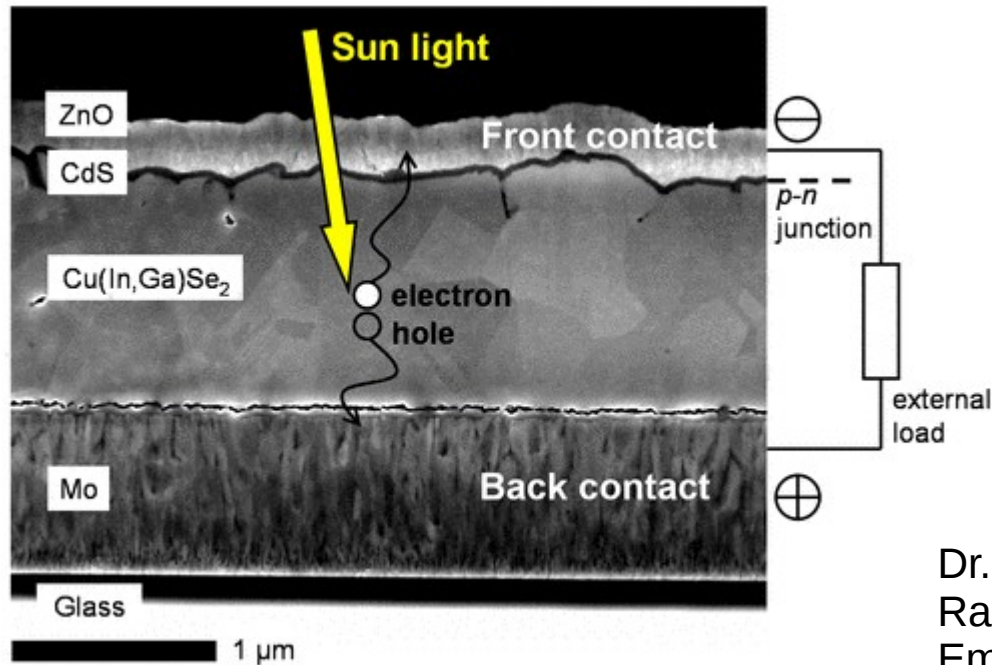
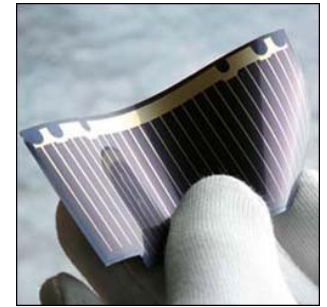
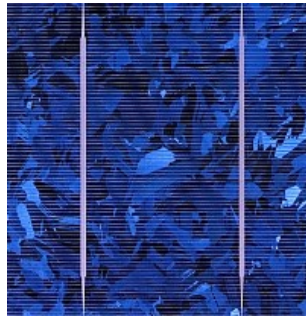


Photovoltaik (23467 HS15)

(Dienstag, 10:15 - 12:00 Departement Physik, Seminarzimmer 3.12)



Dr. Thilo Glatzel
Raum 3.04
Email: thilo.glatzel@unibas.ch

Energy demand

of a human

100 W to sustain biological life
(2.4 kWh/day or 876 kWh/year)

>3 kW to sustain comfortable life
(>72 kWh/day or >26.28 MWh/year)

of mankind

more than 6×10^9 individuals

> 1.8×10^4 GW to sustain comfortable life

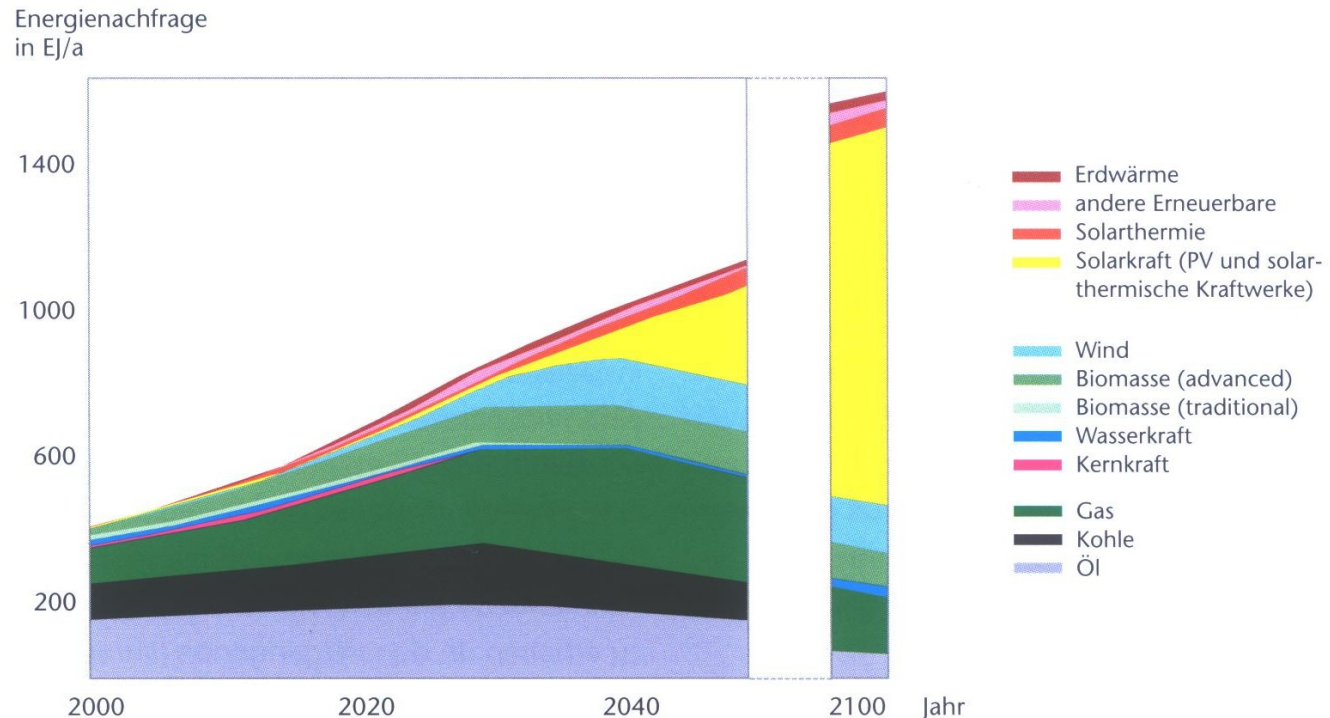
for comparison

energy in 100 g chocolate about 1 kWh

energy in 1 l gasoline about 10 kWh

power of one nuclear power plant about 1 GW

Scenario of worldwide energy demand



„good“ sources of information:

- Intergovernmental Panel on Climate Change IPCC, <http://www.ipcc.ch>
- International Energy Agency IEA, <http://www.iea.org/>
- Umweltbundesamt UBA, <http://www.umweltbundesamt.de/>
- Potsdam-Institut für Klimafolgenforschung PIK, <https://www.pik-potsdam.de/institut>
- Wuppertal Institut, <http://wupperinst.org/home/>

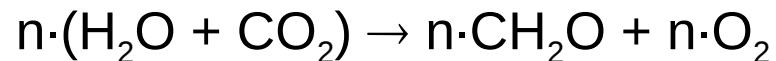
The big problems with energy

1. Limitation of resources
2. Political imbalance
3. Environmental impact

Fossil energy resources

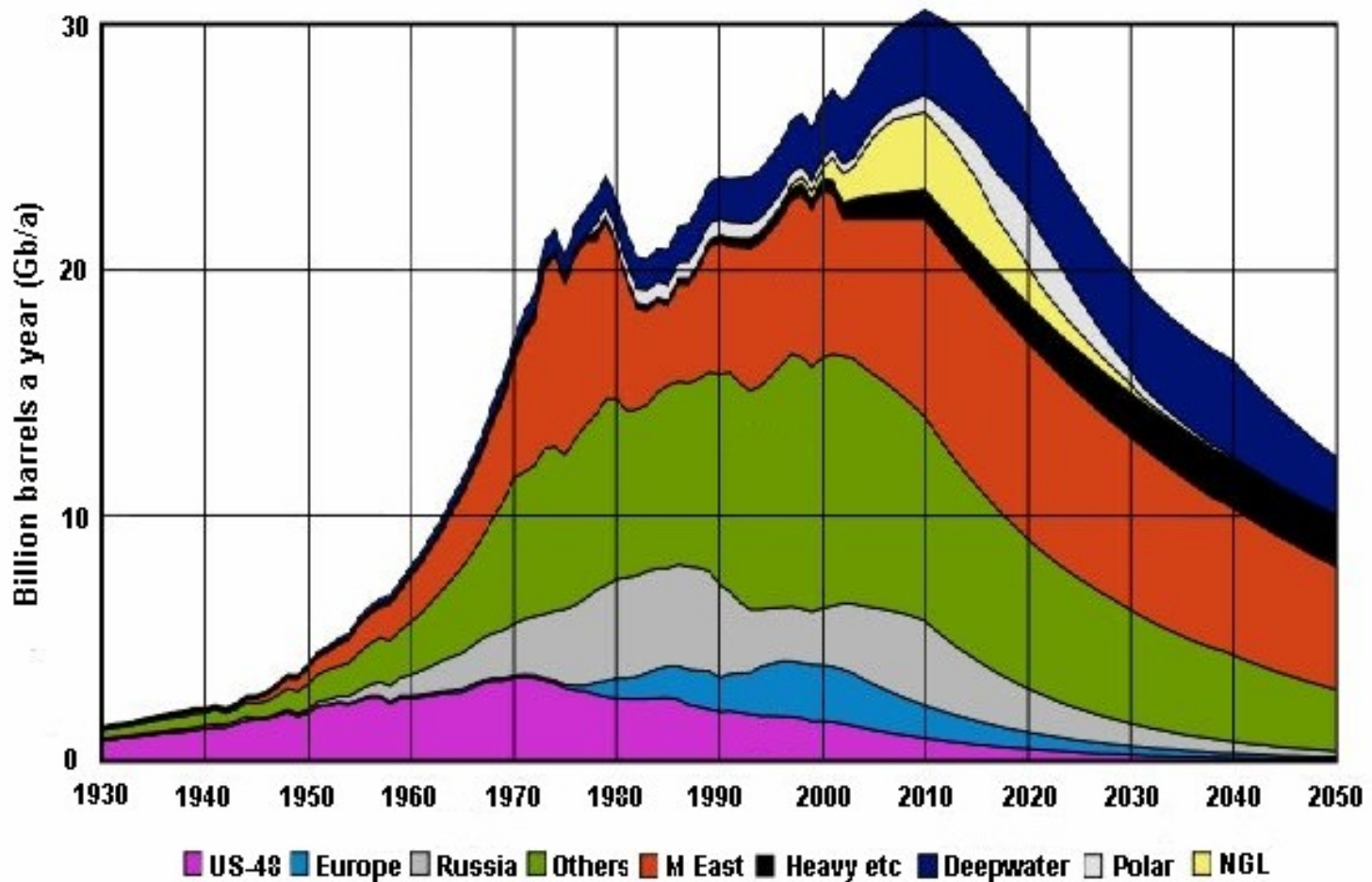
carbon, oil, gas

Produced by photosynthesis over millions of years



Photovoltaik

One of several predictions.....



