Welcome,
Basics of Photovoltaic Solar Energy Generation

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Fraunhofer Institute for
Solar Energy Systems ISE

European Summer Campus 2013,
Energy on All Scales,
University of Strasbourg /
Fraunhofer ISE
Freiburg, 02.09.2013

Fraunhofer
ISE

Program

09:00-10:00	G. Willeke, Welcome, Basics of photovoltaic solar energy conversion
10:00-11:00	S. Rogalla, Basics of inverter technology and grid integration
11:00-12:00	J. Mayer, Impact of PV and wind energy generation on the German electricity market
12:00-12:45	lunch break
12:45-13:00	S. Rogalla, Visit Megawatt laboratory
13:00-14:30	G. Willeke, Status of PV technology development and perspectives
14:30-16:00	A. Schaadt, Hydrogen production and storage
16:00-17:00	G. Willeke / C. Schmitz, Guided tour of Fraunhofer ISE including hydrogen fuel station

Fraunhofer Institute for Solar Energy Systems ISE

Director:
Prof. Eicke R. Weber

Staff: 1270

2012 Budget: € 77 million

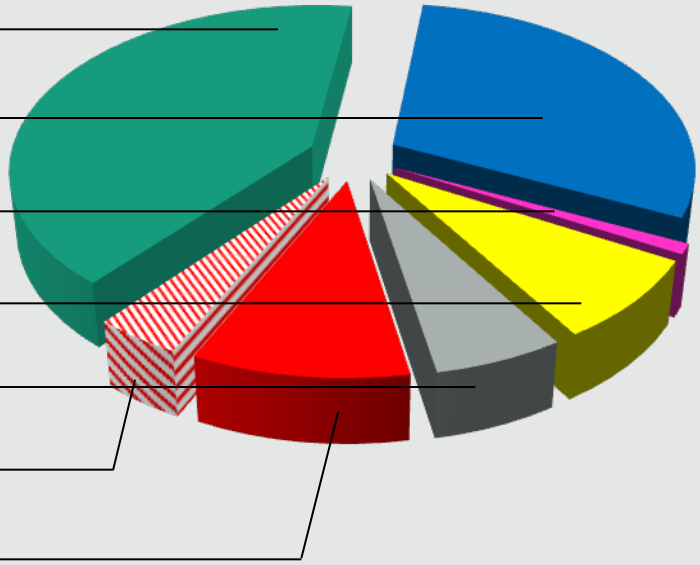
Established: 1981

Fraunhofer ISE

Revenue Structure Fraunhofer ISE, Operations 2012

Operations:	€66.8 million
Investment**:	€10.2 million
Total:	€77.0 million

Industry	41 %
Federal Gov. Projects	30 %
Regional Gov. Projects	1 %
European Union	8 %
Other	6 %
Special Programms, FhG	4 %
Basic Funding*	10 %



* of which 90% federal and 10% state funds

** without building investment and economic program

Status: March 2013

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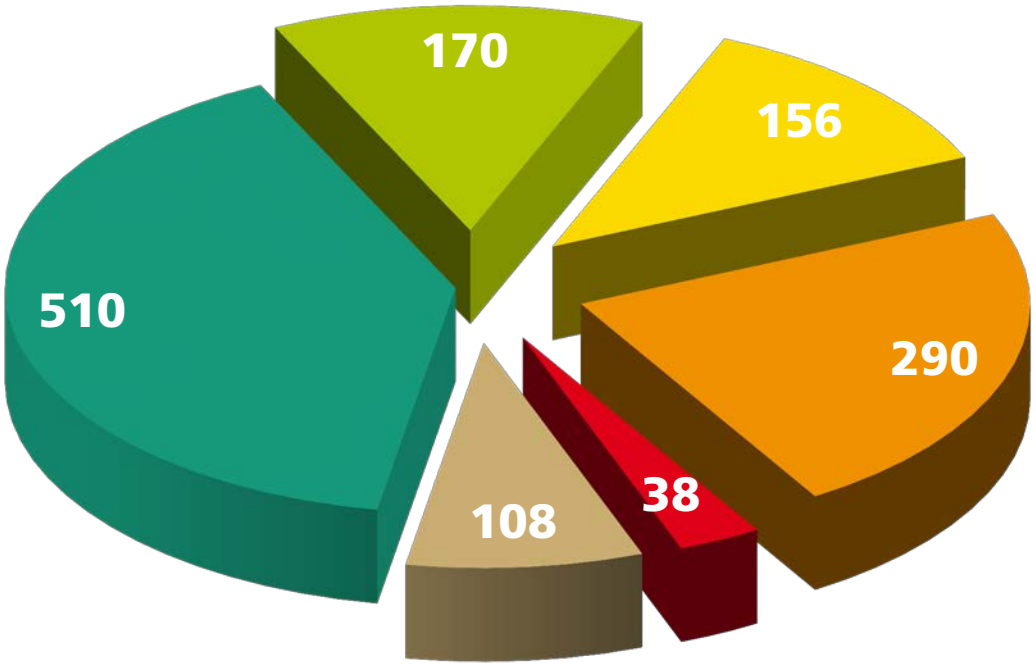
Personnel at Fraunhofer ISE

- Staff Members
- Doctoral Students
- Diploma Students
- Scientific Assistants
- Trainees
- Others



Total: 1272

Status: 31 Dec. 2012

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Areas of Business at Fraunhofer ISE

