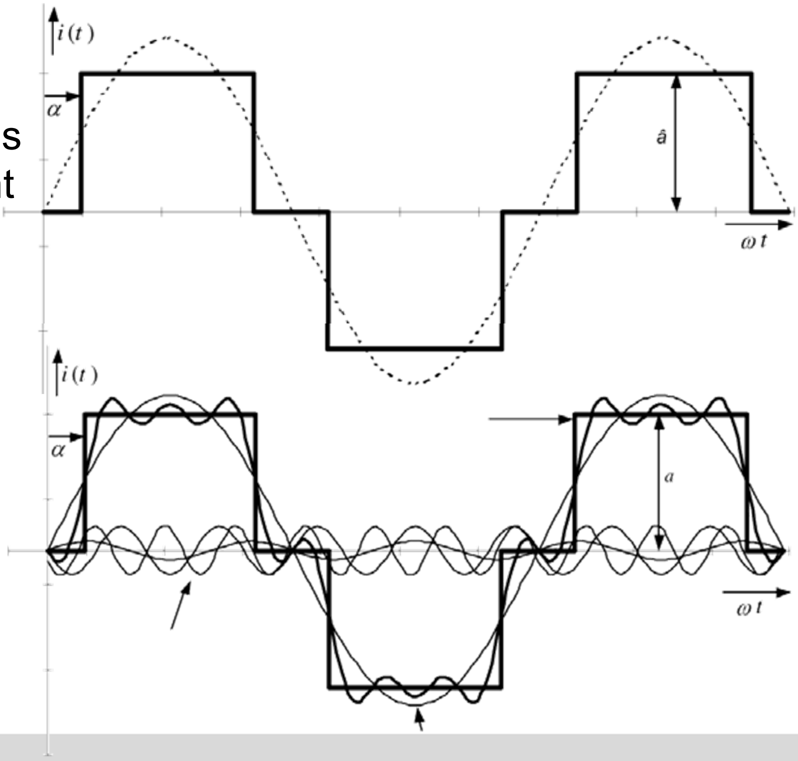


Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

Inverters

- Current output of this circuit ⇒ shape very different to sine wave!
- Besides the desired sinusoidal first-order harmonic ⇒ also various oscillations with different periods (order ≥ 2)
- Such harmonics not acceptable to regulations or grid operators
- Only acceptable for insensitive loads like heaters or motors (off-grid)

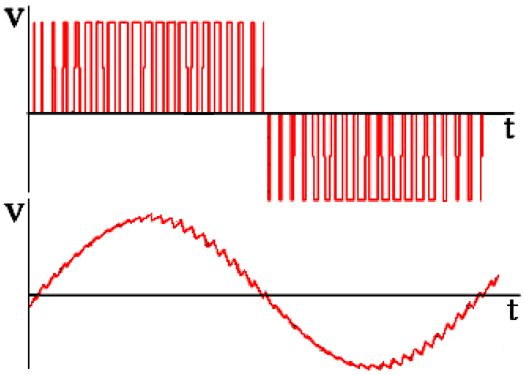


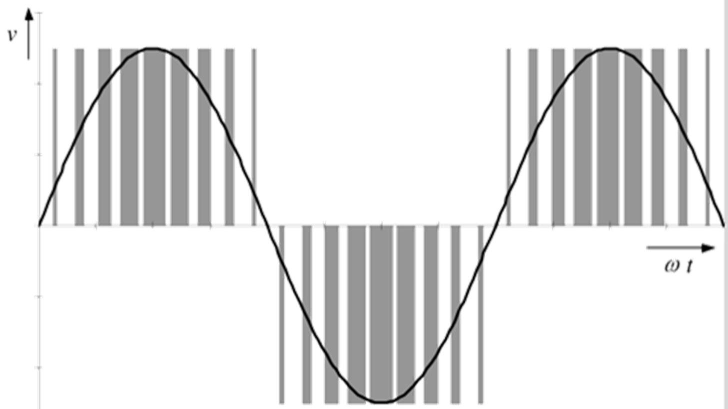
Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

Inverters

Pulse-width modulation (PWM)

- PWM inverters work on same bridge circuit principle, however, thyristors do not switch just once per half-wave ⇒ instead multiple switching generates pulses of different widths
- Quality of sinusoidal oscillation much better than square-wave inverters ⇒ PWM inverters exhibit much less harmonics content ⇒ most common inverter





Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005
https://www.electro-tech-online.com/threads/sine-wave-from-pwm-h-bridge.142930/

Key Take-Home Points

- What challenges can be overcome via the use of a MPPT?
- Understand the operating principle of:
    - DC-DC converter (step-down)
        - Key component?
    - MPPT
        - Relationship to a DC-DC converter?
    - Inverter
        - Key component?
- Understand why 18.5 V is needed from a PV module when connected in a system with a 12 V lead acid battery
- Be able to apply Ohm's law to quickly estimate power losses