Estimation of fossil energy resources

Assumption:

all O₂ in the atmosphere originates from photosynthesis since all oxygen was consumed by oxidation in the early life of earth.

Calculation:

$$\text{mass of air} \quad m_{air} \cdot g = p \cdot 4\pi \cdot R_e^2$$

$$\text{mass of O}_2 \quad m_{O_2} \approx m_{air} / 5$$

$$\text{mass of C} \quad m_C = M_C / M_{O_2} \cdot m_{O_2}$$

With:

$$g = 10 \text{ m/s}$$

$$p = 10 \text{ N/cm}^2$$

$$R_e = 6.4 \cdot 10^6 \text{ m}$$

$$M_C = 12 \text{ g/mol}$$

$$M_{O_2} = 32 \text{ g/mol}$$

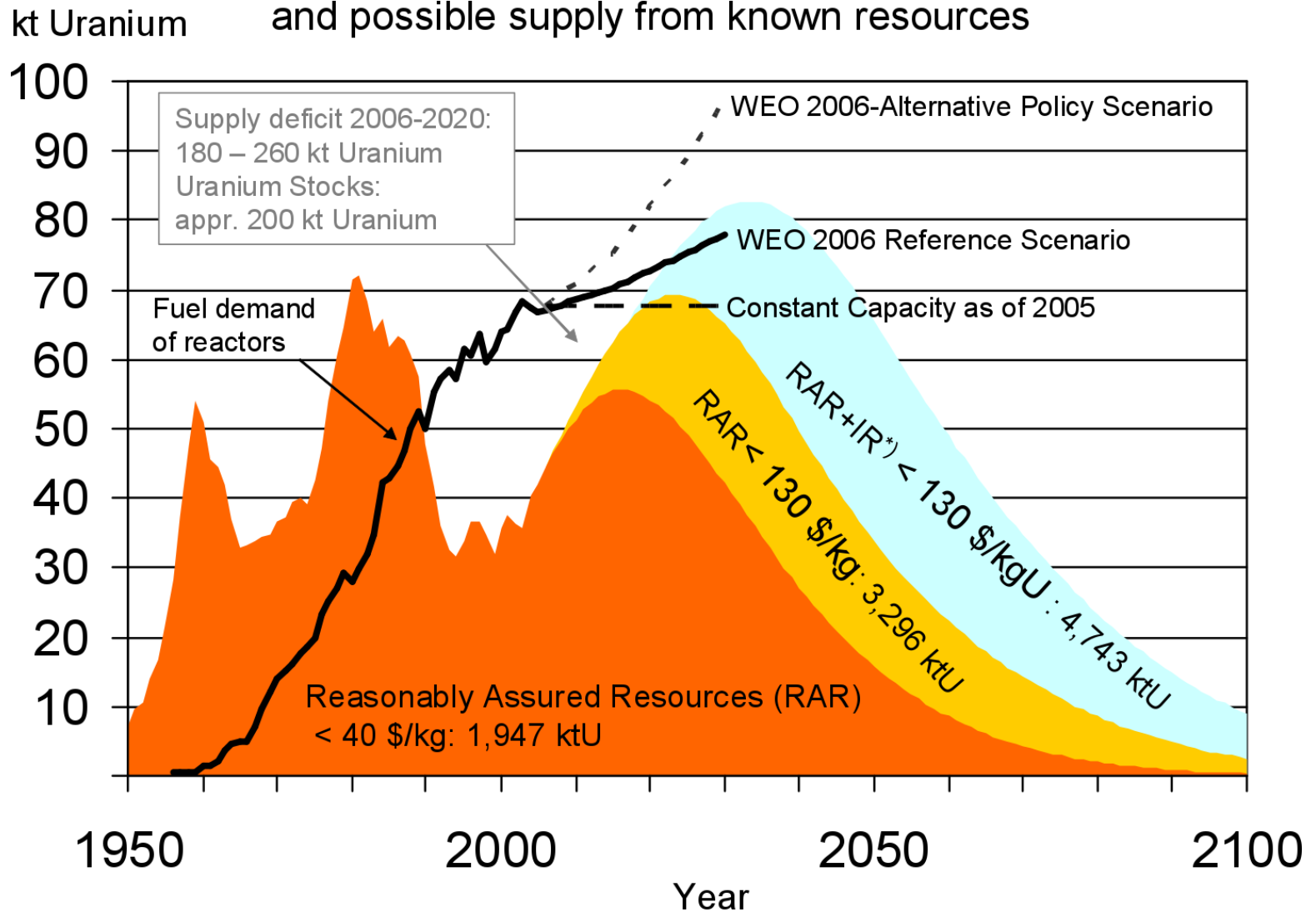
$m_C(\text{world})$ about $4 \cdot 10^{14}$ t

discovered about 10^{13} t

demand 2002 about $3 \cdot 10^{10}$ t

Photovoltaik

Uranium demand according to IEA scenarios
and possible supply from known resources



*) IR = Inferred Resources

The sun is a hot fire ball

spectrum of the black body radiation (Planck)
(energy flux as a function of the photon energy and of the temperature)

$$\frac{dJ_S(h\nu)}{d(h\nu)} = \frac{8\pi}{h^3 c^2} \cdot \frac{(h\nu)^3}{\exp\left(\frac{h\nu}{k_B T_S}\right) - 1}$$

$$(h\nu)_{\max} = 2.82 \cdot k_B T$$

with

$$h = 6.6 \cdot 10^{-34} \text{ Js}$$

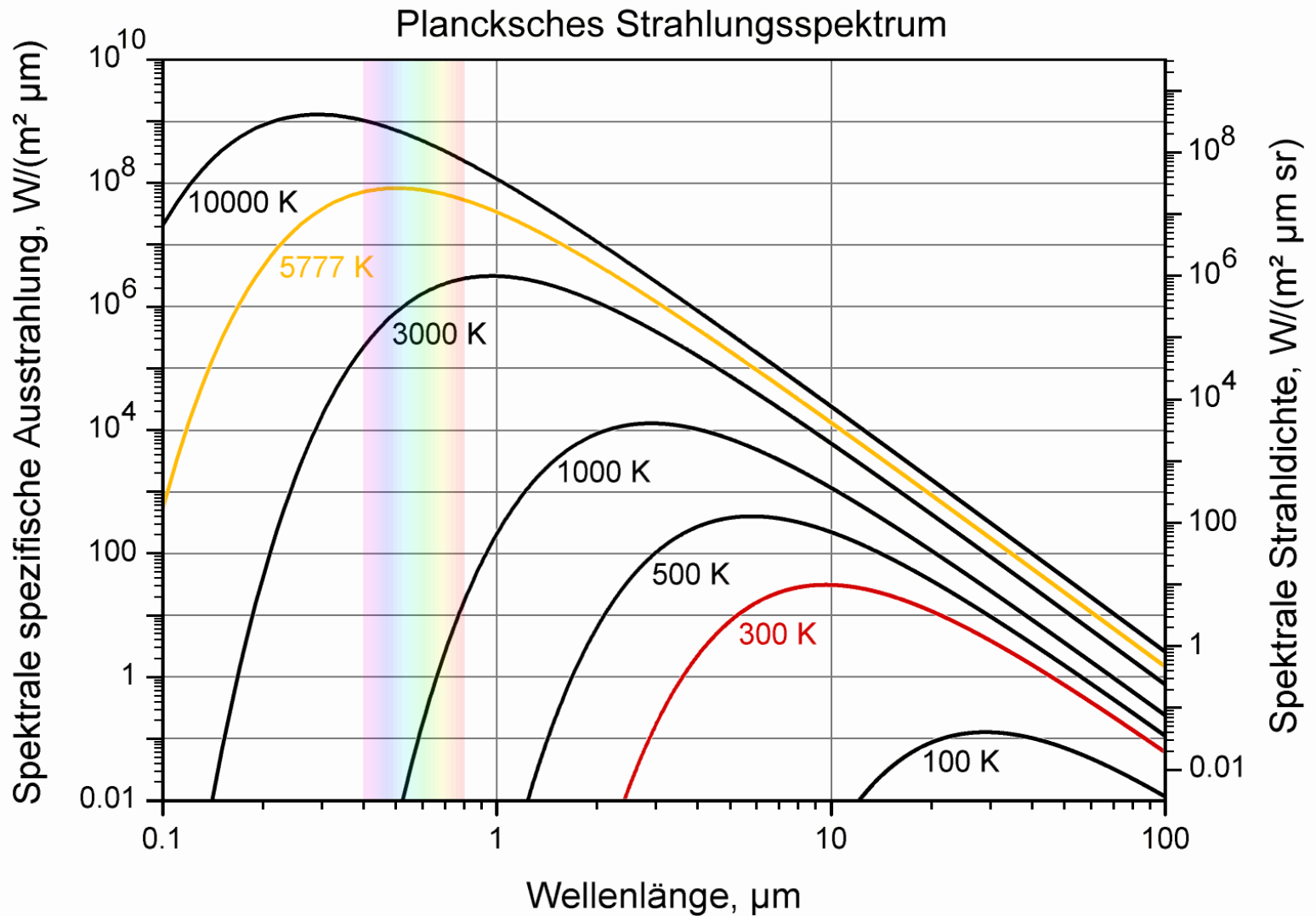
$$c = 3 \cdot 10^8 \text{ m/s}$$

$$k_B = 1.38 \cdot 10^{-23} \text{ J/K}$$

By measuring the photon energy at the maximum of the sun spectrum T_s can be obtained.