BIPV

Interference lithography nano-texturing, concentrator optics

Energy Efficient Buildings

Applied Optics and Functional Surfaces

Solar Thermal Technology ← PVT

Silicon Photovoltaics

Photovoltaic Modules and Systems

Alternative Photovoltaic Technologies

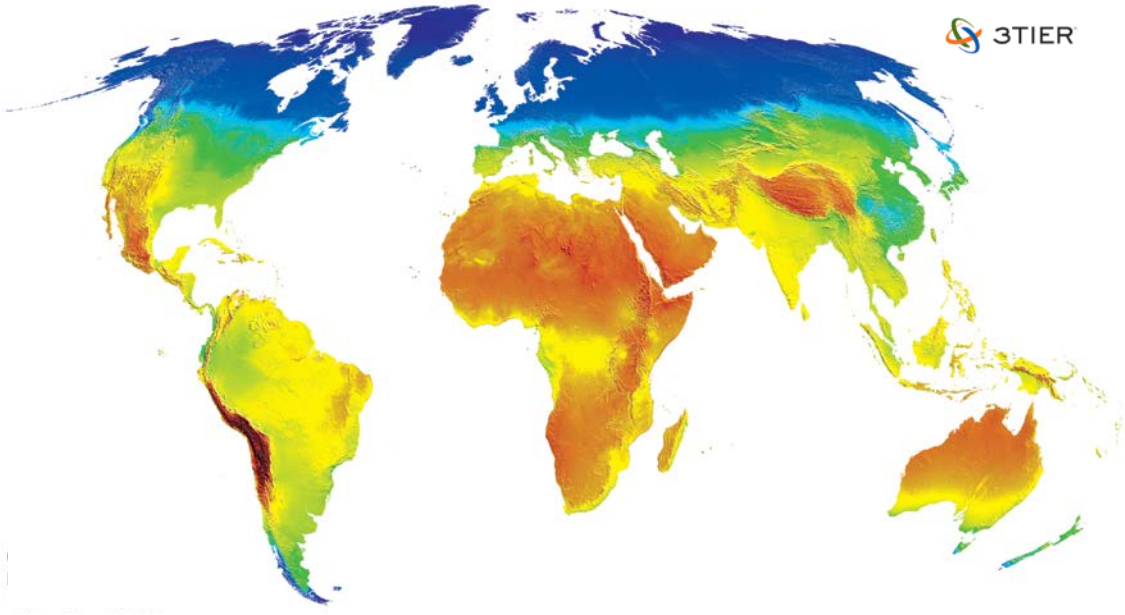
Renewable Power Supply

Hydrogen Technology

PV inverters, grid integration and batteries

PV hydrogen production and storage

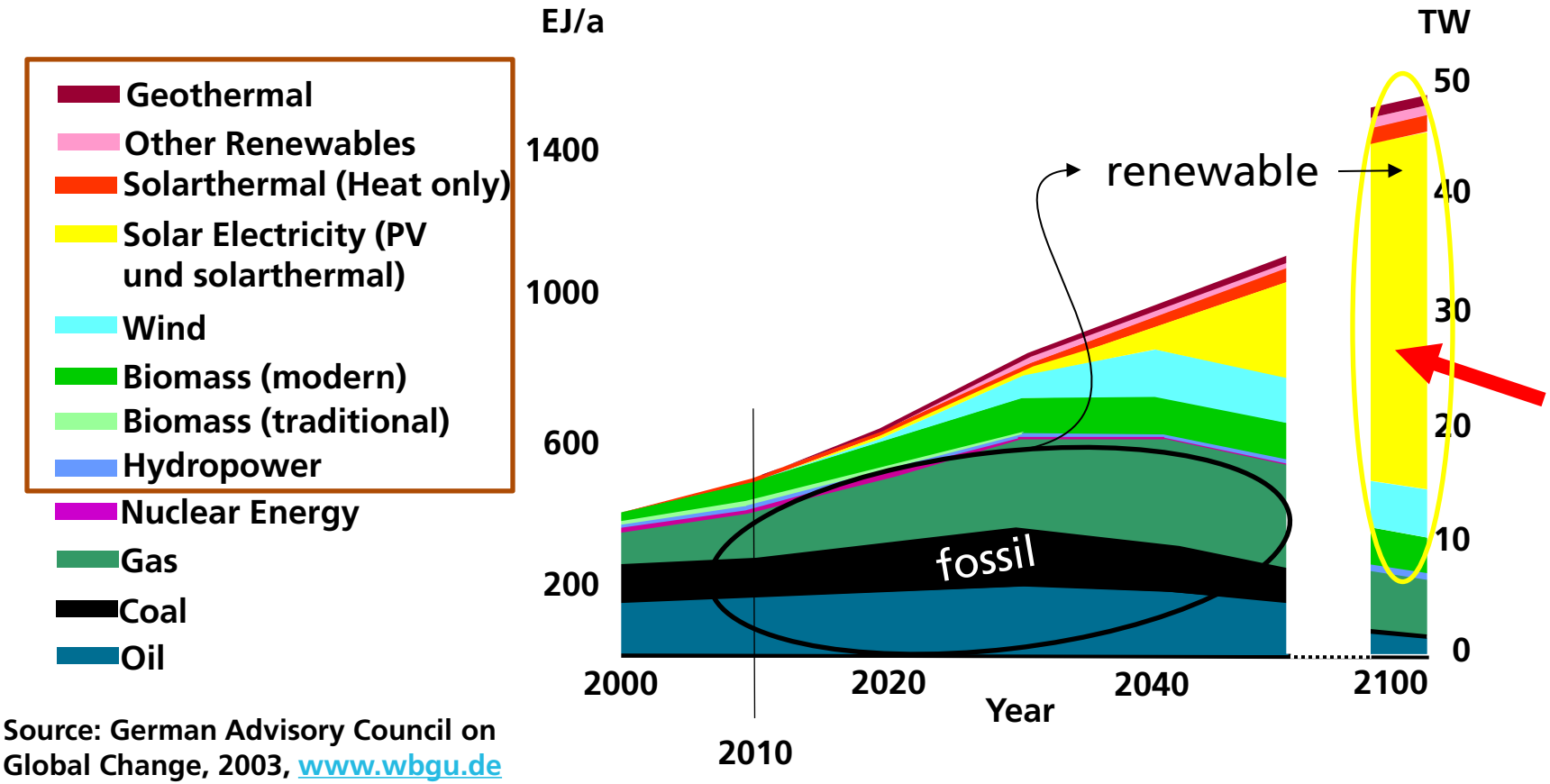
Overview



Quelle: www.3tier.com, 2011

- **21st century: a transition to renewable energies**
- **On the physics of the crystalline silicon solar cell**

Exemplary Path, Global Primary Energy Consumption



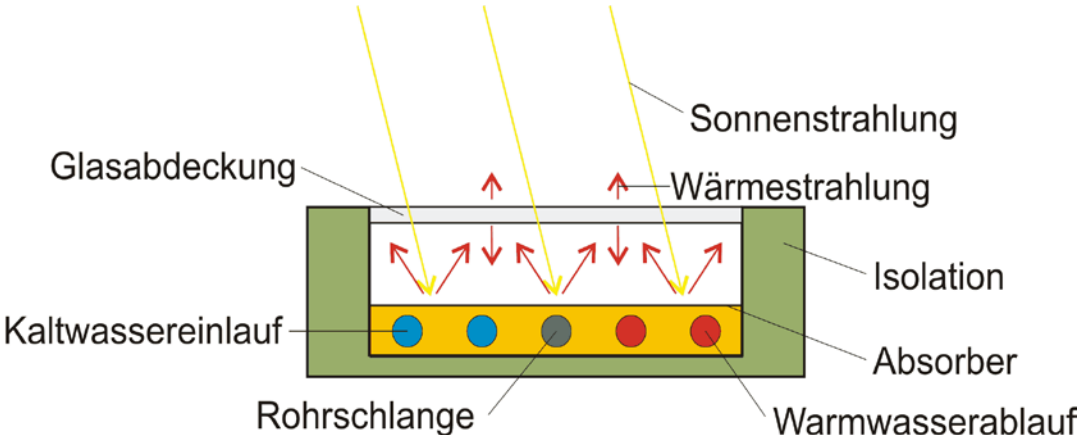
Source: German Advisory Council on Global Change, 2003, www.wbgu.de

Solar Energy Conversion

Solar thermal

Efficiency 60-75%

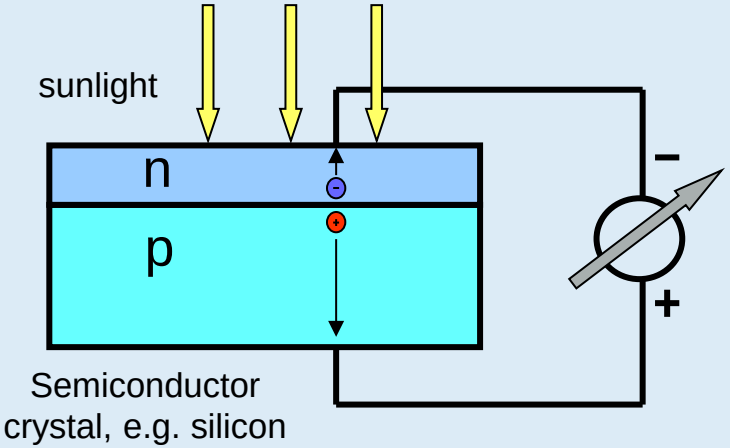
Typical Lifetime > 25 years



Photovoltaics

Efficiency 10-15% (System)

Typical Lifetime > 25 years



Solar cell

PV Relevant c-Si Physics I

Pros and cons of c-Si

Elemental semiconductor

Abundance

Environmentally benign

High purity possible

Ease of p and n doping

Stable passivating oxide

Large (defect-free) crystals

Large carrier mobilities

Large recombination lifetimes

Use in Microelectronics

Ease of up-scaling

Proven PV system reliability

I	II	III	IV	V	VI
		B	C	N	O
		Al	Si	P	S
Cu	Zn	Ga	Ge	As	Se
Ag	Cd	In	Sn	Sb	Te

Weak absorption

Brittle material

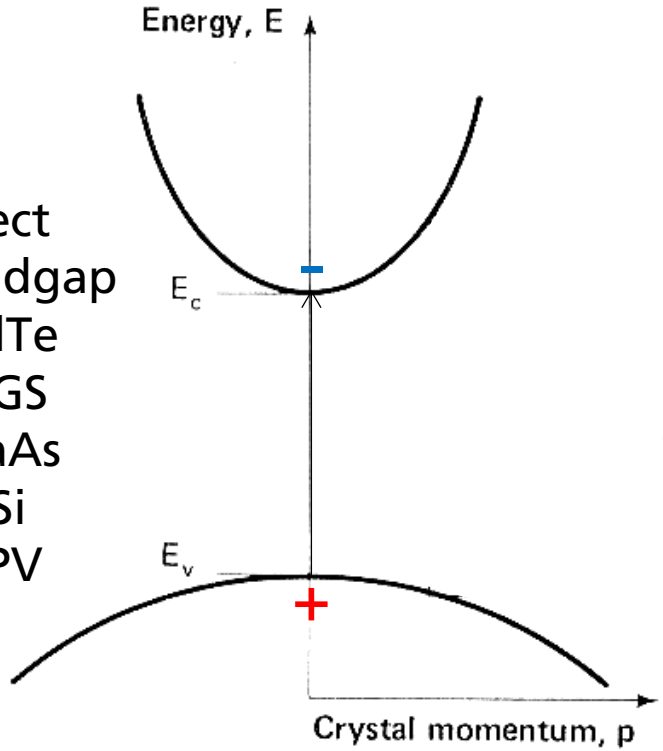
High temperature processing

B-O defect (LID)

PV Relevant c-Si physics II

Charge carrier generation

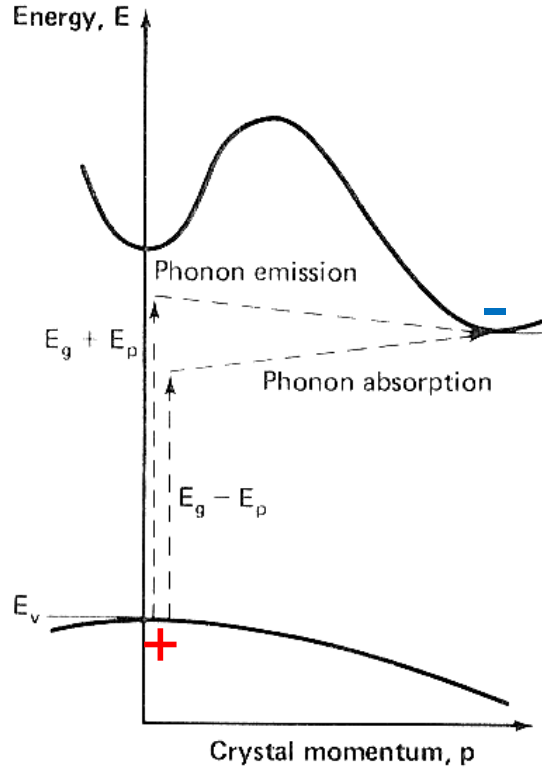
Direct bandgap
- CdTe
- CIGS
- GaAs
- a-Si
- OPV



Strong absorption

Strong recombination

Excitons possible!



