"Solar Energy" WS 2014/2015

Lecture 15: Photovoltaic Components and Systems

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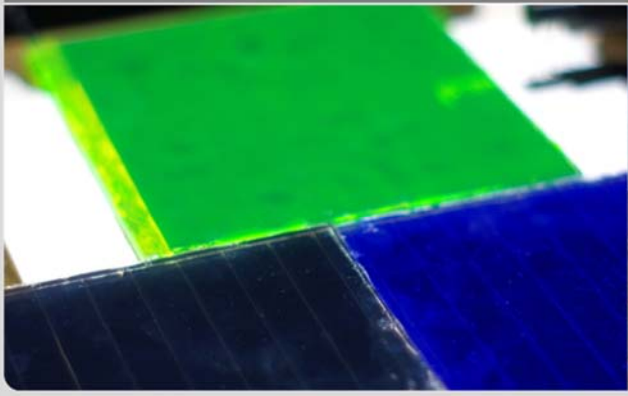
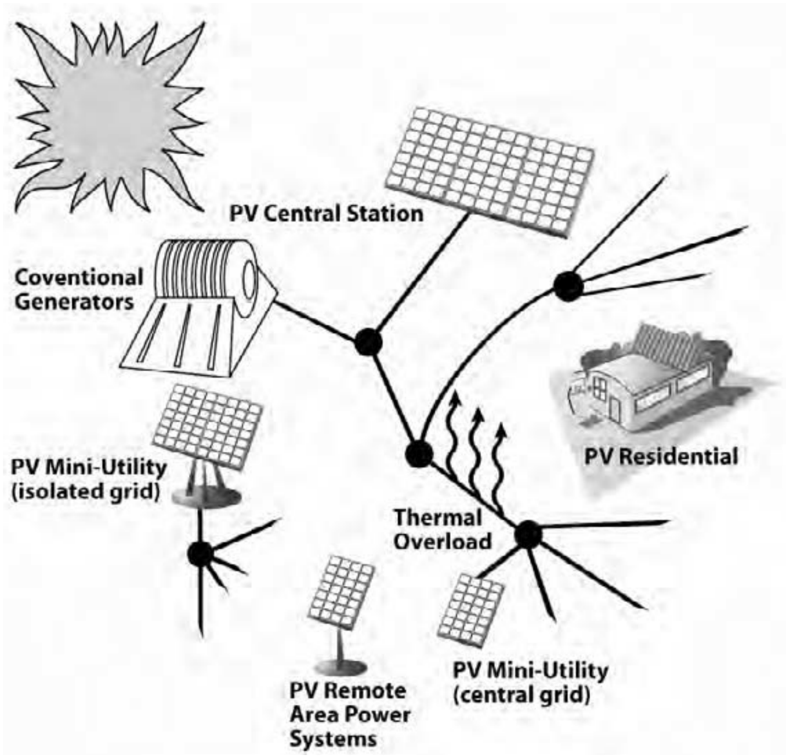
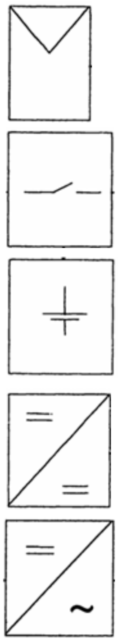


Applications of Photovoltaics



Source: *Wenham et al., "Applied Photovoltaics", 2nd ed, Earthscan 2007*

PV System Components



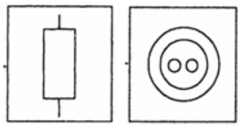
PV generator: PV modules connected to achieve a device-specific output voltage

Charge controller: (between PV module and battery) has over- and under-voltage monitoring to limit against overcharge and deep-discharge. Blocking diodes protect against nocturnal discharge of the battery through PV module

Energy storage: stores the solar energy in lead acid batteries (or other types: nickel cadmium, nickel metal hydride, lithium ion, or supercapacitors)

Power conditioning: conversion of the system (battery) voltage to a suitable DC voltage using a DC-DC converter. Often includes a maximum power point tracker (MPPT)

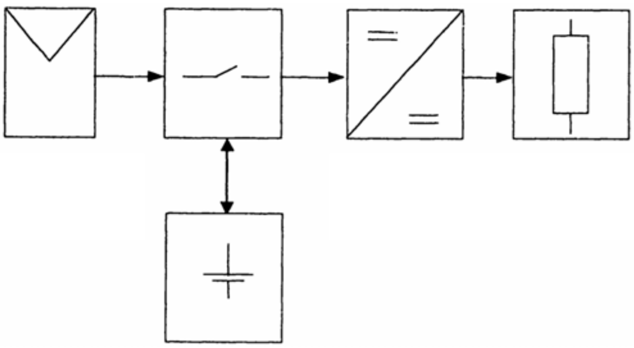
Inverter: for AC loads, the power conditioning electronics are typically together with the inverter, which typically produces a sine-wave for 50 Hz / 230V connection



Loads: consumer loads are typically AC due to cost and convenience, however in some situations DC loads are preferred

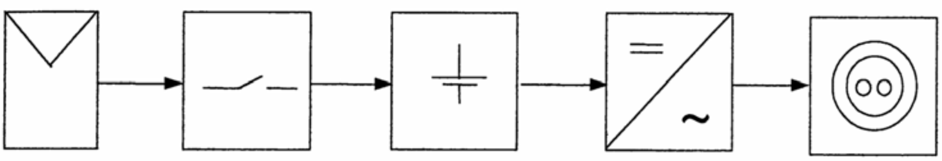
PV System Components: Off-Grid

PV System Configuration for off-grid system with DC loads



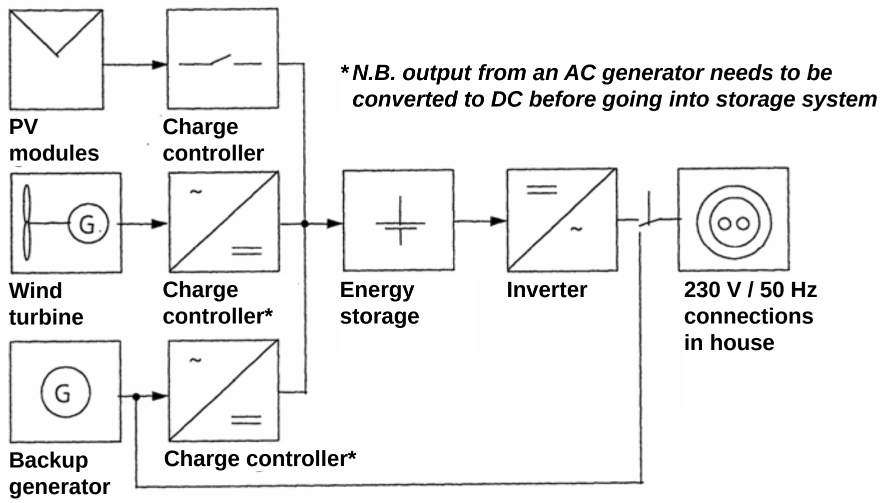
If $V_{load} = V_{battery}$ then no DC-DC conversion required