temperature at the surface of the sun:

$$T_s \approx 5800 \text{ K}$$



Power of the sun received on earth

Stefan-Boltzmann law

$$I_S = \sigma \cdot T^4$$

power of the sun

$$P_S = \sigma \cdot T^4 \cdot 4\pi \cdot R_s^2$$

power received on earth

$$P_e = P_S \cdot \frac{\pi \cdot R_e^2}{\pi \cdot (AU)^2}$$

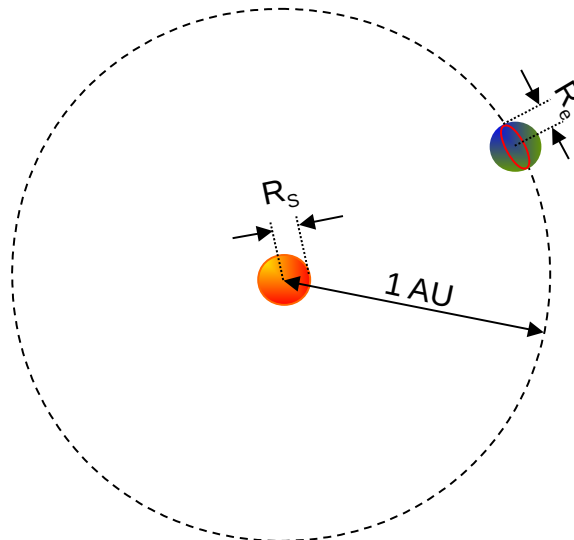
with

$$\sigma = 5.67 \cdot 10^{-8} \text{ W/(m}^2\text{K}^4)$$

$$R_s = 7 \cdot 10^5 \text{ km}$$

$$R_e = 6.4 \cdot 10^3 \text{ km}$$

$$AU = 1.5 \cdot 10^8 \text{ km}$$



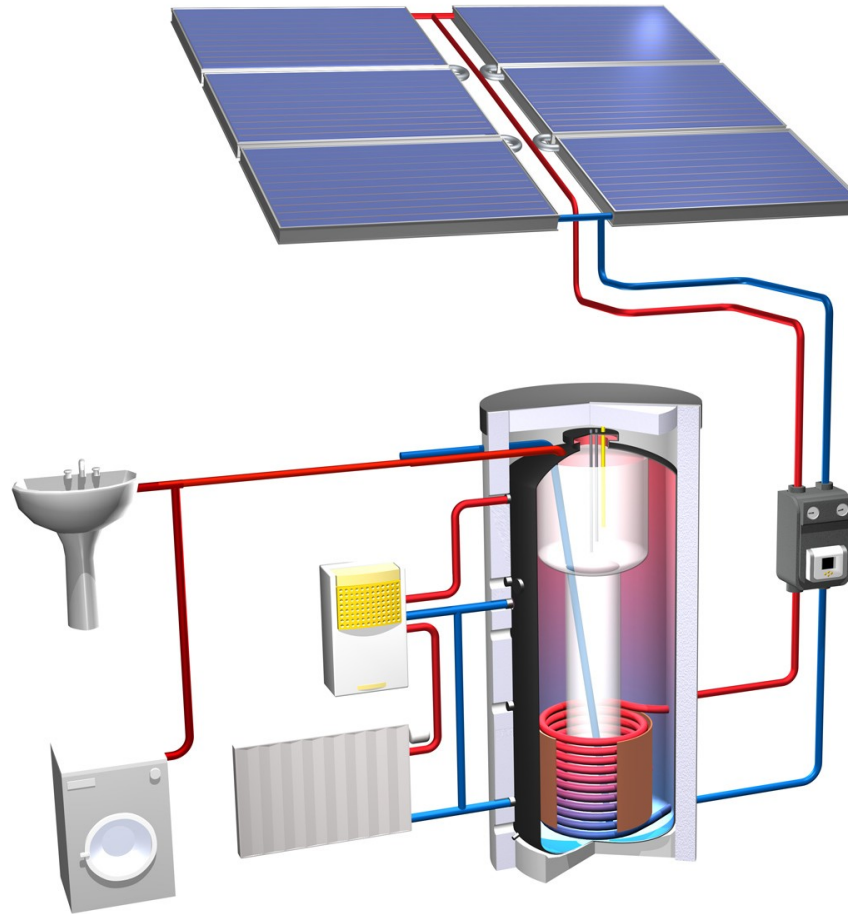
$$P_e \approx 1.5 \cdot 10^8 \text{ GW}$$

more than 1000...10000 times
the energy demand of mankind

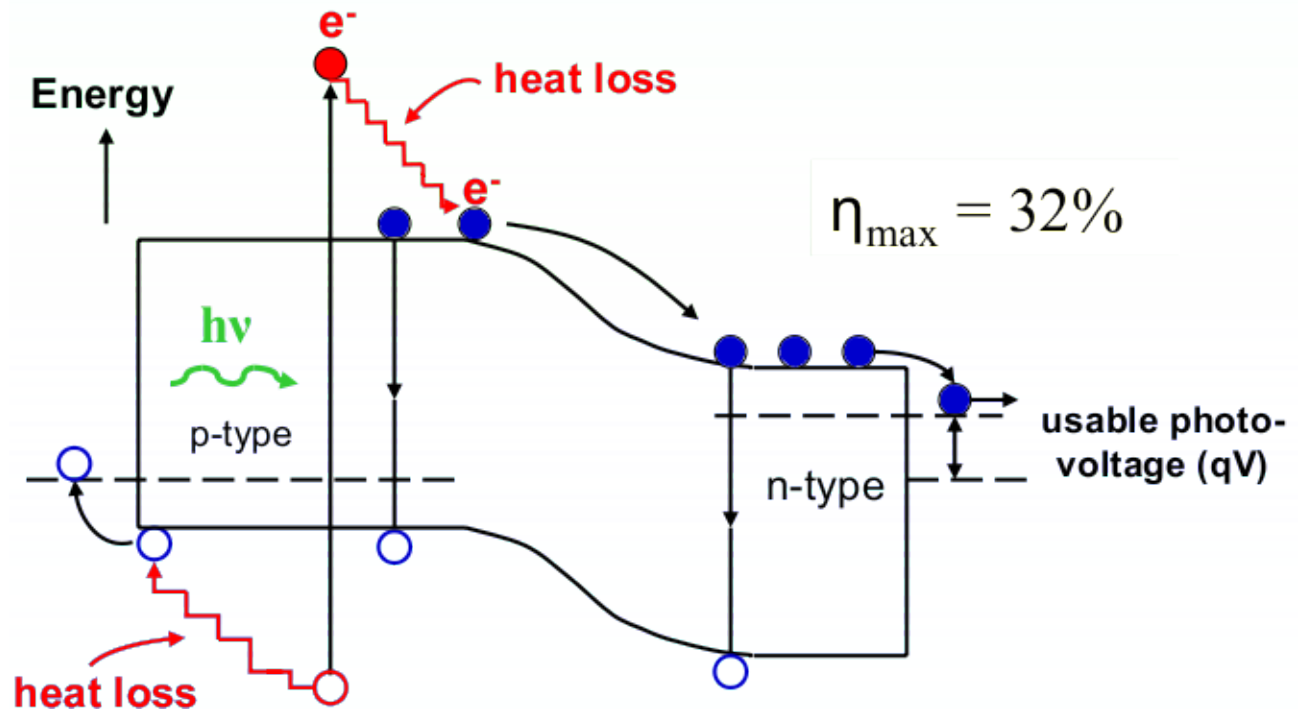
energy flux of sun light to the earth
normalized to the area of 1 m^2

$$J_s = 1.35 \text{ kW/m}^2$$

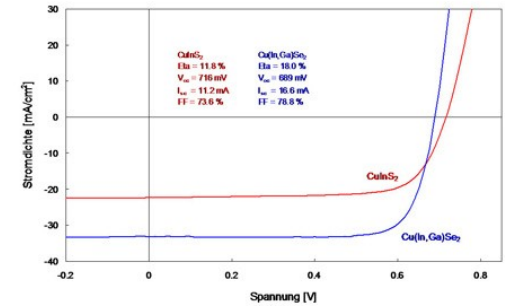
Solarthermie



Der pn-Halbleiterübergang



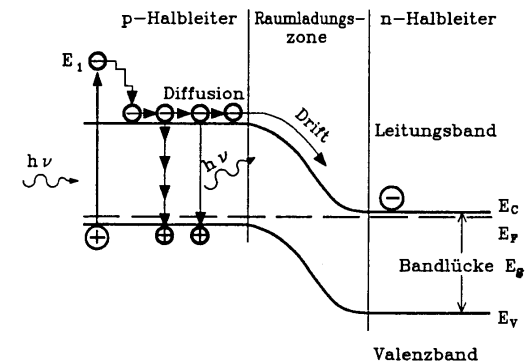
Inhalt - Einführung



- Historischer Rückblick - Photovoltaik und Halbleiter
- Grundlegende Begriffe: FF, η , I_{SC} , V_{OC}
- Strom-Spannungs-Kennlinien
- Sonnenspektrum
- Abschätzung der maximalen Effizienz
- Grundprinzipien der solaren Energiewandlung

Bücher: *The Physics of Solar Cells*, Jenny Nelson, Imperial College Press
Physik der Solarzelle, Peter Würfel, Spektrum Akademischer Verlag
Sonnenenergie: Photovoltaik, A. Götzberger, Teubner Studienbücher