Indirect bandgap
- c-Si
- Ge
- InP

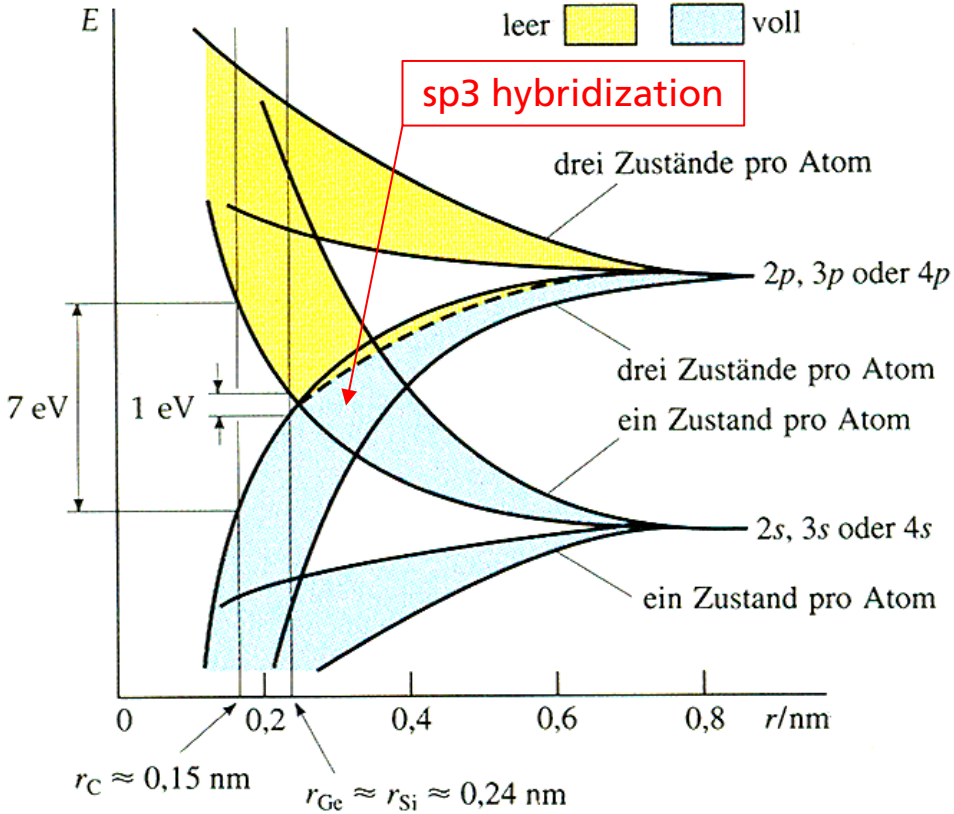
Weak absorption

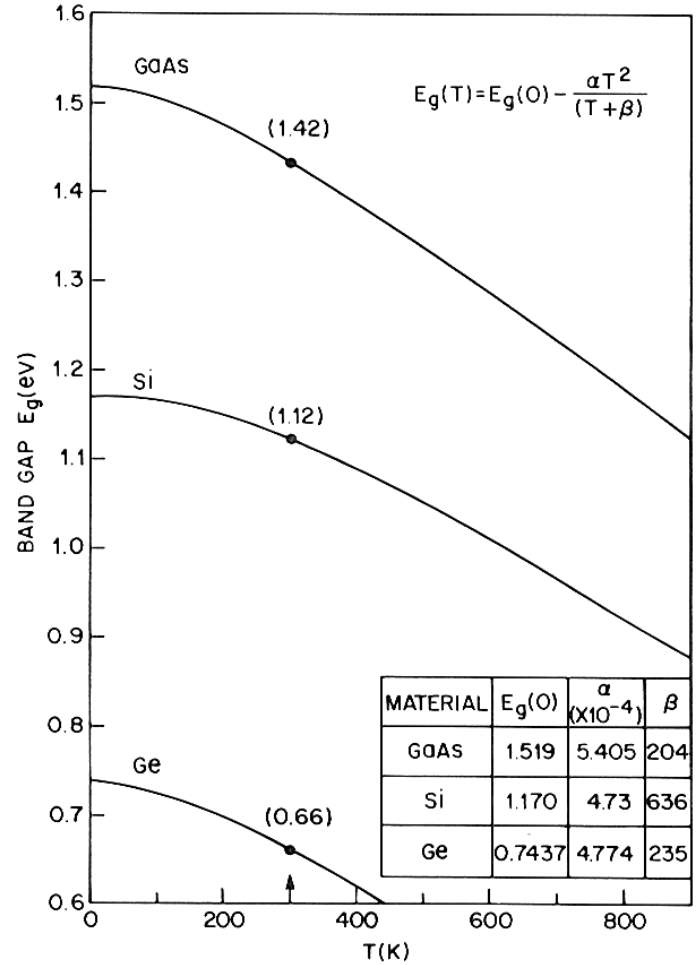
Weak recombination

Excitons unlikely!

PV Relevant c-Si physics III

Negative coefficient of PV power





MATERIAL	$E_g(0)$	α ($\times 10^{-4}$)	β
GaAs	1.519	5.405	204
Si	1.170	4.73	636
Ge	0.7437	4.774	235

sp³ hybridization in covalent bonding leads to decreasing E_g with T

A resulting decreasing V_{oc} leads to a negative coefficient of power

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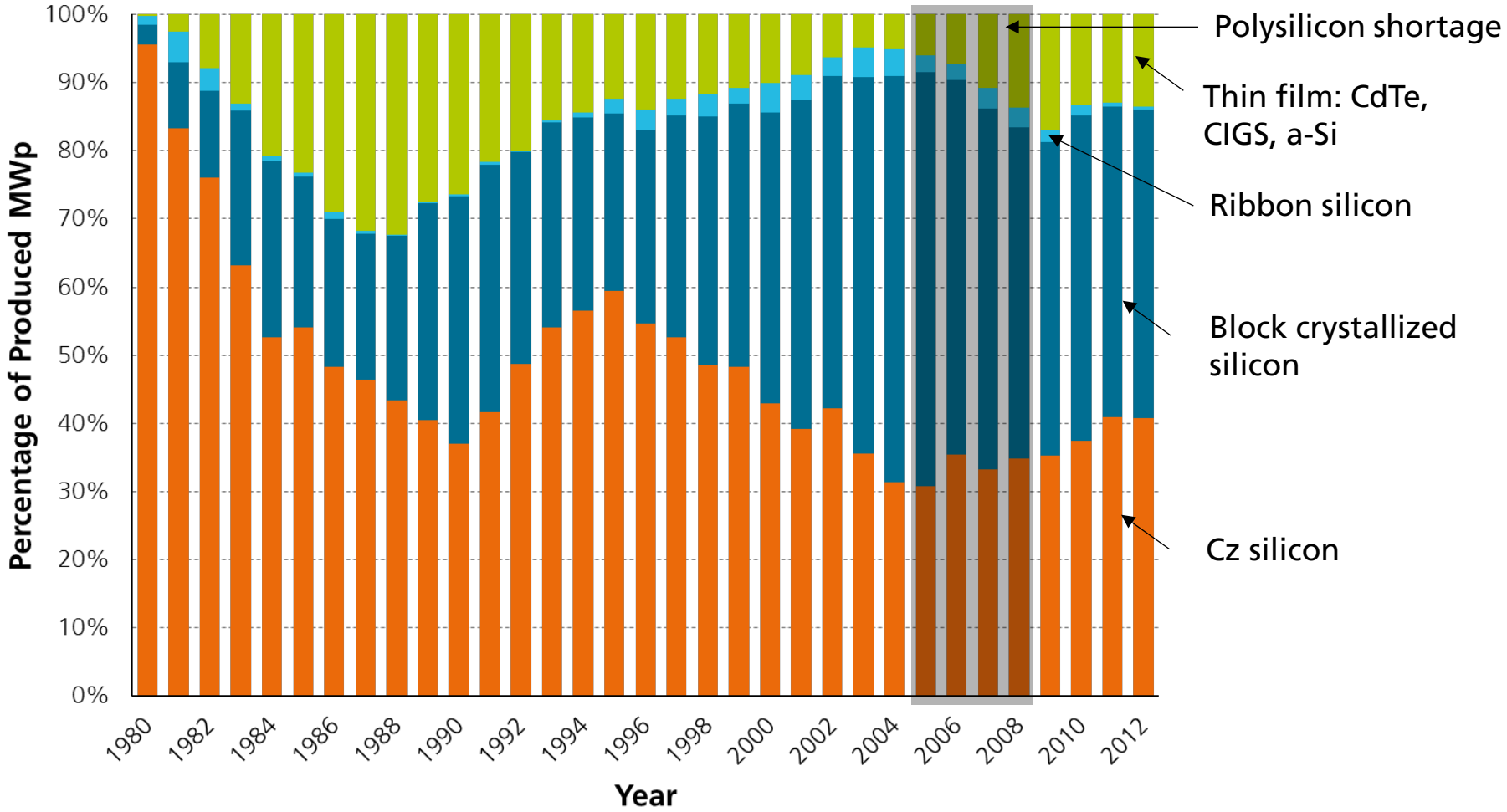
Overview of PV Technologies

Abbr.	Technology	Market leader 2013
c-Si	Crystalline Silicon wafer technology	Yingli (China)
CdTe	Cadmium Telluride thin film (glass)	First Solar (USA)
CIGS	CopperIndiumGalliumSelenide TF (glass)	Solar Frontier (Japan)
a-Si	Amorphous silicon TF (glass)	Sharp (Japan)
OPV	Organic semiconductors (plastics)	-
DSC	Dye-sensitized TF (glass)	-
CPV	Concentrating PV (III-V TF on wafer, 500x, 2-axis tracking)	Soitec Solar (F)