PV System Configuration for off-grid system with AC loads



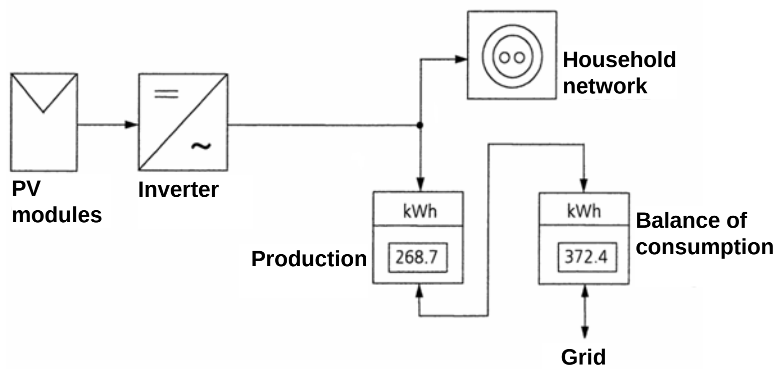
Hybrid PV Systems: Off-Grid

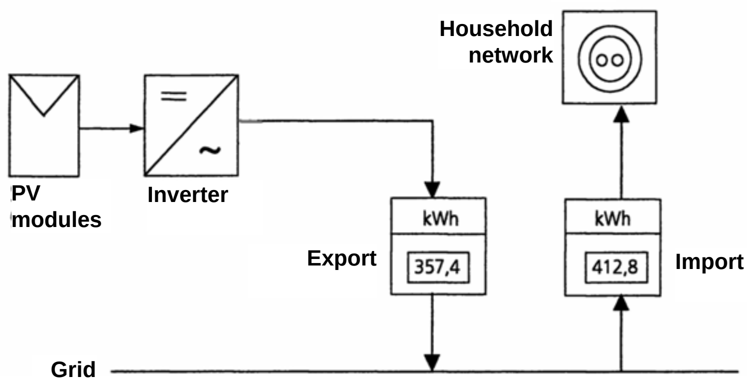
Hybrid System comprises of PV modules and another generator (e.g. back-up petrol or diesel generator; wind turbine)



- A PV-only system needs to be designed carefully to allow to correct power and energy consumption and to allow for variations in solar radiation
- Hybrid system (shown above) allows ensured security of supply similar to what the electricity grid offers

On-Grid PV Systems



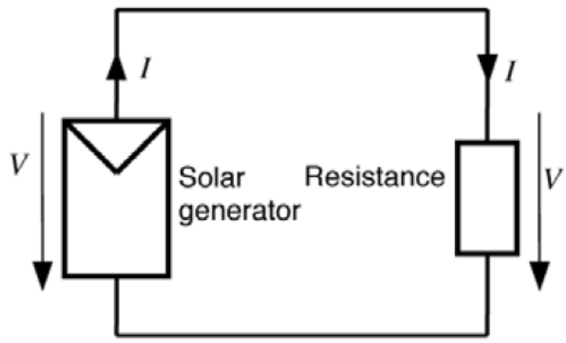


Solar power consumed within household as well as being difference being taken from grid. Regarded as small decentralised producer and electricity purchased at less than retail price from utility

All solar power is exported to the electricity grid, and purchased at more than utility price. Electricity then purchased at standard retail price from utility.

Solar Generator with Load

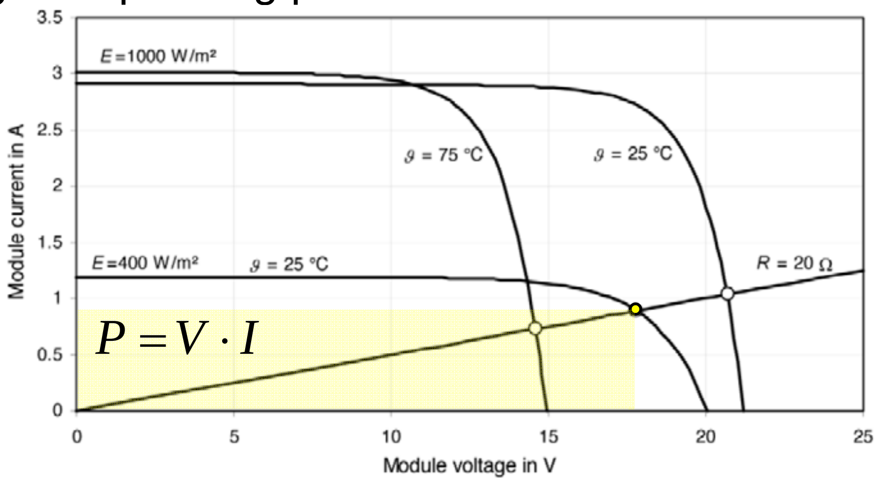
- Previous lectures have discussed the characteristics of solar cells and PV modules, but…
- To be useful we need PV modules that provide electricity that to a consumer with an electric load
- The simplest load is an electric resistance *R*
- Ohm's law describes linear relationship between *I* and *V*:



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

Solar Generator with Load

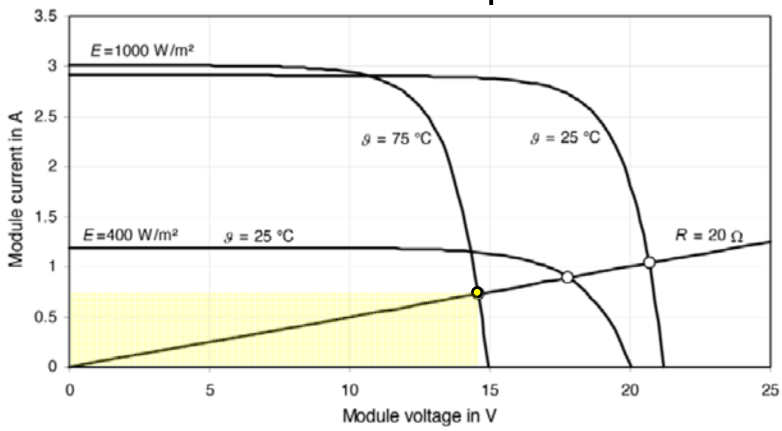
- If *I* through resistor = *I* of solar cell ⇒ common voltage and the operation point found by solving the for voltage V
- Typically using numerical methods, shown graphically below, with intersection of both characteristics then providing the operating point