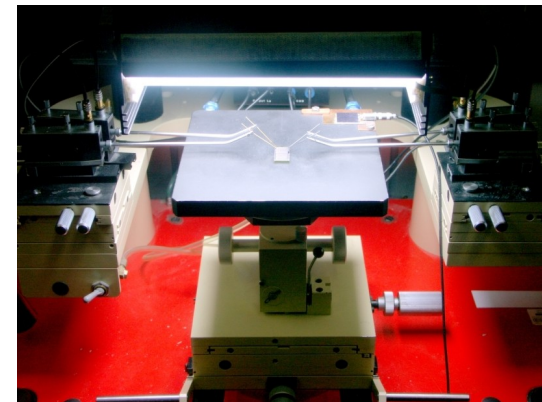
Inhalt – Physik der Solarzelle



- Elektronen und Löcher
- Lichtabsorption
- Halbleiter, Bändermodell, Energielücke, pn-Übergang
- Dunkelstrom, pn-Übergang unter Beleuchtung
- Generation und Rekombination
- Ladungsträgerbeweglichkeit, Driftgeschwindigkeit
- 1 und 2 Dioden-Modell
- Metall-Halbleiterkontakte, Heteroübergänge

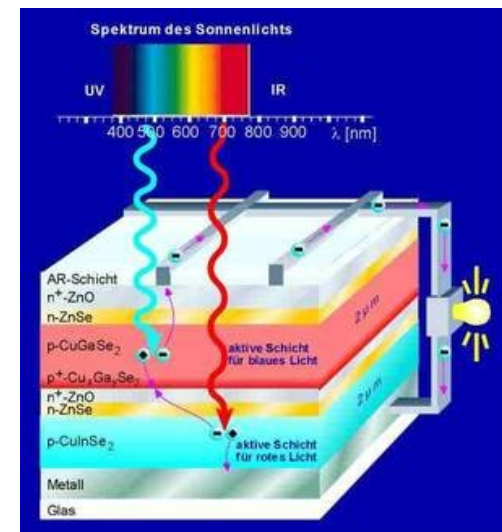
Inhalt – Experimentelle Methoden

- Sonnensimulator, IV(T)-Kennlinien
- Messung der Quantenausbeute (interne und externe)
- Solarzellenherstellung (CVD, PVD, OVPD, Silizium)
- Charakterisierung SPV, PES, Photolumineszenz



Inhalt - Solarzellenkonzepte

- Mono- und Polykristalline Silizium-Solarzellen
- Dünnschichtsolarzellen (amorphes Silizium, Chalkopyrite)
- Konzentratorsolarzellen, flexible Solarzellen
- III-V Halbleiter, Tandemsolarzellen
- Quantumwellsolarzellen
- organische Solarzellen
- Perovskitsolarzellen



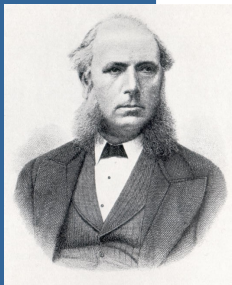
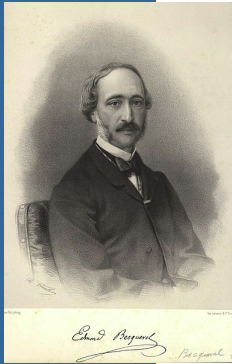
Historische Übersicht

1839: konstruiert der französische Physiker *Alexandre-Edmond Becquerel* das erste photoelektrische Element.

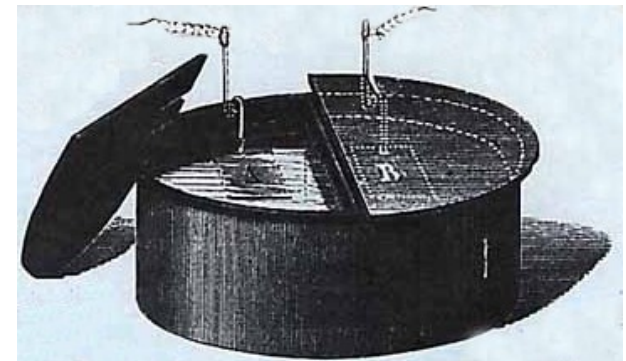
1873: Entdeckt Willoughby Smith eine Änderung der Leitfähigkeit von Selen unter Beleuchtung.

1907: Theoretische Erklärung des licht-elektrischen Effekts durch Albert Einstein.

1954: Calvin Fuller, Gerald Pearson, und Daryl Chapin präsentieren die ersten Siliziumzellen mit einem Wirkungsgrad von 4 - 6 % in den amerikanischen Bell Laboratories.



Bell Solarzellen



Becquerel Experiment

"Effect of Light on Selenium During the Passage of an Electric Current"

Feb. 20, 1873]

NATURE

303

system the opposed propositions, which do show their subject to be unreasonable, are intended to do duty as contradictories. But in Kant's system the opposed propositions in an antinomy are only seeming contradictories, are virtually contraries, and their common subject remains the subject of an intelligible proposition, and one that Kant believes himself to have substantiated, after the contraries are invalidated: so that the subject is after all amenable to the processes of human thought, though not representing an object of experience. I dare not further trespass on the columns of NATURE to comment upon Prof. Clifford's views of the two legs of Kant's philosophy! Certainly the one leg is wholly due to my opponent's "exuberant imagination:" it is Hamilton's leg, not Kant's.

Athenæum Club, Feb. 17

C. M. INGLEBY

Inherited Feeling

THE remarkable case of an inherited feeling of dislike for a special class of persons, communicated by Mr. Darwin, appears to me to support a view I have long held (but not yet published) as to the explanation of another class of so-called instincts. The three separate instances given in which the dogs showed a violent antipathy to butchers, either without seeing them or when they were dressed as gentlemen, clearly indicates that it was through the sense of smell that the painful sensation was experienced; and this is quite in accordance with the wonderful delicacy and importance of this sense in most animals, and especially in dogs. It is natural to suppose that some ancestor of these dogs was systematically and cruelly ill-treated by several butchers, perhaps from some thievish propensity or other bad habit which required frequent punishment, so that the smell of a butcher came to be invariably associated with pain and a desire for revenge. But the most important fact to observe is, that there must be some peculiar odour developed in human beings by constant contact with flesh, which a dog can recognise apart from individual peculiarities and in spite of perfect disguise. Now the power

children (who always find the attraction of a fine dog irresistible) made me stop to admire a tall and remarkably handsome mastiff, apparently the property of a man who stood by with a hand-barrow. He was speaking to two other men of this dog, and of another of the same kind which he had at home, and telling them that they were quiet and amiable to all men but butchers, and that it was not safe for a butcher to come near either of them. One of the men said that he believed all dogs of that breed showed the same antipathy; and added that when they were left loose at night to guard premises, they would always allow a policeman to enter.

This chance conversation is perhaps hardly worth troubling you with, as I have no means of ascertaining whether these dogs claimed kindred with Turk, but I send it to you, nevertheless.

M.

Kensington Square, Feb. 17

EFFECT OF LIGHT ON SELENIUM DURING THE PASSAGE OF AN ELECTRIC CURRENT.*

BEING desirous of obtaining a more suitable high resistance for use at the Shore Station in connection with my system of testing and signalling during the submersion of long submarine cables, I was induced to experiment with bars of selenium, a known metal of very high resistance. I obtained several bars varying in length from 5 to 10 centimetres, and of a diameter from 1 to 1½ millimetres. Each bar was hermetically sealed in a glass tube, and a platinum wire projected from each end for the purpose of connection.

The early experiments did not place the selenium in a very favourable light for the purpose required, for although the resistance was all that could be desired—some of the bars giving 1,400 megohms absolute—but there was a great

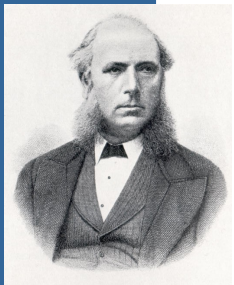
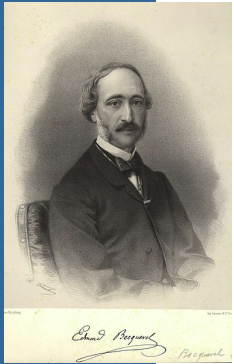
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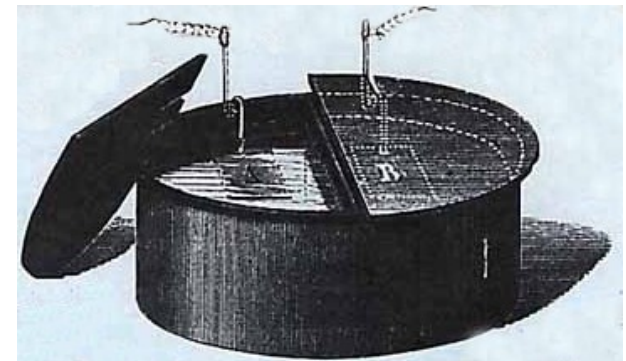
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1954: Calvin Fuller, Gerald Pearson, und Daryl Chapin präsentieren die ersten Siliziumzellen mit einem Wirkungsgrad von 4 - 6 % in den amerikanischen Bell Laboratories.