PV Module Production Technology Share Development



- **Thin Film PV Module Market Share 2012: 14%**

Source: Data: Navigant Consulting, Graphics: PSE AG 2013

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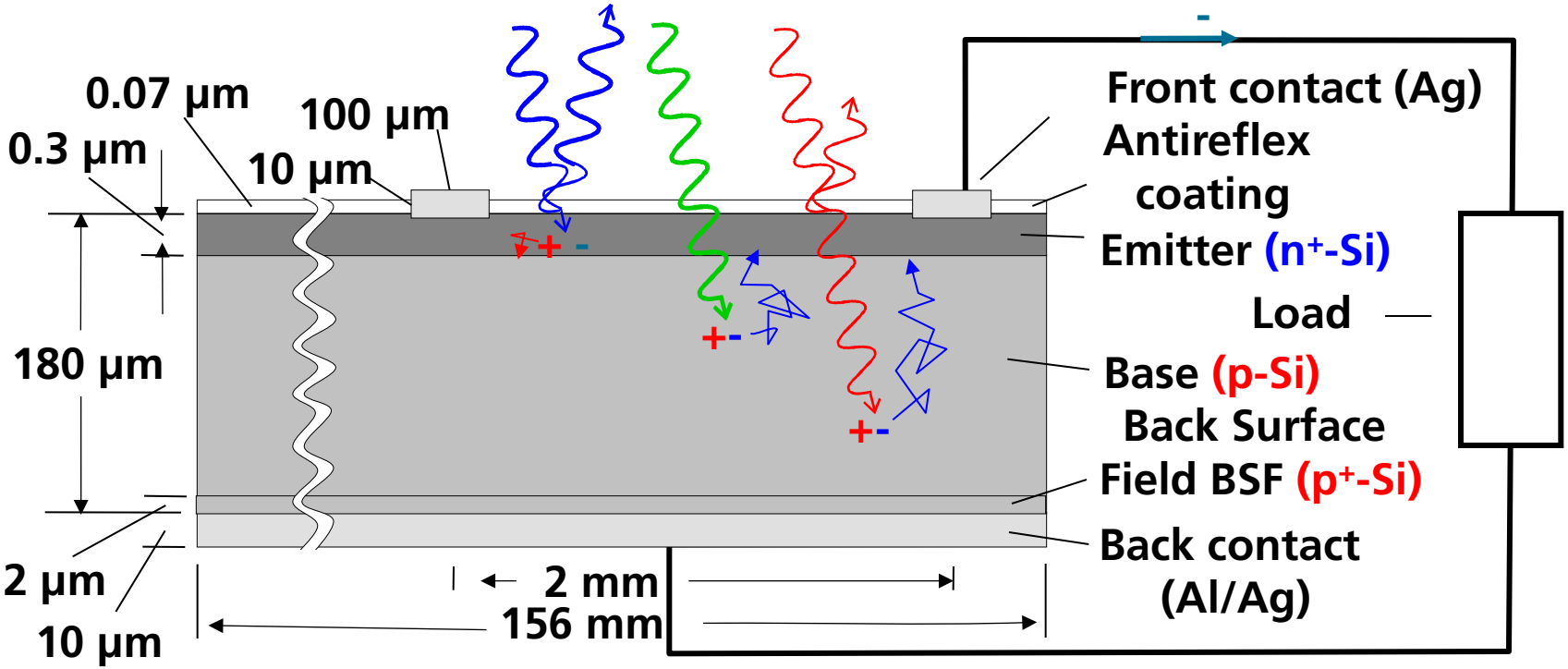
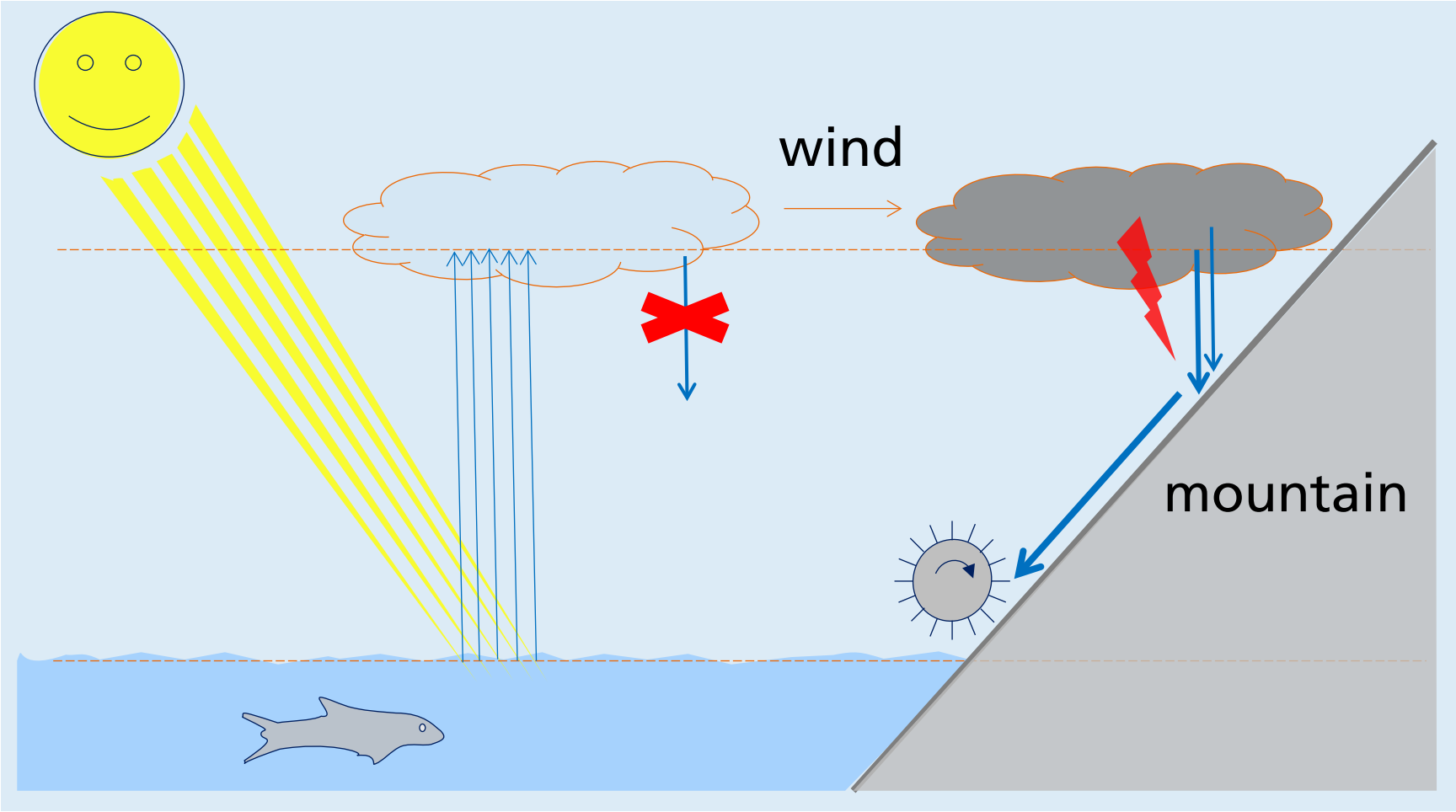
The Standard c-Si Solar Cell Structure