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

Solar Generator with Load

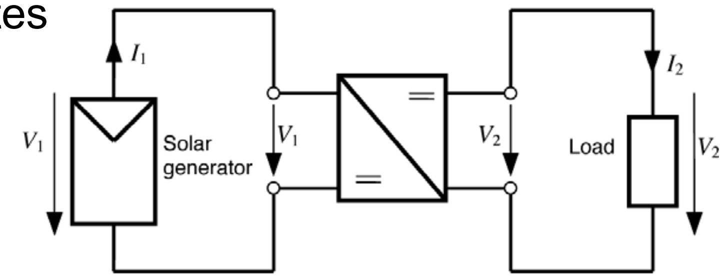
- But the operating point of PV module varies strongly with operating conditions
- Previously, module is operated close to MPP at irradiance of 400 W/m^2 and T = 25°C $\Rightarrow$ at other irradiances and temperatures, the module is operated sub-optimally
  $\Rightarrow$ output power is much less than the possible maximum



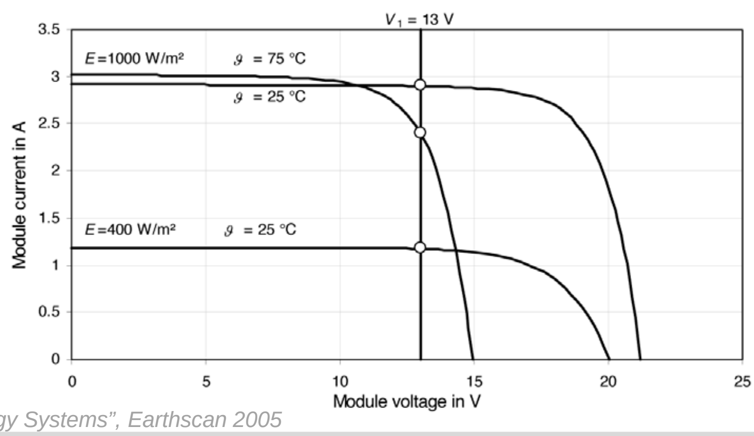
Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

DC-DC Converters

- DC-DC converter generates a voltage at load that is different from that of solar generator



- E.g. from previous resistance example, power output of PV module can increases at higher irradiances if PV module operated instead at constant *V*



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

DC-DC Converters

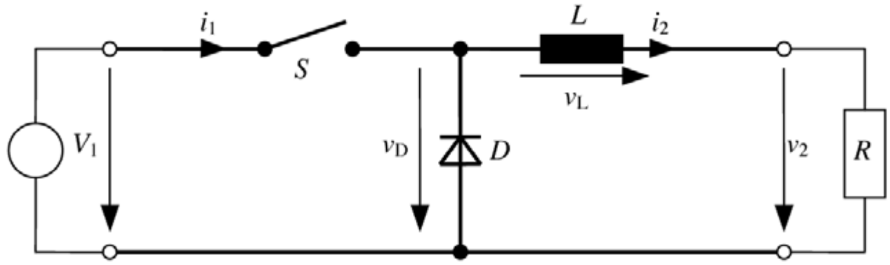
- Power output can be increased even more if solar generator voltage also varies with temperature, i.e. if V_{oc} increases with falling T
- Input power P_1 and output power P_2 are identical for an ideal converter with an efficiency of 100%

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

- In practice, good DC–DC converters have efficiencies of >90% $\Rightarrow$ only a small part of the generated power lost as heat
- Back to some electronics to see how this is achieved….

DC-DC Converters:

- If load voltage is always lower than the PV module voltage $\Rightarrow$ so-called “buck converter” is used



N.B. Switches and diodes are considered as ideal in the following calculations

- Operation: Switch S is closed for the time period T_E and the current i_2 through the inductance L creates a magnetic field that stores energy. The voltage v_L at the inductance is:

$$v_L = L \cdot \frac{d i_2}{d t}$$

Source: *Quashing, “Understanding Renewable Energy Systems”, Earthscan 2005*

DC-DC Converters

- Switch (e.g. FET) is then opened for a time period T_A and the magnetic field of the inductance collapses and drives a current through the resistance *R* and the diode *D*.
- Neglecting the forward voltage drop at the diode, the output voltage v_2 at the contacts becomes:

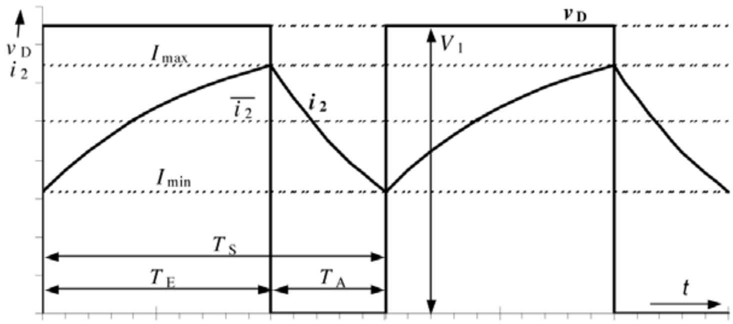
$$v_2 = \begin{cases} v_D - v_L = V_1 - v_L & \text{with } v_L > 0 \quad \text{for } 0 \le t \le T_E \\ v_D - v_L \approx -v_L & \text{with } v_L < 0 \quad \text{for } T_E \le t \le T_E + T_A \end{cases}$$

- After the period $T_S = T_E + T_A$ the cycle starts again $\Rightarrow$ mean voltage $\overline{v_D}$ with the *duty cycle* $\delta = T_E / T_S$ is:

$$\overline{v_D} = V_1 \cdot \frac{T_E}{T_S} = V_1 \cdot \delta$$

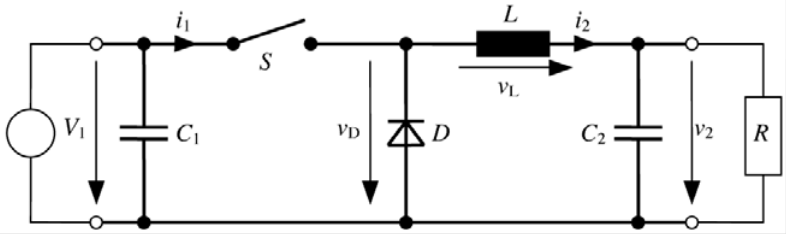
DC-DC Converters

- Output:



- In practice, v_2 should be relatively constant $\Rightarrow$ capacitors C_1 and C_2 are used.
- C_1 buffers solar output when switch is open; C_2 reduces ripple on output voltage
- Switching frequencies are typically between 20 – 200 kHz
- For ideal inductance *L*, the mean output voltage across load *R* is:

$$V_2 = \overline{v_2} = V_1 \cdot \frac{T_E}{T_S} = V_1 \cdot \delta$$



DC-DC Converters

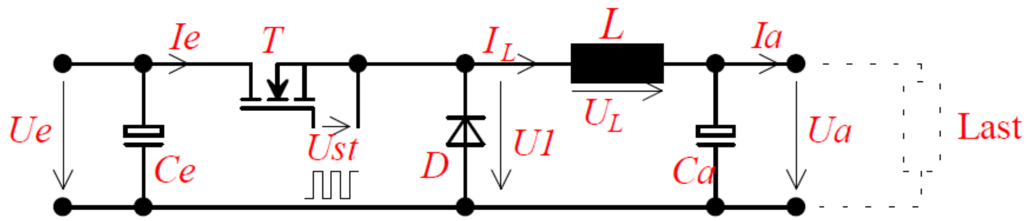


Abbildung 1.1.1: Abwärtswandler

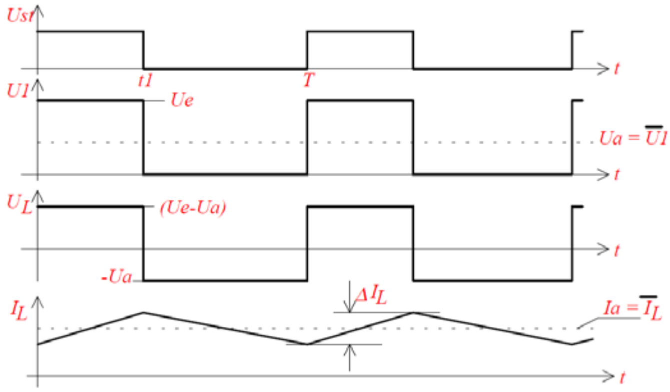


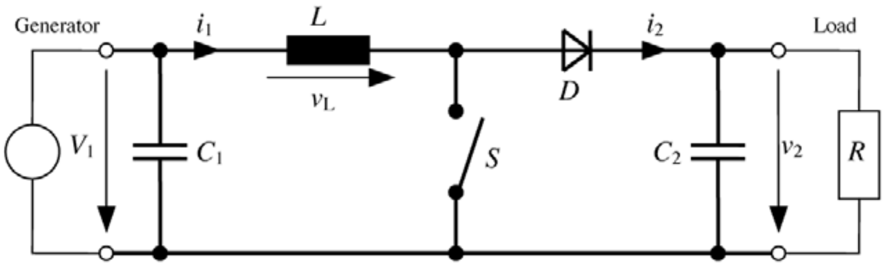
Abbildung 1.1.2: Spannungen und Ströme beim Abwaärtswandler

As well as buck converter, also called step-down converter

Source: http://schmidt-walter.eit.h-da.de

DC-DC Converters:

- If load voltage higher than the PV module voltage ⇒ "boost converter" (similar to buck except that *D*, *S* and *L* change positions)



- Operation: if switch *S* is closed, a magnetic field is created in the inductance *L* with the voltage $v_L = V_1$ ($v_L > 0$). When *S* opens, voltage $v_2 = V_1 – v_L$ ($v_L < 0$) is applied to load. This voltage is higher than the input voltage V_1 as when *S* closes, the capacitor C_2 retains the load voltage and diode *D* avoids the discharging of C_2 through the switch *S*.
- Output voltage given by $V_2 = V_1 \cdot \dfrac{T_S}{T_A}$

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

DC-DC Converters:

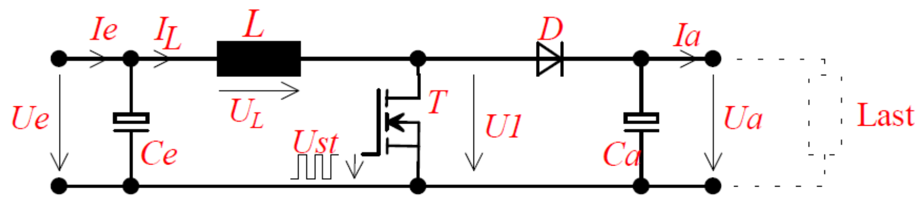


Abbildung 1.2.1: Aufwärtswandler

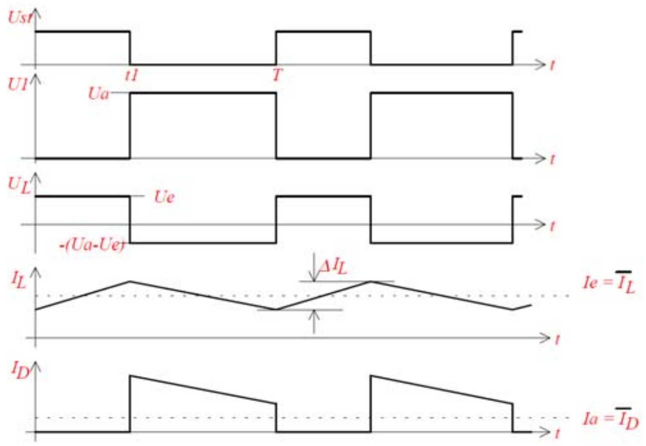


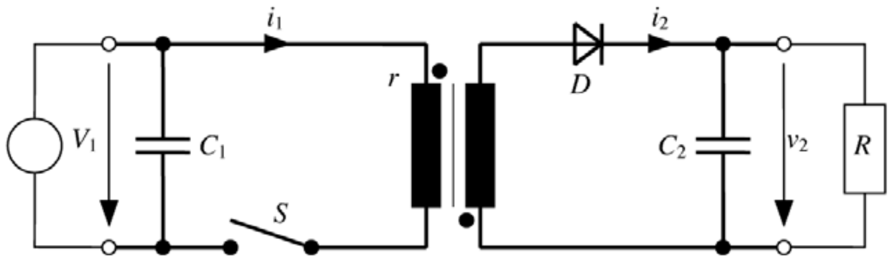
Abbildung 1.2.2: Spannungen und Ströme beim Aufwärtswandler

As well as boost converter, also called step-up converter

Source: http://schmidt-walter.eit.h-da.de

DC-DC Converters:

- Also other types of converters – shown here a flyback converter:



- Uses a transformer instead of an inductor
- Output voltage can be determined considering the ratio *r of* the number of turns in the winding on either side of transformer ⇒ output voltage becomes:

$$V_2 = V_1 \cdot \frac{T_E}{T_A} \cdot \frac{1}{r}$$

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

DC-DC Converters:

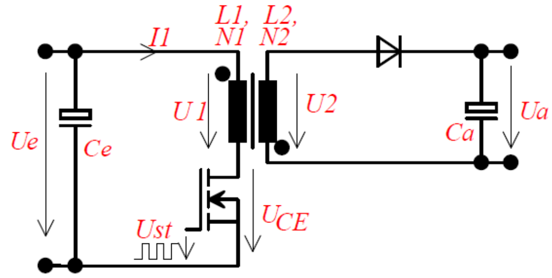


Abbildung 2.1.1: Sperrwandler

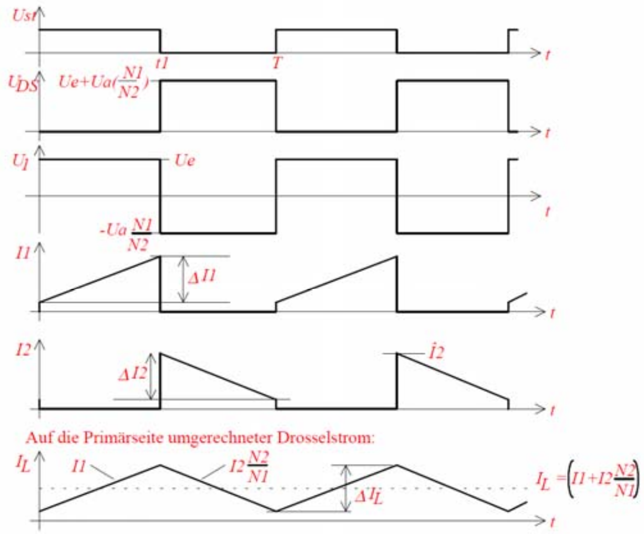


Abbildung 2.1.2: Spannungen und Ströme beim Sperrwandler

Source: http://schmidt-walter.eit.h-da.de

Maximum Power-Point Trackers:

- Voltage converters can maintain different voltages at the solar generator and at the load, however the optimal operating voltage varies depending on irradiance and temperature.
- Therefore, a variation in the duty cycle of the DC–DC converter changes the solar generator voltage and thus can improve the energy yield.
- Fluctuations in temperature ϑ have highest influence on optimal solar generator voltage. A temperature sensor attached to the back of a solar module can measure its temperature.

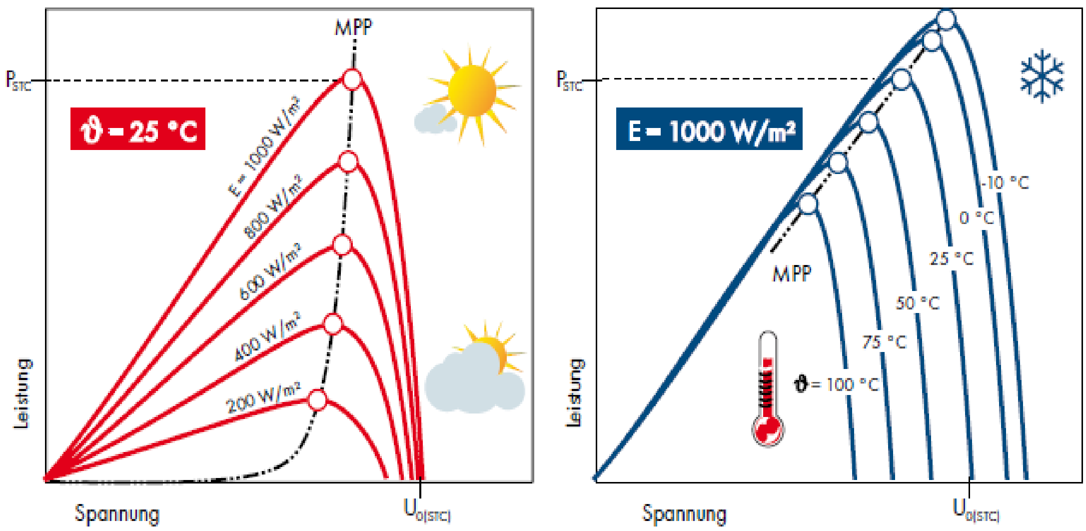
Maximum Power-Point Trackers:

- With the temperature coefficient of the open circuit voltage for silicon solar cells: $\alpha_{VOC} = -4 \cdot 10^{-3}$/°C (i.e. – 0.4 rel.% change in V_{oc} per °C increase in temperature the duty cycle for a buck converter can be estimated with the MPP voltage V_{MPP} at a reference temperature and the known output voltage $V2$:

$$\delta = \frac{V_2}{V_1} = \frac{V_2}{V_{MPP}(\vartheta)} = \frac{V_2}{V_{MPP(\vartheta=25°C)} \cdot (1+\alpha_{VOC} \cdot (\vartheta - 25°C))}$$

- If the duty cycle additionally is adapted to the solar irradiance ⇒ solar generator can be operated at the MPP in most cases.
- MPPT ≡ a DC–DC converter that operates the PV module at its MPP

Maximum Power-Point Trackers:



Concept: At variable temperatures and irradiances the greatest amount of power (Leistung) is extracted from the PV module <u>not</u> with a fixed voltage (Spannung) or duty cycle, but via varying the duty cycle of the DC-DC converter to realise operation at V_{MPP}

Source: www.sma.de

Maximum Power-Point Trackers:

- Several methods for implementing MPP tracker control:

1. Sensor-controlled regulator: As described above, the MPP voltage is calculated as a function of the temperature and irradiance sensor input.
2. Control using a reference cell: The characteristics (V_{OC} and I_{SC}) of a small reference solar cell mounted near the PV array generator are recorded $\Rightarrow$ allows estimation of V_{MPP} and uses simple equivalent circuit to find I_{MPP}:

$$I_{\mathrm{MPP}} = I(V_{\mathrm{MPP}}) = I_{SC} - I_{\mathrm{S}} \cdot \left(\exp\left(\frac{V_{\mathrm{MPP}}}{m \cdot V_{\mathrm{T}}} \right) - 1 \right) \qquad \text{(here } I_S = I_0\text{)}$$

Maximum Power-Point Trackers:

The derivative of the power with respect to the voltage is equal to zero at the power maximum:

$$\frac{\mathrm{d}\,P(V_{\mathrm{MPP}})}{\mathrm{d}V} = \frac{\mathrm{d}(V_{\mathrm{MPP}} \cdot I(V_{\mathrm{MPP}}))}{\mathrm{d}V} = I(V_{\mathrm{MPP}}) + V_{\mathrm{MPP}} \cdot \frac{\mathrm{d}\,I(V_{\mathrm{MPP}})}{\mathrm{d}V} = 0$$

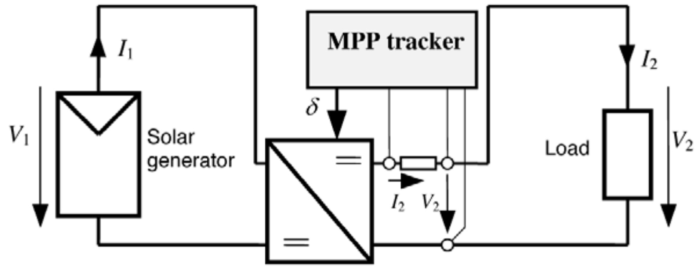
Insert I_{MPP} into equation and solve for MPP voltage V_{MPP}:

$$V_{\mathrm{MPP}} = m \cdot V_{\mathrm{T}} \cdot \ln\left(\frac{I_{SC} + I_{\mathrm{S}}}{I_{\mathrm{S}}} \right) - m \cdot V_{\mathrm{T}} \cdot \ln\left(1 + \frac{V_{\mathrm{MPP}}}{m \cdot V_{\mathrm{T}}} \right) = V_{OC} - m \cdot V_{\mathrm{T}} \cdot \ln\left(1 + \frac{V_{\mathrm{MPP}}}{m \cdot V_{\mathrm{T}}} \right)$$

Numerical or approximation methods can be used to solve this equation.