Bell Solarzellen



Becquerel Experiment

Patent: Light Sensitive Electric Device

Patented June 25, 1946

2,402,662

UNITED STATES PATENT OFFICE

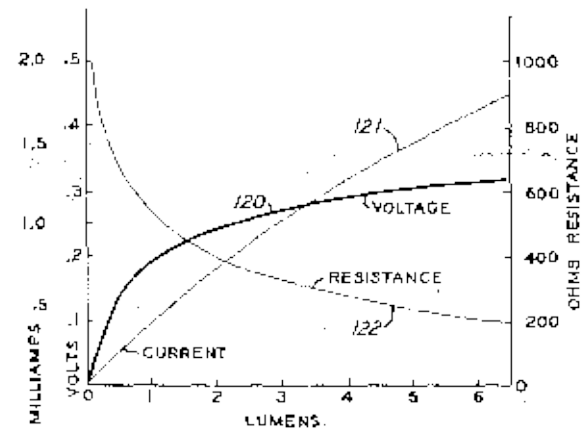
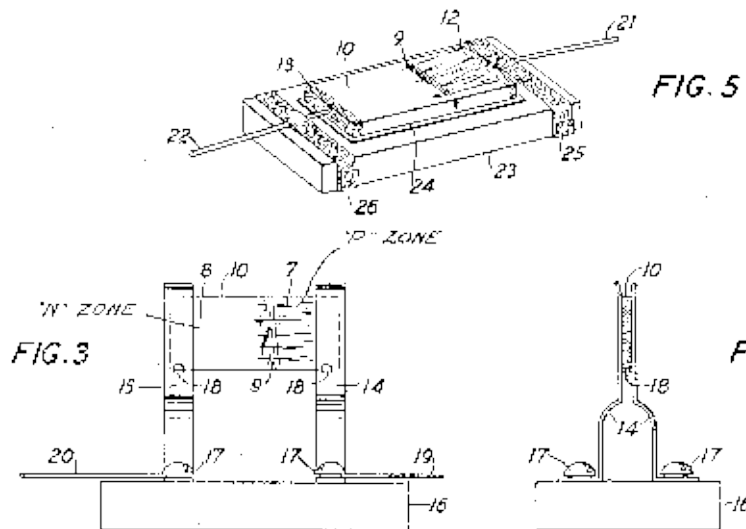
2,402,662

LIGHT-SENSITIVE ELECTRIC DEVICE

Russell S. Ohl, Little Silver, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application May 27, 1941, Serial No. 395,410

24 Claims. (Cl. 136-89)



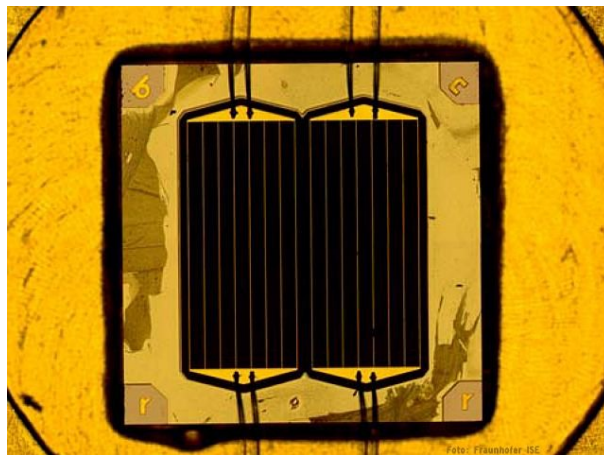
Historische Übersicht

1958 Vanguard I, der zweite Satellit der USA, flog mit einer Photovoltaikanlage ins All.

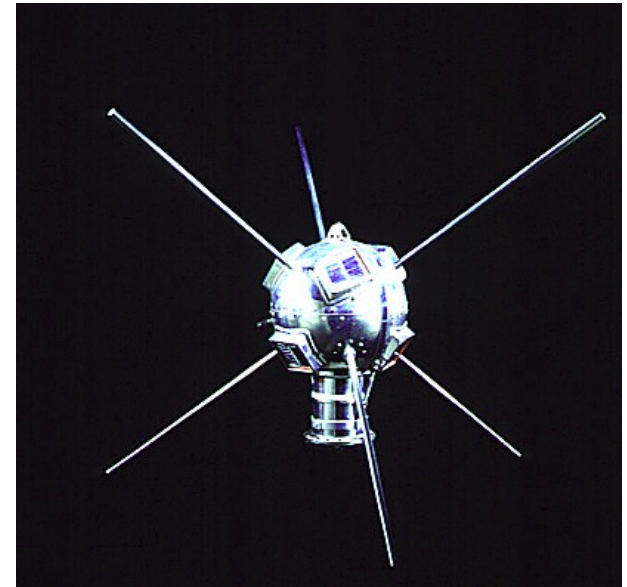
1970's: Die Ölkrise steigert sehr stark das Interesse an der Solarenergie!

1983: 50.000.000 Taschenrechner verwenden amorphe Silizium Solarzellen

2000: Kleine Solarzellen erreichen 30% Wirkungsgrad



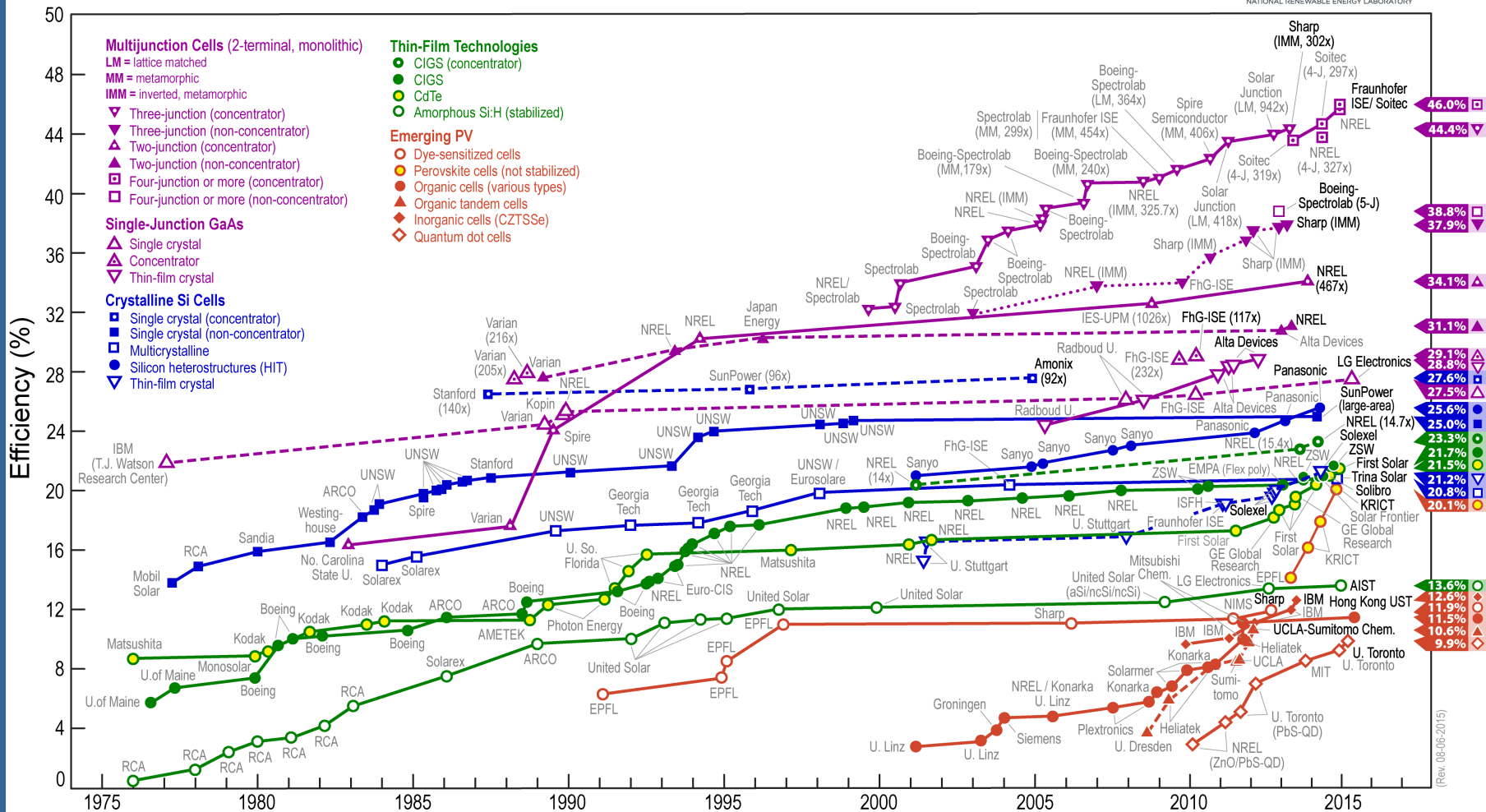
Fraunhofer-ISE: Wirkungsgrad von 41,1% bei 454-fachen Konzentrierung auf eine 5mm² große III-V-Halbleitern GaInP/GaInAs/Ge Mehrfachsolarzelle.



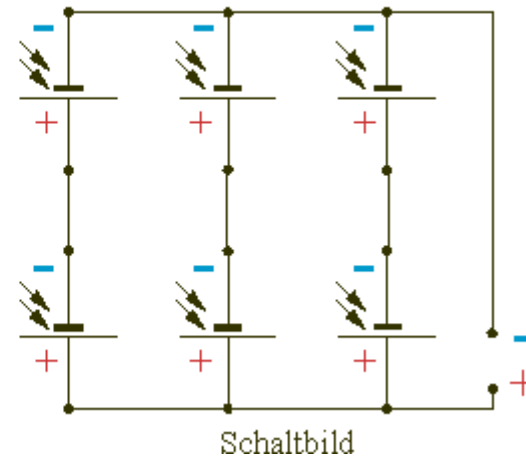
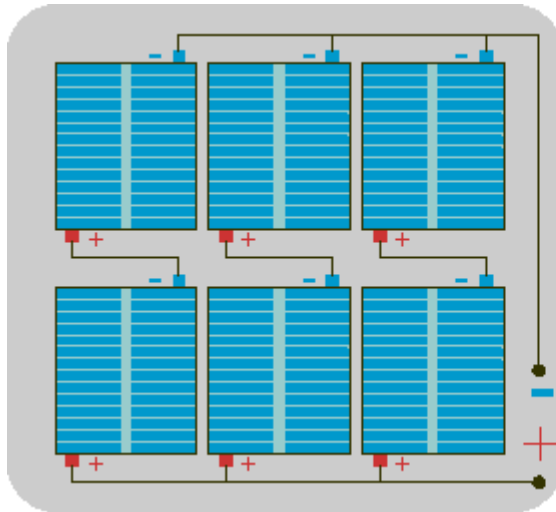
Wirkungsgrad Rekorde



Best Research-Cell Efficiencies



Solarmodule



- Eine einzelne Solarzelle liefert je nach Fläche mehrere 100 mA Strom bei einer Spannung von 0.5-0.6V.
- In einem Modul sind 28-36 Solarzellen in Serie geschaltet um geeignete Spannungen (typisch 12V) zu erhalten.
- Durch die Parallelschaltung sogenannter Schutzdioden können defekte Dioden im Schadensfall "überbrückt" werden.