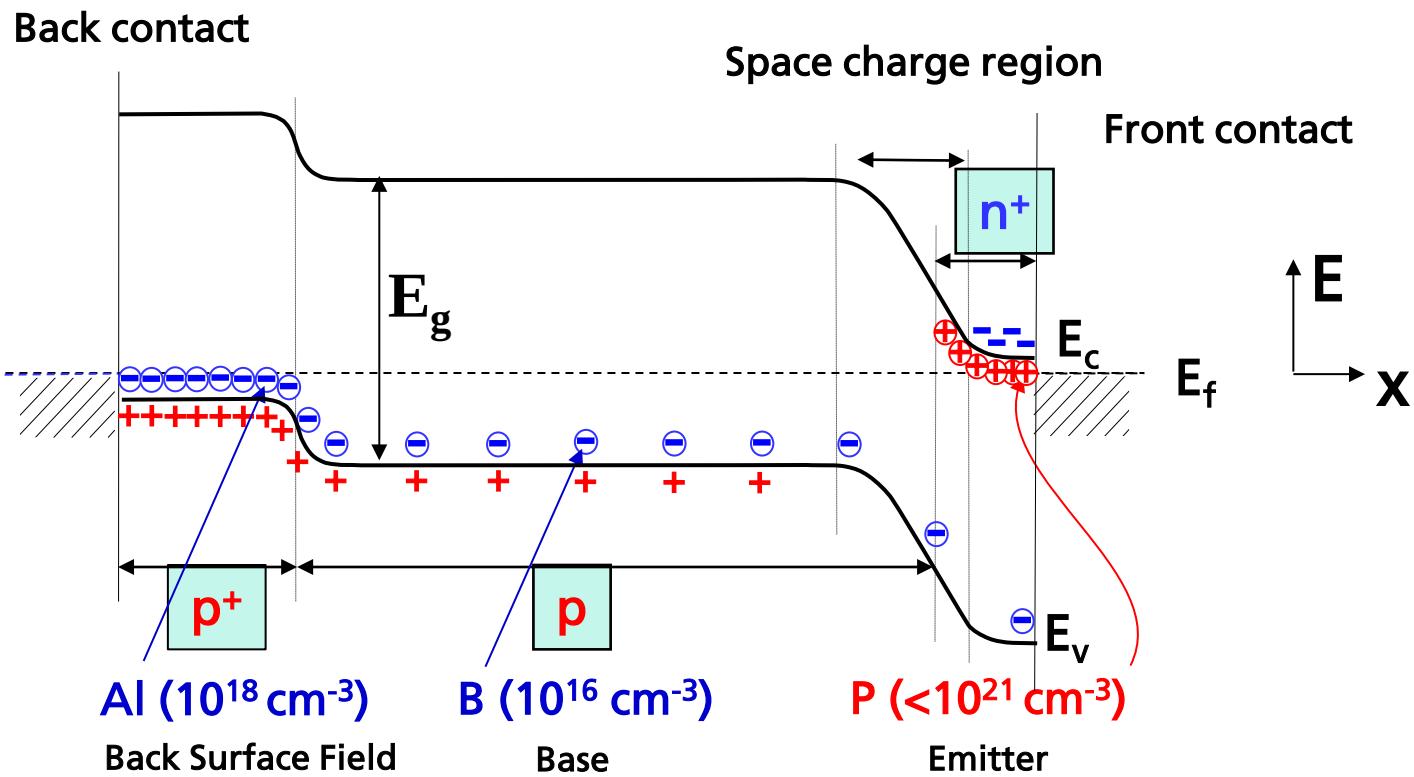


The Working of a Solar Cell: a Hydrodynamic Model

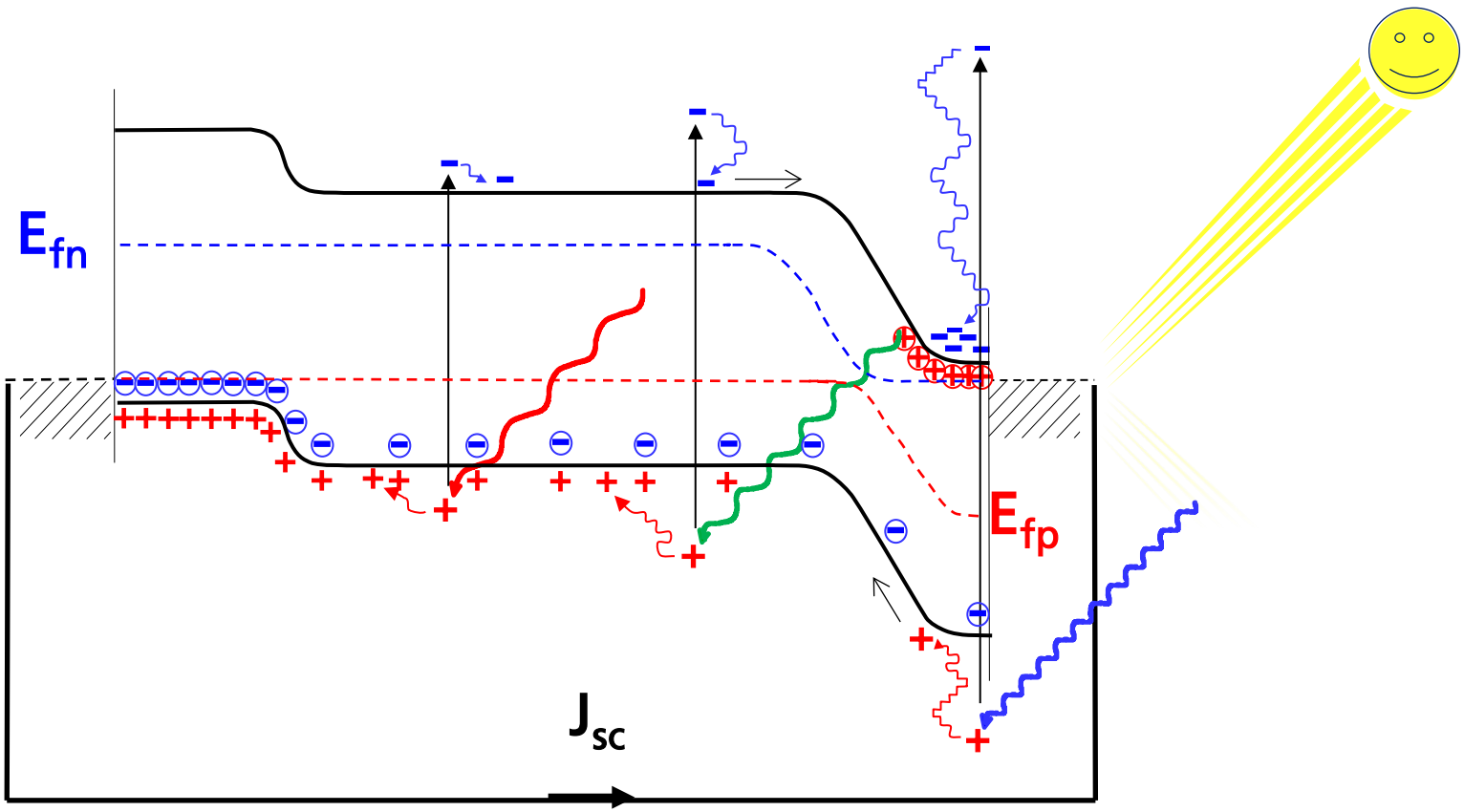


- The sun drives a water molecule (electron) cycle on two levels

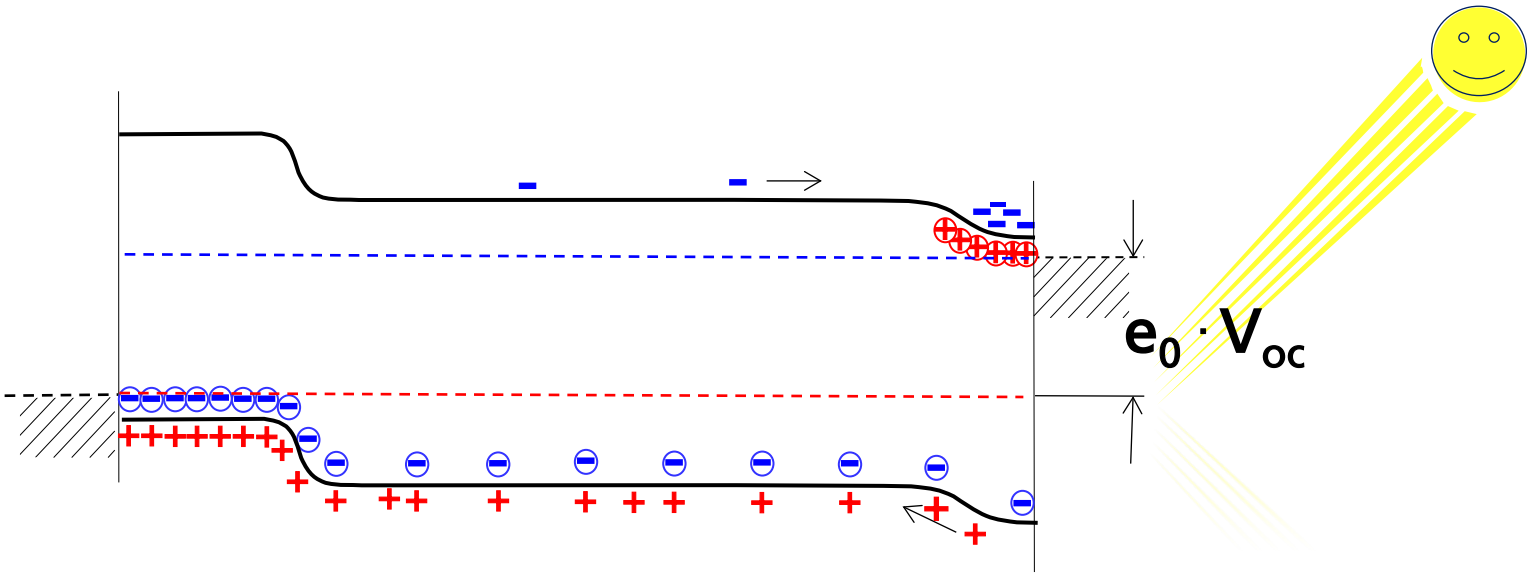
The Solar Cell in Thermodynamic Equilibrium



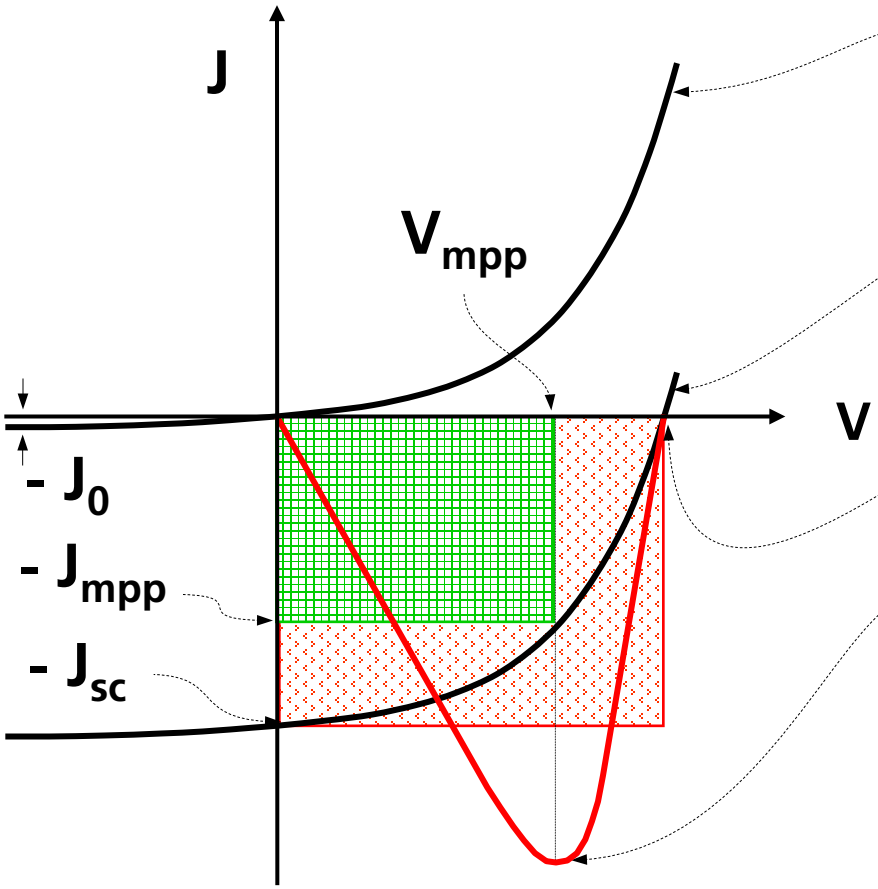
A Short-circuited Solar Cell under Illumination