Maximum Power-Point Trackers:

3. Oscillating search control (hill climbing): Voltage and current are measured at the converter input or output and the power is calculated and stored.



Small changes in the duty cycle cause a voltage change. The power is then estimated again. If the power increases, the duty cycle is changed again in the same direction. Otherwise, the duty cycle is changed in the opposite direction. For constant output voltages, the search for the maximum output current is sufficient. In this case, the power itself need not to be estimated.

Maximum Power-Point Trackers:

4. Zero transit method: here, the voltage and current are measured and multiplied and the derivative dP/dV determined. The voltage is then increased or decreased depending whether the derivative is positive or negative

- Various MPPT technologies have difficulty in finding the optimal operating point when:
  - i. the solar generator is partially shaded,
  - ii. in rapidly changing conditions or
  - iii. for non-standard modules.
- Shading occurring over long time = lost electricity (and money!); therefore, a good MPP tracker should also provide good results for irregular operating conditions, in which multiple local maxima can occur in the I-V characteristic

Maximum Power-Point Trackers:

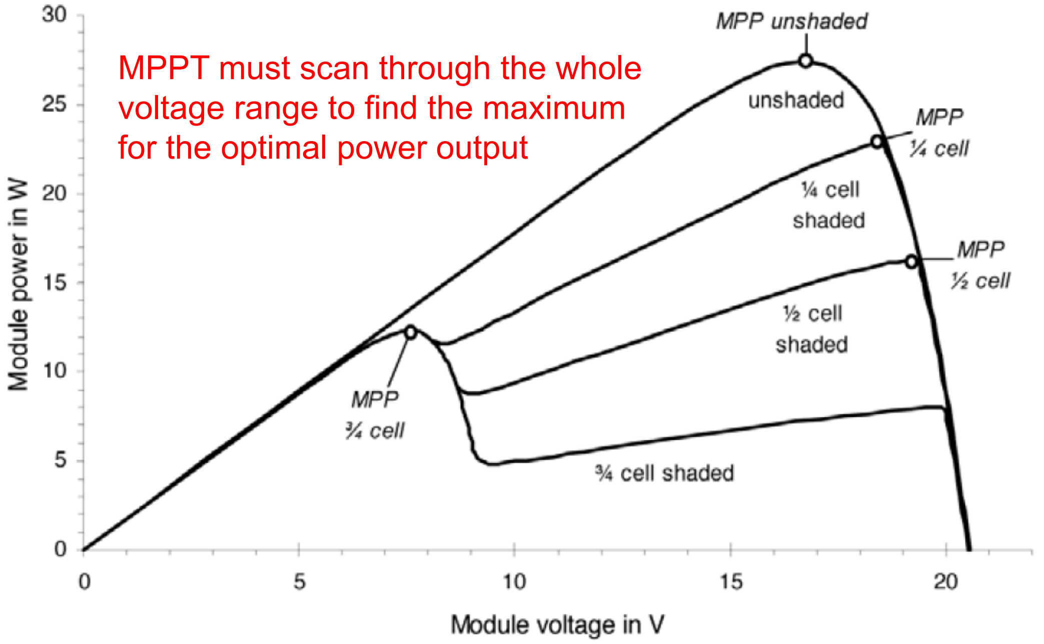


Figure 4.28 *P-V Characteristic of a Module with 36 Cells and Two Bypass Diodes. A Single Cell is Shaded to Different Degrees; All Other Cells Are Fully Irradiated (E = 574 W/m², T = 300 K)*

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

Electrical Energy Storage:

- Electricity consumers are hardly ever connected directly to a PV system due to:
    i. fluctuations in power availability throughout the day, and
    ii. night.
- Hence storage of electrical energy is usually required
- Storage systems 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 to compensate for seasonal variations in the solar irradiation in summer and winter.

Electrical Energy Storage:

- Since long-term storage is typically expensive, the PV array is usually oversized so that it also can provide sufficient energy in to meet winter-time loads while relying on batteries for storage
- Another solution is a hybrid with wind or diesel generators – depends on factors relating to resource availability (e.g. wind), economics (how much does it cost to transport fuel to the location), as well as how critical the load is…
- E.g. if the lights go out during the night one can use candles or torches for a couple of hours. However, if the light in a lighthouse doesn't shine any more…?

Electrical Energy Storage:

- Secondary electrochemical elements are mainly used for storage over short- and medium-term periods $\Rightarrow$ usually called batteries
- For economic reasons, the lead–acid battery dominates the current market
- When higher energy densities are needed due to weight considerations, e.g. in laptop computers, other batteries such as nickel–cadmium (NiCd) or nickel–metal hydride (NiMH) are used. Other batteries such as sodium–sulphur (NaS) have been tested for use in electrical (battery-powered) vehicles
- Table below compares various types of rechargeable batteries

Electrical Energy Storage:

Table 4.7 *Data for Various Types of Rechargeable Battery*

	Lead–acid	*NiCd*	*NiMH*	*NaS*
Positive electrode	PbO_2	NiOOH	NiOOH	S
Negative electrode	PbO	Cd	metals	Na
Electrolyte	$H_2SO_4+H_2O$	$KOH+H_2O$	$KOH+H_2O$	β-Al2O3
Energy density (Wh/l)	10–100	80–140	100–160	150–160
Energy density (Wh/kg)	25–35	30–50	50–80	100
Cell voltage (V)	2	1.2	1.2	2.1
Charge/discharge cycles	500–1500	1500–3000	about 1000	about 1500
Operating temperature (°C)	0–55	–20 to 55	–20 to 45	290–350
Self-discharge rate (%/month)	5–15	20–30	20–50	0
Wh efficiency	70–85%	60–70%	60–85%	80–95%

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

Lead acid battery:

- Most common battery for electricity storage is rechargeable lead–acid battery ⇒ main reason is cost
- Builds on expertise from automotive industry, however so-called solar batteries have a slightly modified structure compared with car batteries and achieve longer lifetimes.
- Structure:
  Two electrodes – in charged state, positive electrode consists of lead dioxide (PbO_2) and the negative electrode of pure lead (Pb). A membrane embedded in a plastic box separates the two electrodes. Diluted sulphuric acid (H_2SO_4) fills the empty space between the two electrodes.