Grundlegende Definitionen

Offene Klemmspannung V_{oc}

Kurzschlussstrom I_{sc}

Elektrische Last R_L

$I(V)$ durch Strom-Spannungs-Kennlinie

Kurzschlussstromdichte J_{sc}

$$V = IR_L$$

$$I \propto A$$

Vergleich: Solarzelle – Batterie

- Batterie ist Spannungsquelle
- Solarzelle ist Stromquelle

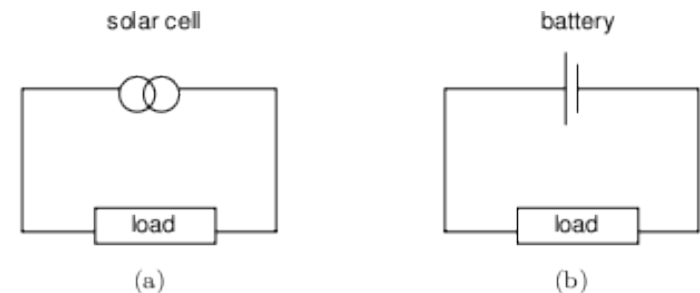
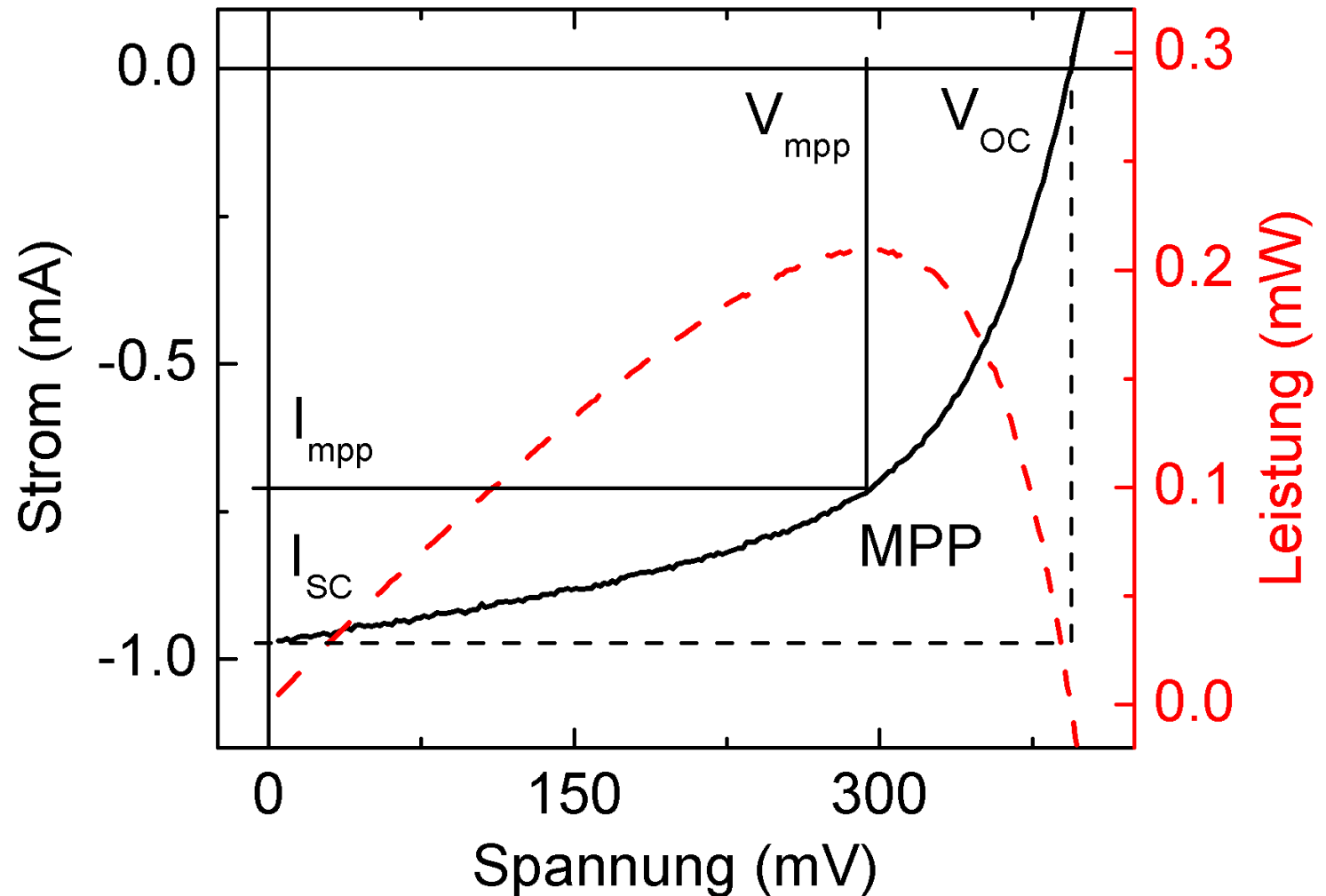


Fig. 1.3. The solar cell may replace a battery in a simple circuit.

Strom-Spannungs-Kennlinie

Strom-Spannungs-Kennlinie einer Farbstoffsolarzelle



Füllfaktor

Offene Klemmspannung V_{oc} bei $I=0$

Kurzschlussstrom I_{sc} bei $V=0$

Der Füllfaktor ist definiert als Quotient aus:

$$FF = \frac{J_{mpp} V_{mpp}}{J_{SC} V_{OC}}$$

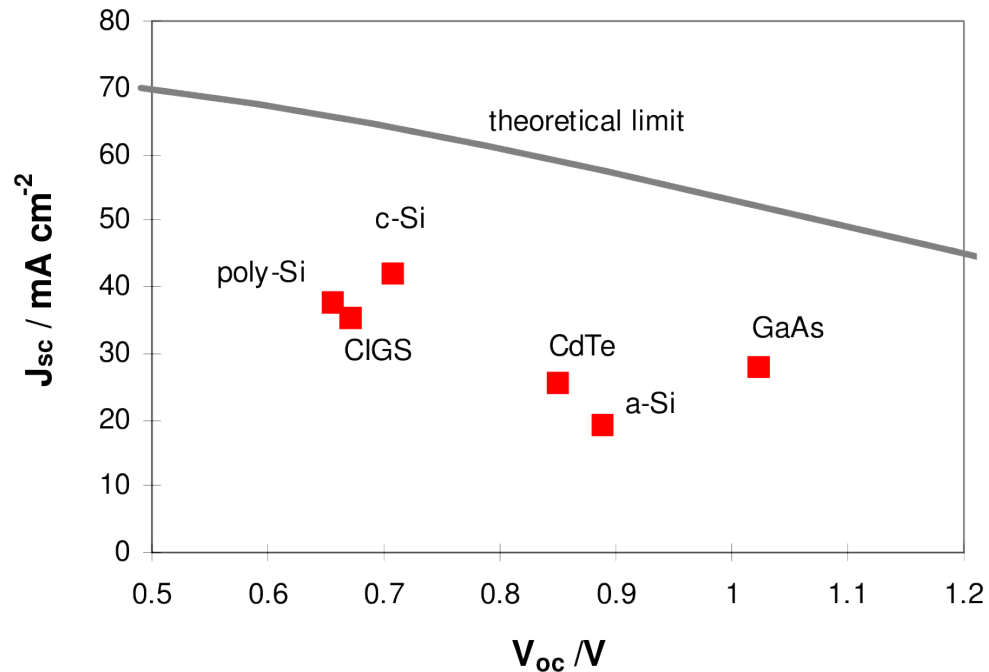
Er gibt die Rechteckigkeit der IV-Kennlinie an, und ist daher ein Mass für die Qualität der Solarzelle.