Open-circuited Solar Cell under Illumination



The Fill Factor FF and Solar Cell Efficiency η



$$J_{diode} = J_0 \cdot (e^{\frac{e_0 V}{kT}} - 1)$$

$$J_{illum} = J_{diode} - J_{sc}(\phi_{illum})$$

$$V_{oc} = \frac{kT}{e_0} \cdot \ln(\frac{J_{sc}}{J_0} + 1)$$

$$p_{max} = V_{mpp} \cdot J_{mpp} = V_{oc} \cdot J_{sc} \cdot FF$$

$$FF = \frac{\square}{\square}$$

$$\eta = \frac{p_{max}}{\phi_{illum}}$$

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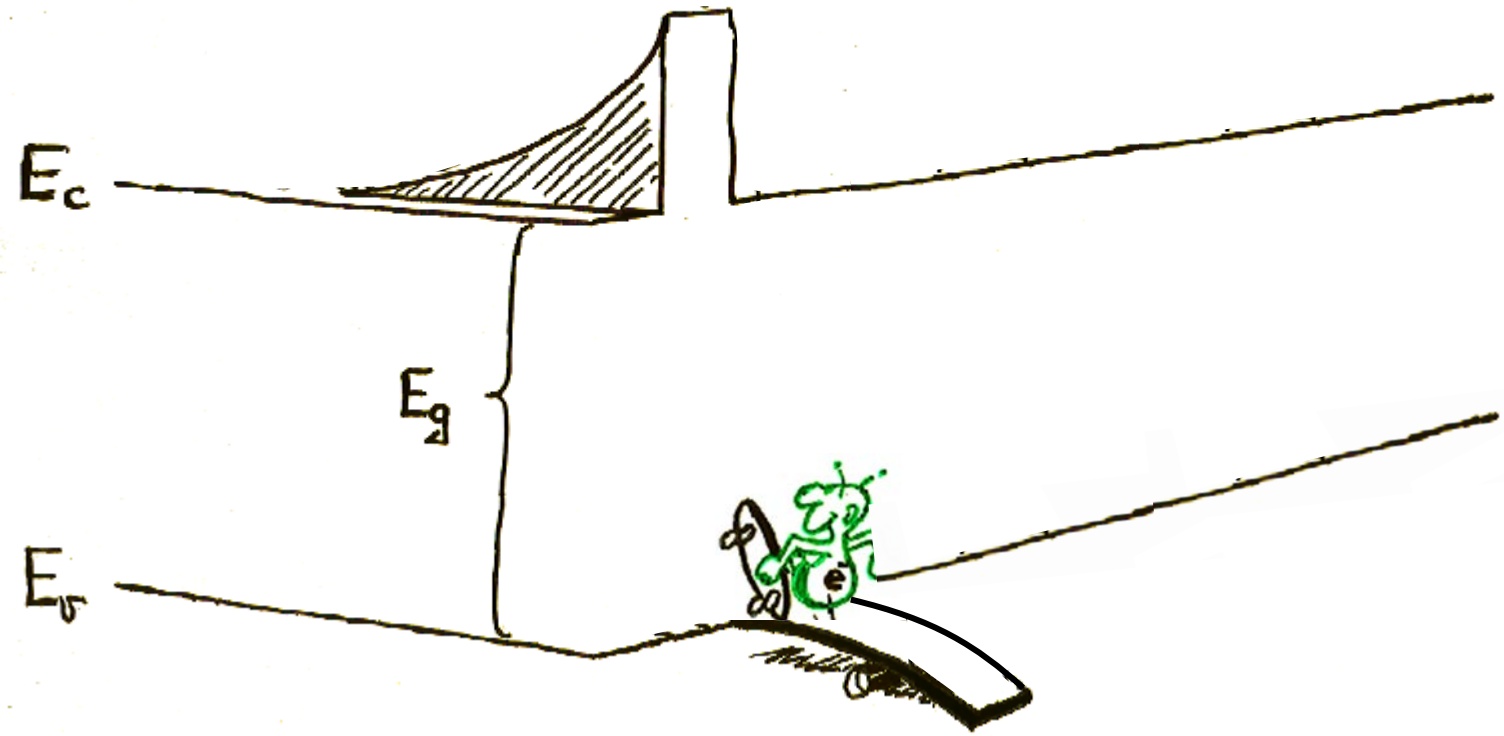
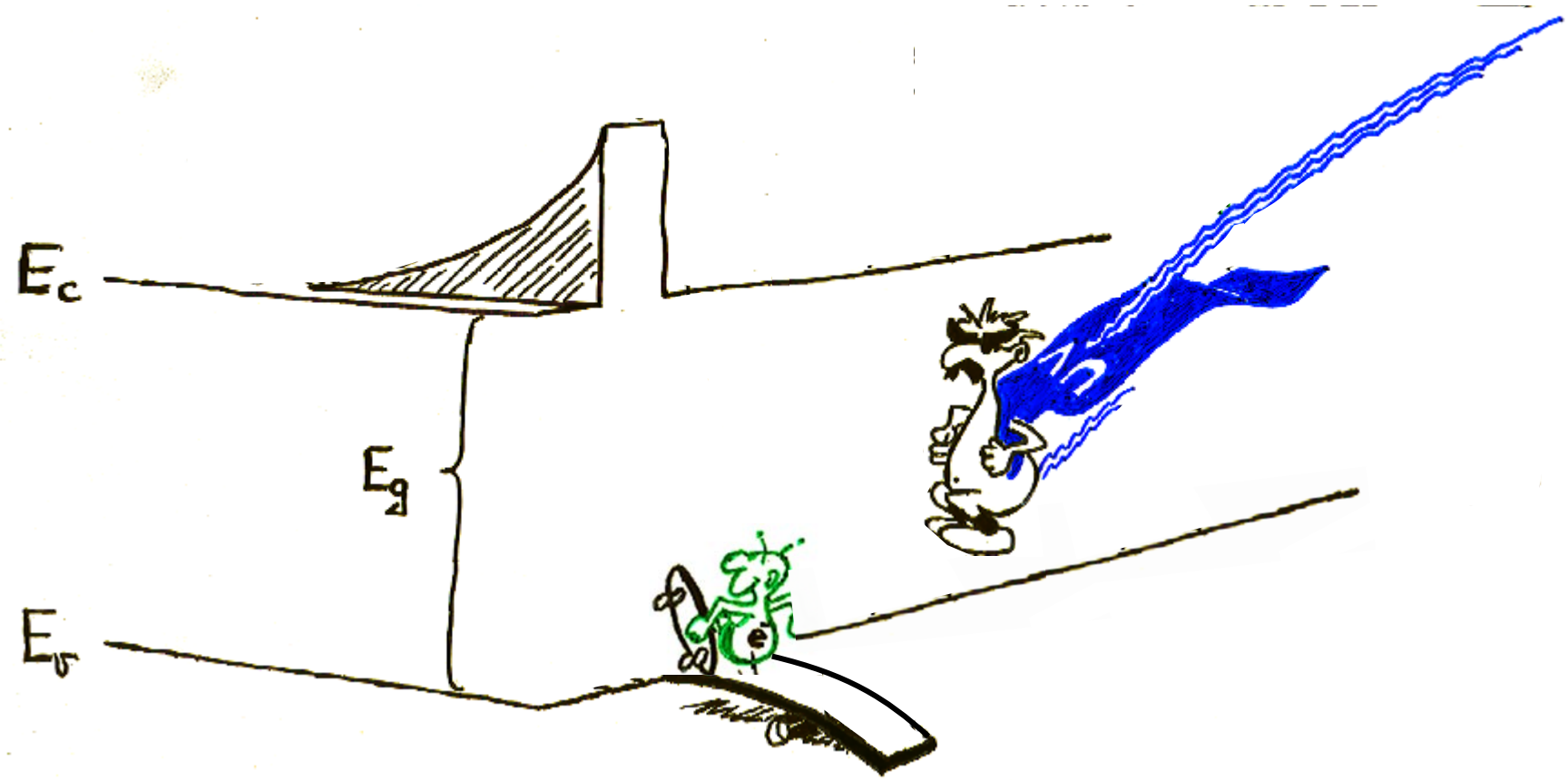
Thermalisation