Lead acid battery:

- A fully charged lead–acid battery has an acid density of about 1.24 kg/litre at a temperature of 25°C ⇒ density changes with the temperature and charge state. An acid density meter or a voltmeter can indicate the charge state of a battery.
- Since the nominal voltage of one lead–acid battery cell is 2V, six cells are connected in series to get common operating voltage of 12V. The number of cells can be adapted for other voltage levels.

Lead acid battery:

- Reversible chemical reactions inside LA battery:

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

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

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

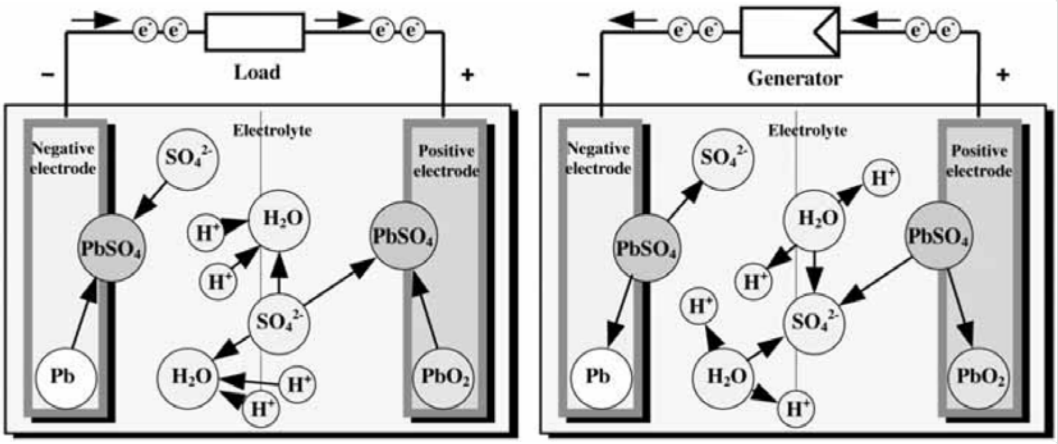


Figure 4.41 *Charging and Discharging a Lead–Acid Battery*

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

Lead acid battery:

- During discharge of LA battery, electrode material and electrolyte react to form lead sulphate ($PbSO_4$) $\Rightarrow$ reaction releases electrons that can be used as electrical energy by the consumer.
- Electrical energy must be fed into the battery for charging. The $PbSO_4$ at the electrodes transform to Pb and PbO_2 again. The charging process needs more energy than is set free during discharging.
- The charge efficiency is the ratio of the discharge over the charge. For the charge efficiency, a distinction is made between the Ah efficiency η_{Ah} and the Wh efficiency η_{Wh}.

Lead acid battery:

- The Ah efficiency is calculated on the basis of integrated currents, while Wh efficiency considers currents and voltages during the discharge and charge periods needed to regain the same charge level as follows:

$$\eta_{\mathrm{Ah}} = \frac{Q_{\mathrm{out}}}{Q_{\mathrm{in}}} = -\frac{\int_0^{t_{\mathrm{discharge}}} I \cdot \mathrm{d}t}{\int_0^{t_{\mathrm{charge}}} I \cdot \mathrm{d}t}$$

$$\eta_{\mathrm{Wh}} = \frac{Q_{\mathrm{out}} \cdot V_{\mathrm{out}}}{Q_{\mathrm{in}} \cdot V_{\mathrm{in}}} = -\frac{\int_0^{t_{\mathrm{discharge}}} V \cdot I \cdot \mathrm{d}t}{\int_0^{t_{\mathrm{charge}}} V \cdot I \cdot \mathrm{d}t}$$

The Ah efficiency of LA battery is about 80 – 90%, while Wh efficiency is ~10% lower.

Wh efficiency is always lower because the battery voltage during charging is higher than during discharging.

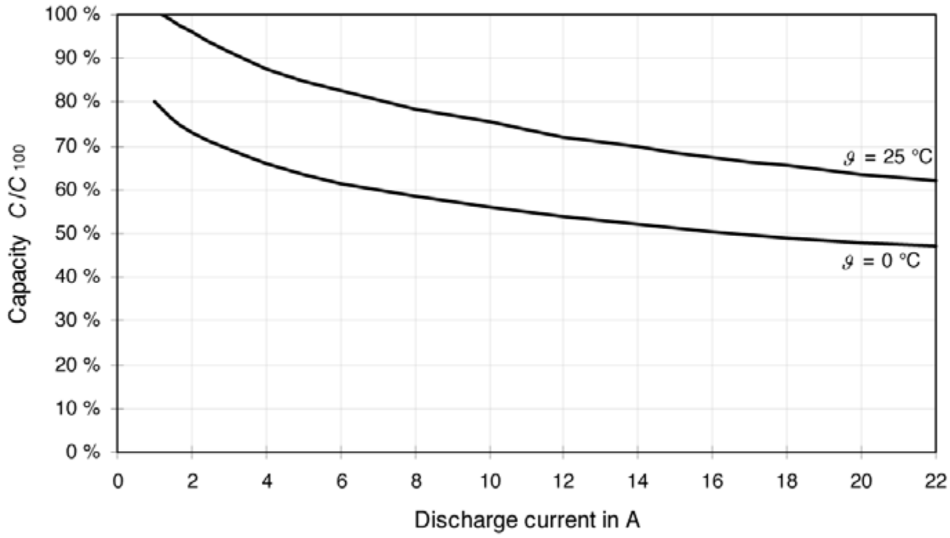
Source: Quashing, "Understanding Renewable Energy Systems", Earthscan 2005

Lead acid battery:

- Battery <u>self-discharge</u> causes additional losses and reduces the system efficiency. The self-discharge rate increases with the temperature and is ~0.3% / day or 10% / month at T = 25°C
- <u>Usable capacity</u> of battery depends on the discharge current $\Rightarrow$ capacity decreases with higher discharge currents and the end of discharge voltage is reached earlier.
- To compare different rechargeable battery types $\Rightarrow$ capacity often reported in combination with discharge duration, e.g. a rechargeable battery with capacity of C_{100} = 100 Ah has a nominal discharge current of $I_{100} = C_{100}$ / 100 hours = 1 A

Lead acid battery:

- If battery is discharged in 10 h with I = 8 A $\Rightarrow$ capacity C_{10} is reduced to less than 80 per cent of C_{100}.
- Usable capacity decreases to about 50% at a temperature of 0°C and a discharge time of 5 hours.