Typische Werte liegen im Bereich von 50-80%

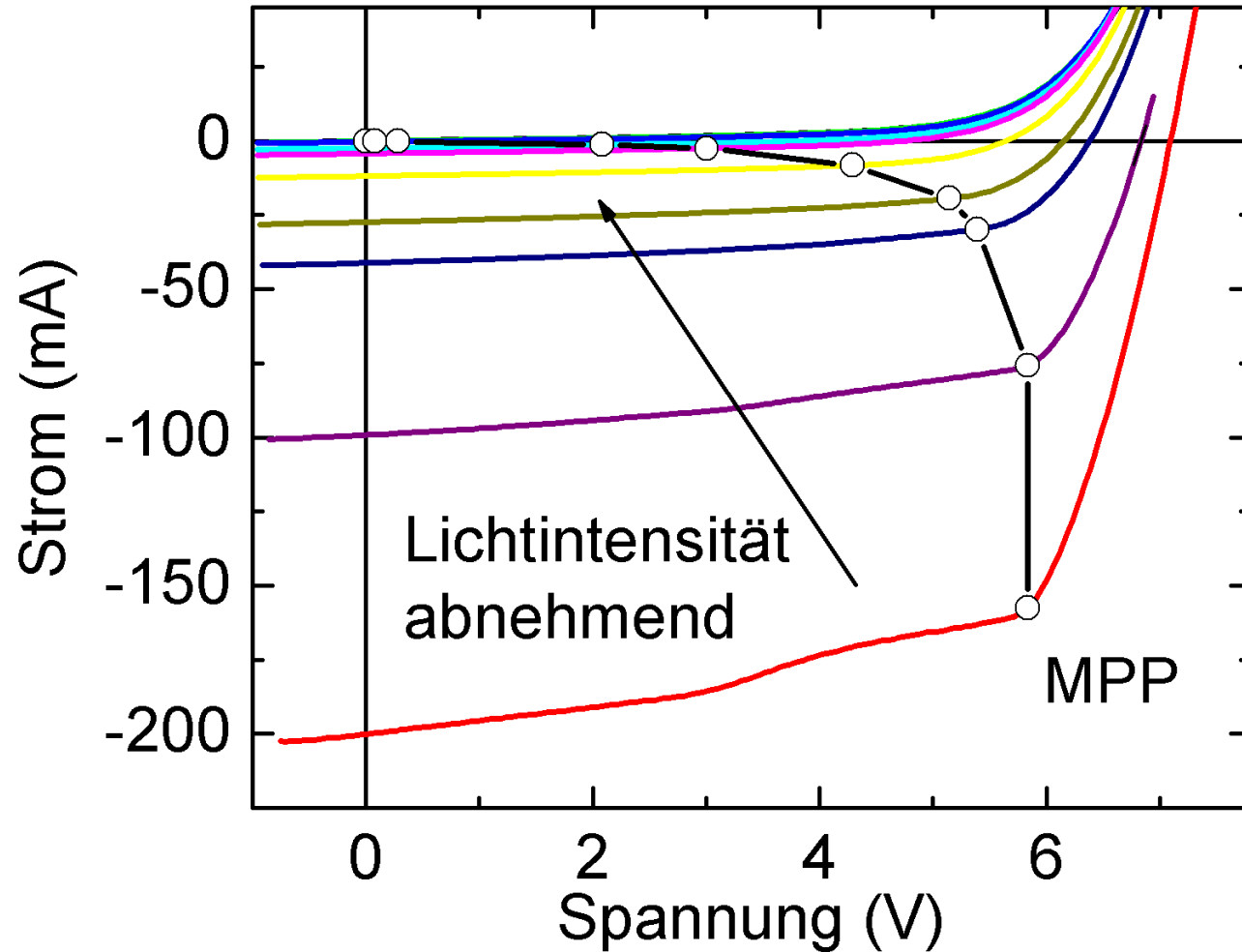
Typische Werte für Solarzellen

Table 1.1. Performance of some types of PV cell [Green *et al.*, 2001].

| Cell Type | Area (cm ²) | V _{oc} (V) | J _{sc} (mA/cm ²) | FF | Efficiency (%) |
|-----------------------|-------------------------|---------------------|---------------------------------------|------|----------------|
| crystalline Si | 4.0 | 0.706 | 42.2 | 82.8 | 24.7 |
| crystalline GaAs | 3.9 | 1.022 | 28.2 | 87.1 | 25.1 |
| poly-Si | 1.1 | 0.654 | 38.1 | 79.5 | 19.8 |
| a-Si | 1.0 | 0.887 | 19.4 | 74.1 | 12.7 |
| CuInGaSe ₂ | 1.0 | 0.669 | 35.7 | 77.0 | 18.4 |
| CdTe | 1.1 | 0.848 | 25.9 | 74.5 | 16.4 |



Einfluss der Lichtintensität



Photostrom und Quanteneffizienz

Um die Stromdichte J_{SC} mit dem einfallenden Lichtspektrum in Zusammenhang zu bringen benötigt man die Quanteneffizienz $QE(E)$ der Solarzelle.

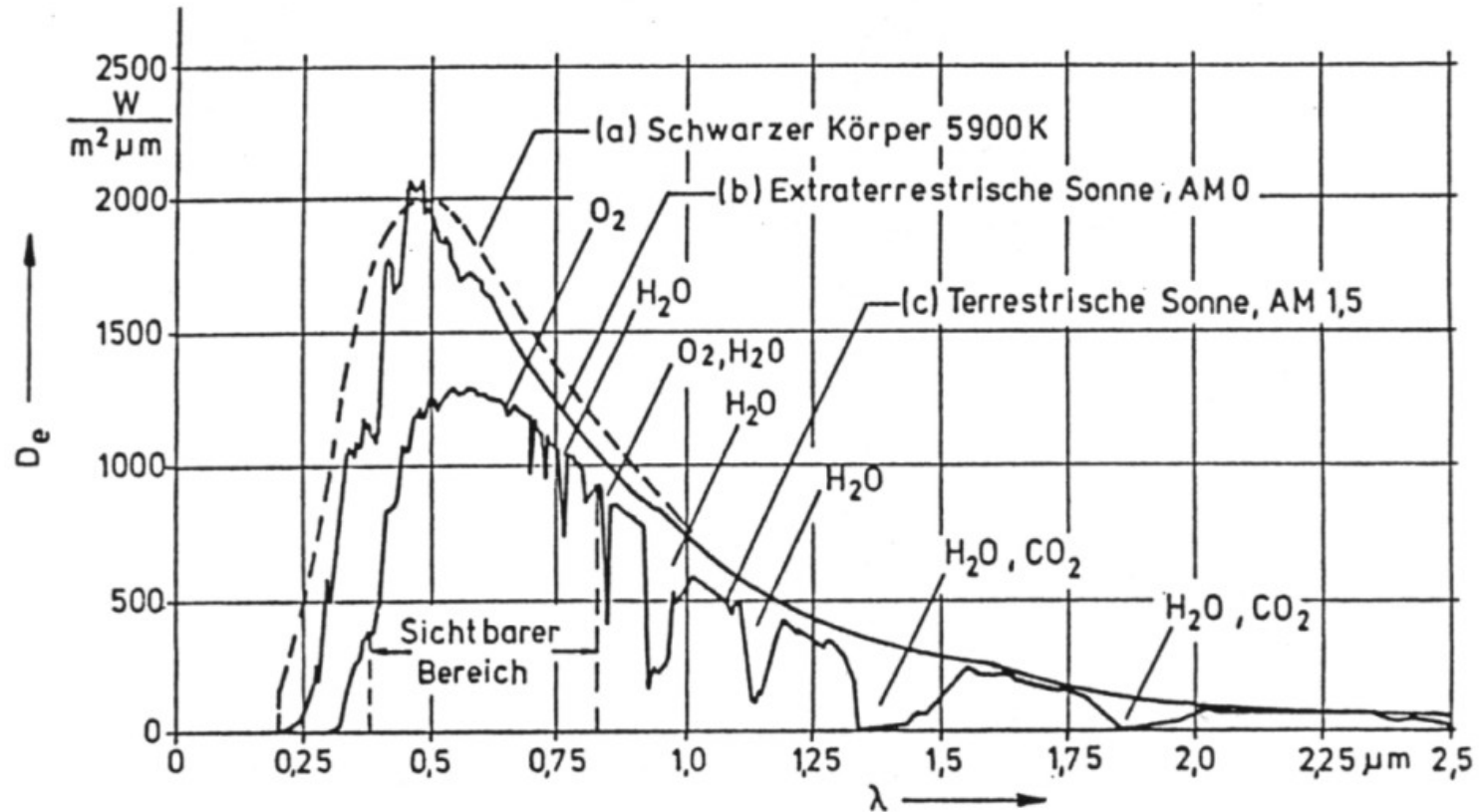
$QE(E)$ ist die Wahrscheinlichkeit, dass ein eintreffendes Photon mit der Energie $E=hc/\lambda$ ein Elektron zum externen Kreislauf beiträgt.

$$J_{SC} = q \int b_S(E) QE(E) dE$$

b_S : einfallende spektrale Photonendichte. QE ist abhängig von:

- Absorptionskoeffizient vom Solarzellenmaterial
- Effektivität der Ladungstrennung
- Leitungsverluste der Solarzelle

Sonnenspektrum



AM0: Spektrale Energiedichte ausserhalb der Atmosphäre senkrecht zur Sonne, 1367 W/m^2 (Solarkonstante)

AM1.5: Spektrale Energiedichte auf der Erde mit einem Winkel von 48° zur Sonne, ohne Wolken! ($\sim 100 \text{ mW/cm}^2$, bei 25°C)

Sonneneinstrahlung

Das *AM* (Air Mass) Spektrum ist definiert als die Luftschicht die das Licht durchdringen muss. In erster Näherung kann man schreiben:

$$AM = \frac{1}{\cos \theta_z}$$

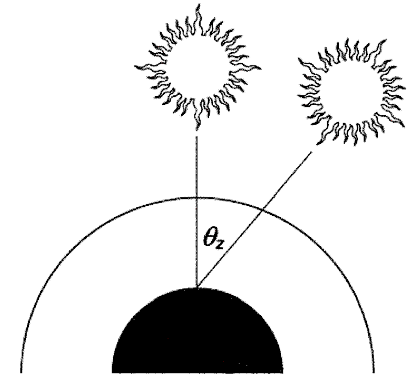


Figure 1.4. The amount of atmosphere (air mass) through which radiation from the sun must pass to reach the earth's surface depends on the sun's position.