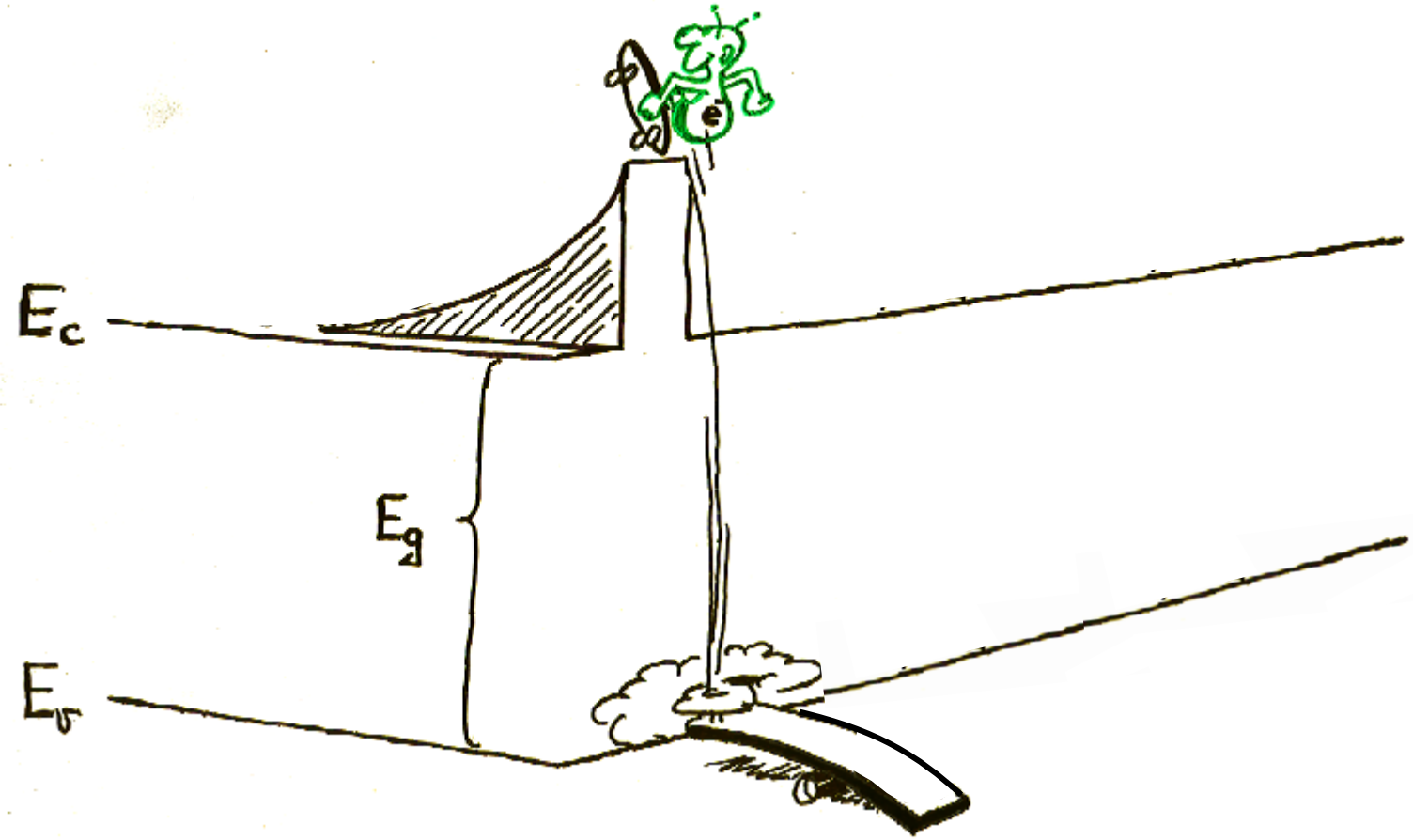
Source: unknown artist, Uni Konstanz, 1999

Thermalisation



Source: unknown artist, Uni Konstanz, 1999

Thermalisation



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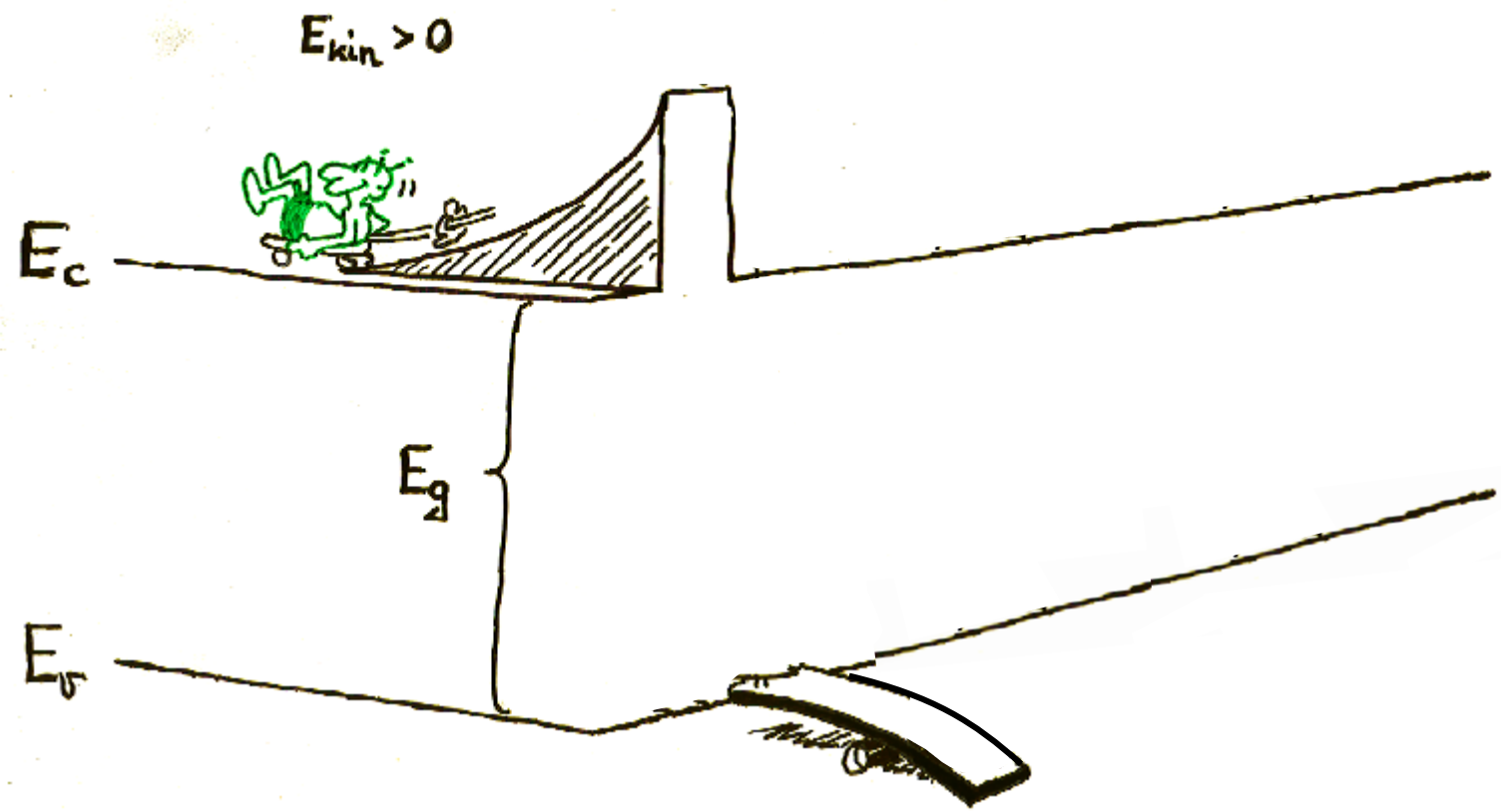
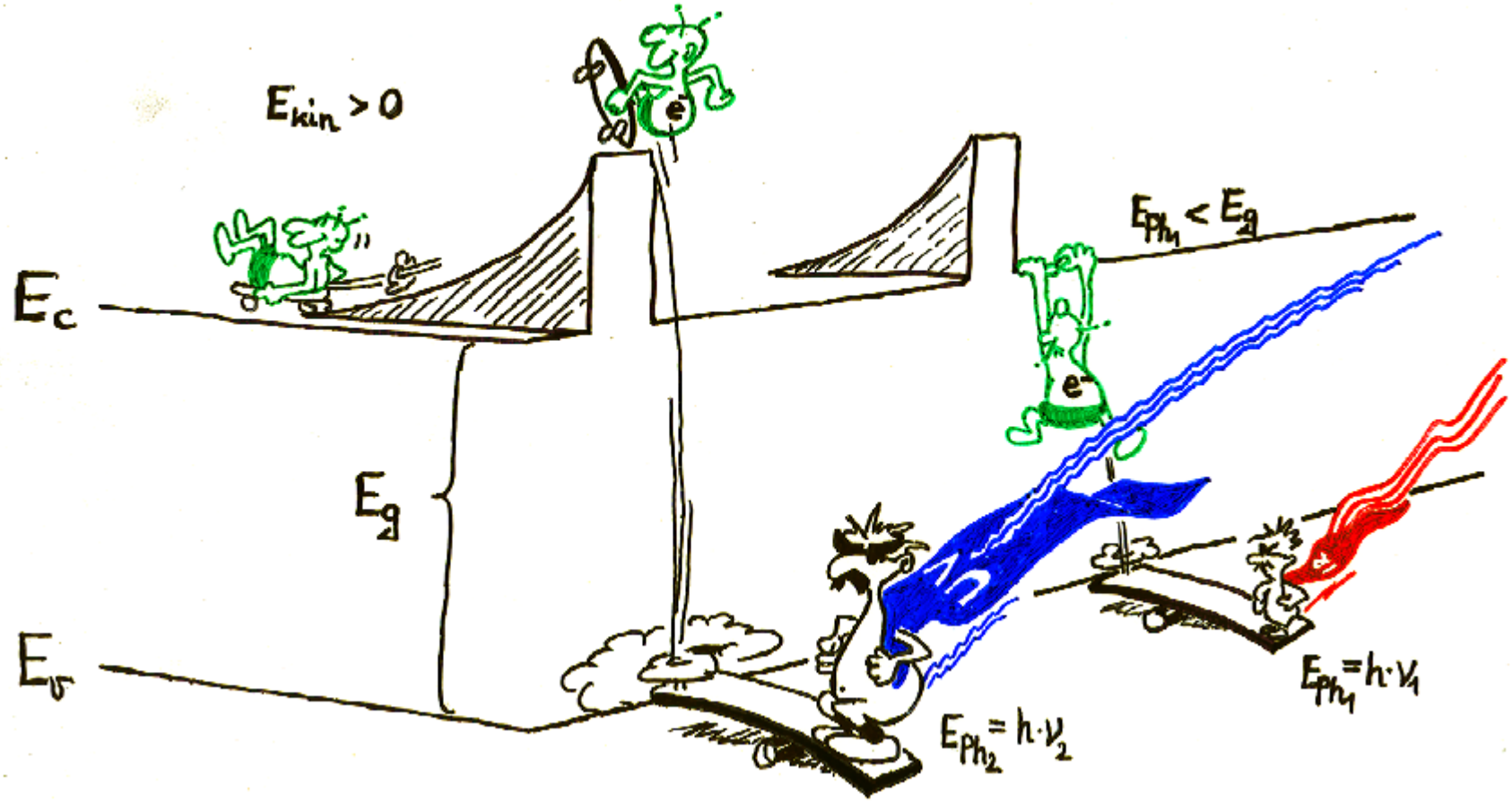
Thermalisation