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

Lead acid battery:

- Lifetime of battery – defined by number of charge/discharge cycles achievable – decreases with increasing *T* and depth of discharge (DOD)
- Maximum recommended DOD is normally about 80%, but in practice DOD's of >50% are avoided if possible

  N.B. has sizing implications as we are now only planning on using half the battery capacity, hence typically need to double the size

- Voltage varies with state of charge (SOC):

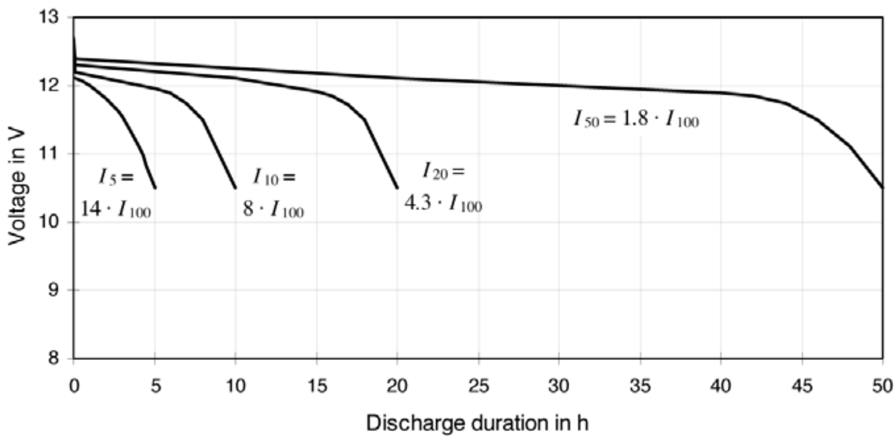
Table 4.8 *Dependence of the Open Circuit Voltage and the Charge Density on the State of Charge of a 12-V Lead–Acid battery*

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:

- When charging or discharging the battery, the *V* is above or below the open circuit voltage. The voltage difference compared with the open circuit voltage depends on current
- Starting at the open circuit voltage of 12.7 V for a fully charged battery, the voltage falls depending on the discharge current. If the initial charge is lower, the voltage drop is higher.
- Effect of *T* on voltage: –25 mV/°C



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

Lead acid battery:

- Voltage is an indicator of SOC of rechargeable battery
- Rechargeable batteries need to be protected against deep discharge or 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 about 30% of the remaining capacity. At typical operating conditions this equates to a battery voltage of ~11.4 V
- If battery is not used for a long time, damage as a result of deep self-discharge is possible ⇒ avoided by simply recharging battery from time-to-time

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

Lead acid battery:

- If LA battery is continuously charged, it starts to produce gas at 14.4 V ⇒ electrolysis decomposes the water within the electrolyte into hydrogen and oxygen and these gases escape from the battery. Therefore, the battery must be refilled with water from time to time.
- Continuous strong gassing can damage a battery ⇒ protected via stopping charging somewhere between 13.8 V and 14.4 V
- N.B. briefly gassing from time-to-time can help mix electrolyte thoroughly
- Batteries located in a dry room at moderate *T*. Battery gases can be explosive ⇒ good ventilation is essential

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

Lead acid battery:

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

Next Lecture:

- Battery systems
- Inverters
- Solar trackers
- Other balance of system components:
    - Wiring
    - Framing
- PV system design
- Examples of PV systems

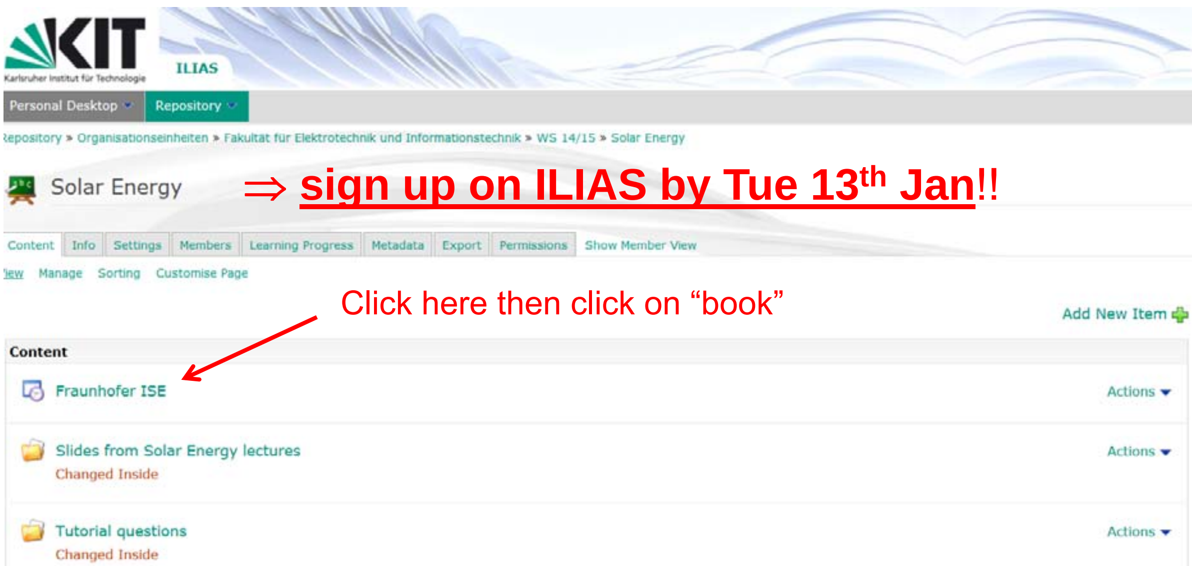
Announcements:

- Written **exam** to be held on 17th March
- Fraunhofer ISE visit Thursday 22nd January
- 8am departure from KIT, returning 5pm
- Programme – “jobs fair” to be arranged:

Time	Topic	Responsible
Presentations		
9:30	Welcome and Overview Fraunhofer ISE	Michaela Ditzenbach
10:45	Organic Photovoltaics	Birger Zimmermann
11:05	Photonmanagement and Upconversion	Jan Christoph Goldschmidt
11:25	Tandem on Si	Stefan Janz
11:45	III-V solar cells	David Lackner
11:05	Power-by-light	Henning Helmers
12:25	Lunch at ISE canteen	
Lab Tours		
13:15	High-Temperature Storage	
13:45	III-V Technology	David Lackner
14:15	Laser Processing	Jan Nekarda
14:45	PVTEC	Andreas Wolf/Tobias Fellmeth

Announcements:

- ETIT will pay for the bus
- ISE already providing lunch for us
- Likely that we can avoid charging if it is popular and worth it!



⇒ **sign up on ILIAS by Tue 13th Jan!!**

Click here then click on “book”

Announcements:

- Survey