Der *AM*-Wert kann durch eine einfache experimentelle Abschätzung bestimmt werden:

$$AM = \sqrt{1 + (s/h)^2}$$

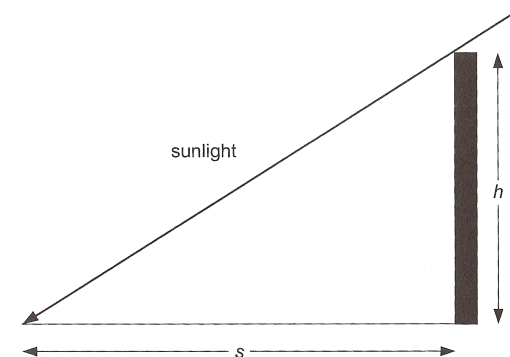
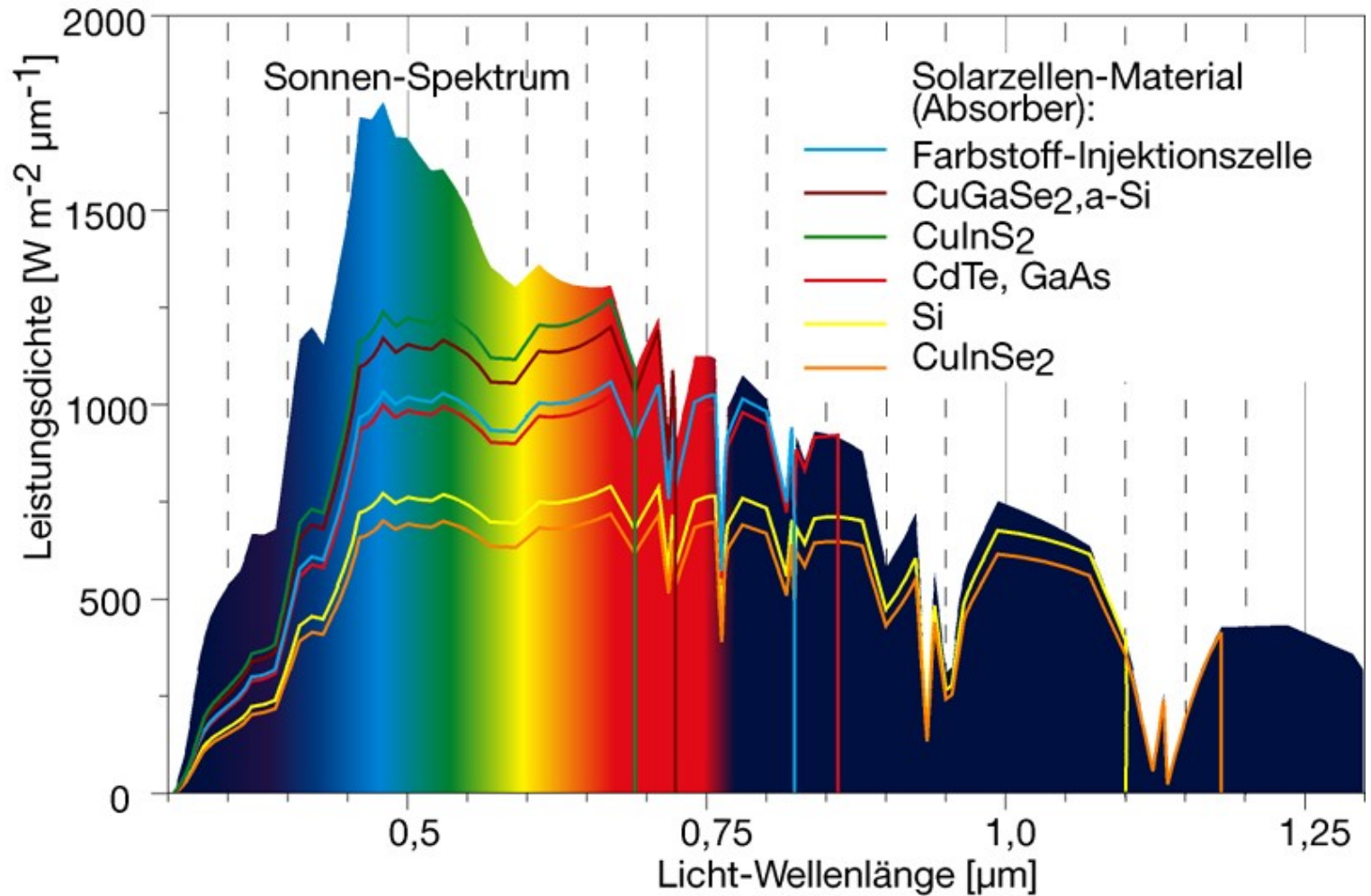


Figure 1.5. Calculation of Air Mass using the shadow of an object of known height.

Quanteneffizienz



Charakterisierung einer Solarzelle

Messung einer IV-Kennlinie im Sonnensimulator:

Ideale Diodengleichung:

$$J_{dark}(V) = J_0(e^{qV/k_B T} - 1)$$

Daraus ergibt sich die Strom-Spannungs-Charakteristik einer beleuchteten Solarzelle zu:

$$J(V) = J_0(e^{qV/k_B T} - 1) - J_{Ph}$$

$$\Rightarrow V_{OC} = \frac{k_B T}{q} \ln\left(\frac{J_{Ph}}{J_0} + 1\right)$$

k_B : Boltzmannkonstante, T : Temperatur, J_{Ph} : Photostrom, J_0 : Sättigungsstrom

1-Diodenmodell

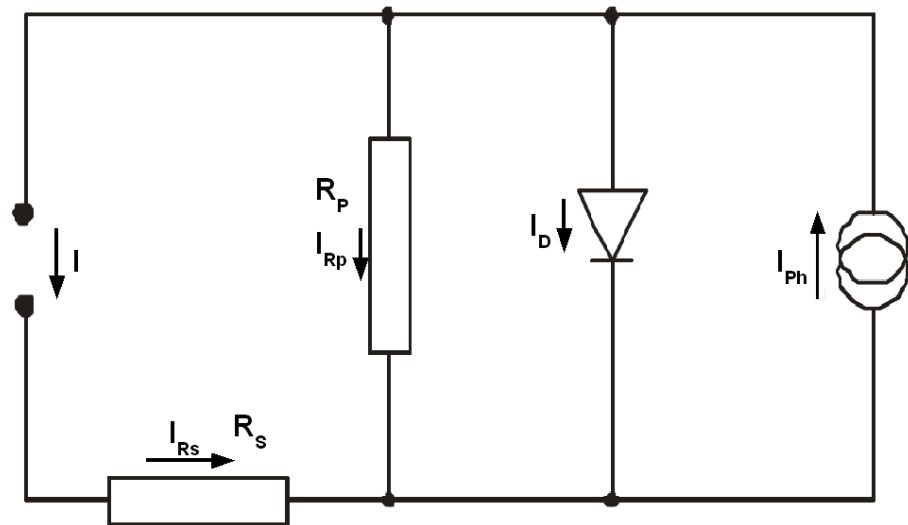
Reale Solarzellen haben elektrische Verluste die mit Hilfe von Serien- und Parallel-Widerständen modelliert werden können:

$$J(V) = J_0 \left(e^{q \frac{V - R_S J}{A k_B T}} - 1 \right) + \frac{V - R_S J}{R_P} - J_{Ph}$$

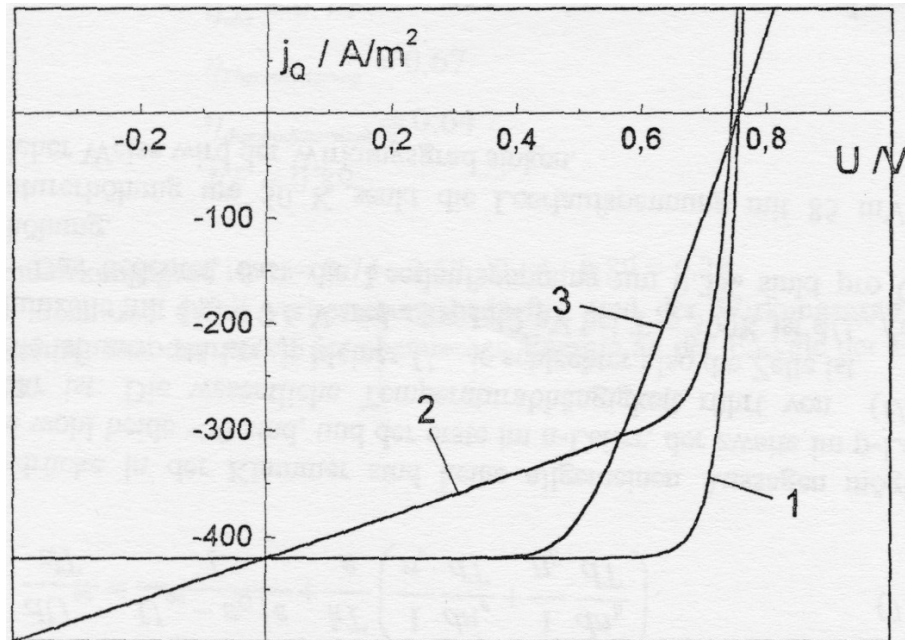
R_S : Serienwiderstand

R_P : Parallelwiderstand

A : Diodenqualitätsfaktor



Einfluss der Verlustströme



1: $R_S = 0 \Omega$, $R_P = 50 \Omega$

2: $R_S = 5 \Omega$, $R_P = \infty$

3: $R_S = 0 \Omega$, $R_P = \infty$

Nicht ideale Werte verringern den Füllfaktor und damit die Effizienz

Wirkungsgrad

Der Wirkungsgrad η einer Solarzelle gibt das Verhältnis von eingestrahelter und maximal möglich umgesetzter Energie an.

$$\eta = \frac{J_{mpp} V_{mpp}}{P_{Ph}} = \frac{J_{SC} V_{OC} FF}{P_{Ph}}$$

P_{Ph} ist die eingestrahelte Leistungsdichte des Lichtes.

Übersicht der Vorlesung

| | |
|-------------------|---|
| 15.09.2015 | allg. Einführung in die Solarenergie |
| 22.09.2015 | Basic Principles of Photovoltaics |
| 29.09.2015 | Electrons and Holes in Semiconductors |
| 6.10.2015 | Absorption, Recombination, and Generation |
| 13.10.2015 | The ideal semi-infinite pn-junction |
| 20.10.2015 | Illuminated pn-junction |
| 27.10.2015 | c-Si solar cells |
| 3.11.2015 | Basics of thin film solar cells |
| 10.11.2015 | Thin film solar cells |
| 17.11.2015 | Concepts of nanostructured solar cells |
| 24.11.2015 | Dye Sensitized Solar Cells |
| 1.12.2015 | Exkursion? |
| 8.12.2015 | |
| 15.12.2015 | Prüfung |

Übungsaufgaben

- es wird 10 Übungsblätter geben (jeweils 10 Punkte)
- davon müssen mindestens 50% (total) erreicht werden
- Assistent **Res Jöhr (Raum 3.04)**
- Abgabe jeweils am
- Übungen am ...
- schriftliche Prüfung am 15.12.
- Experimente nach Absprache (fakultativ)

- Folien und Übungsblätter sind auf ADAM (E. Meyer public)