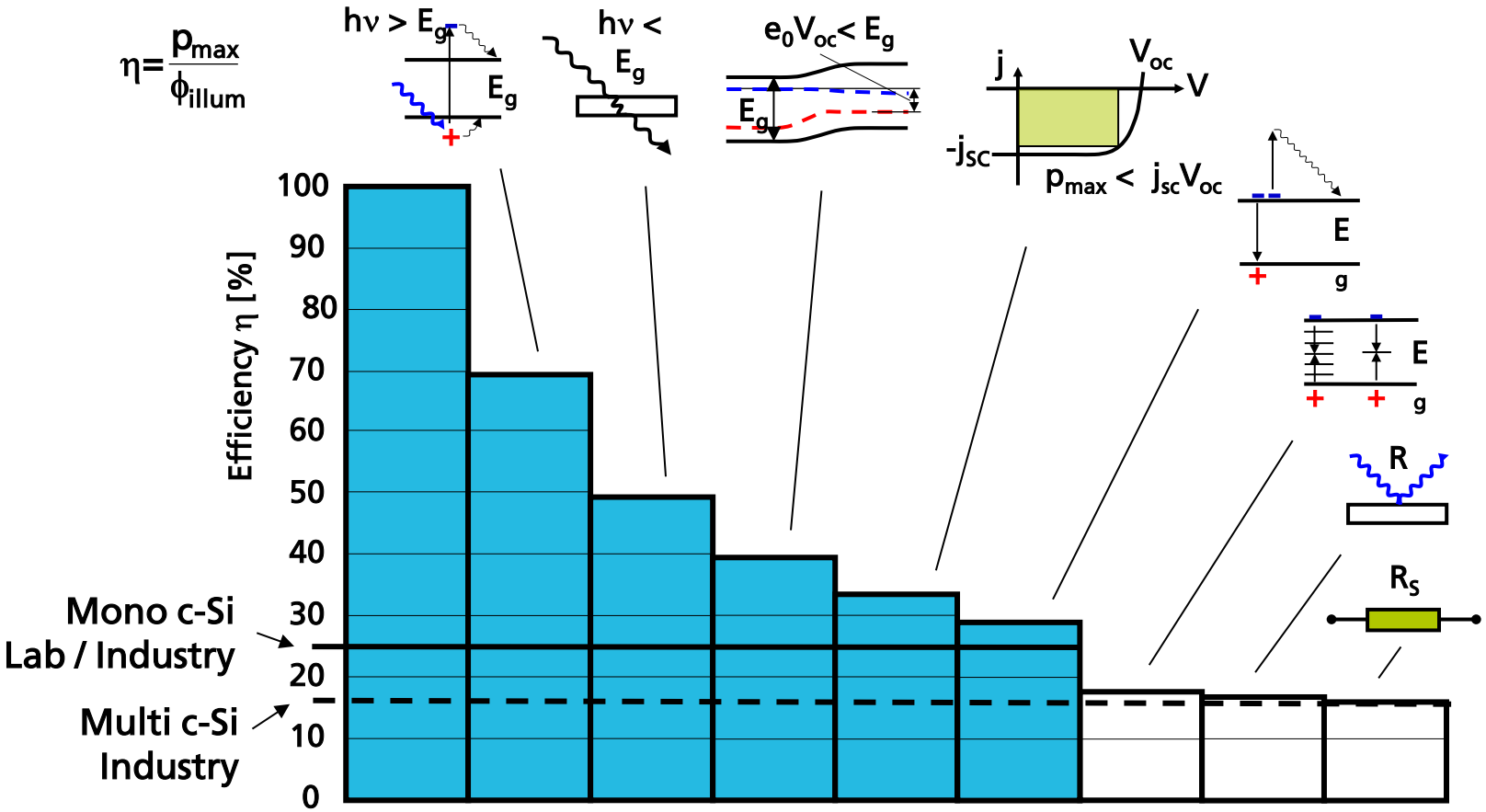
Source: unknown artist, Uni Konstanz, 1999

Thermalisation and Transmission Losses



Source: unknown artist, Uni Konstanz, 1999

Solar Cell Efficiency Limits and Loss Mechanisms



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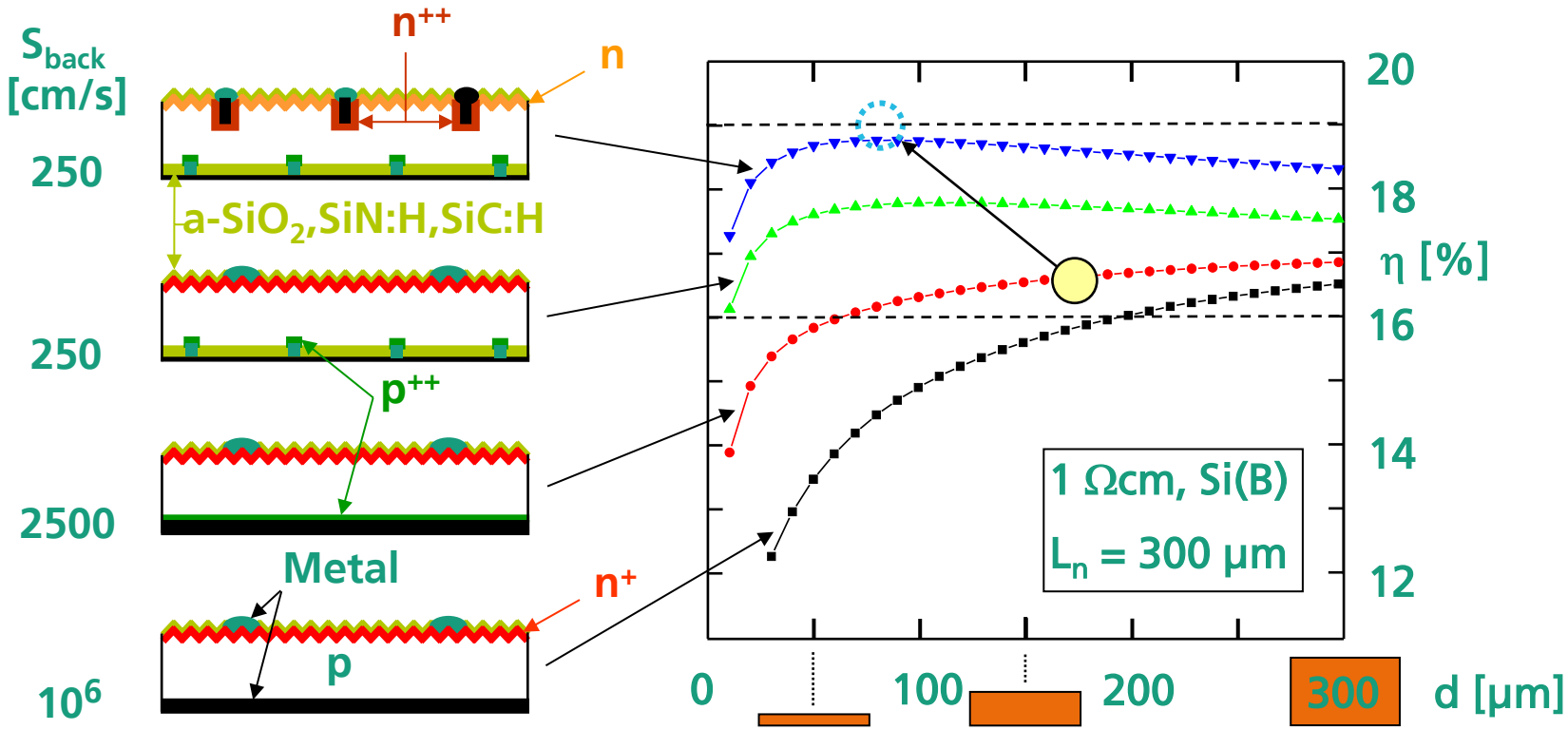
New Cell Concepts and Efficiency Potential



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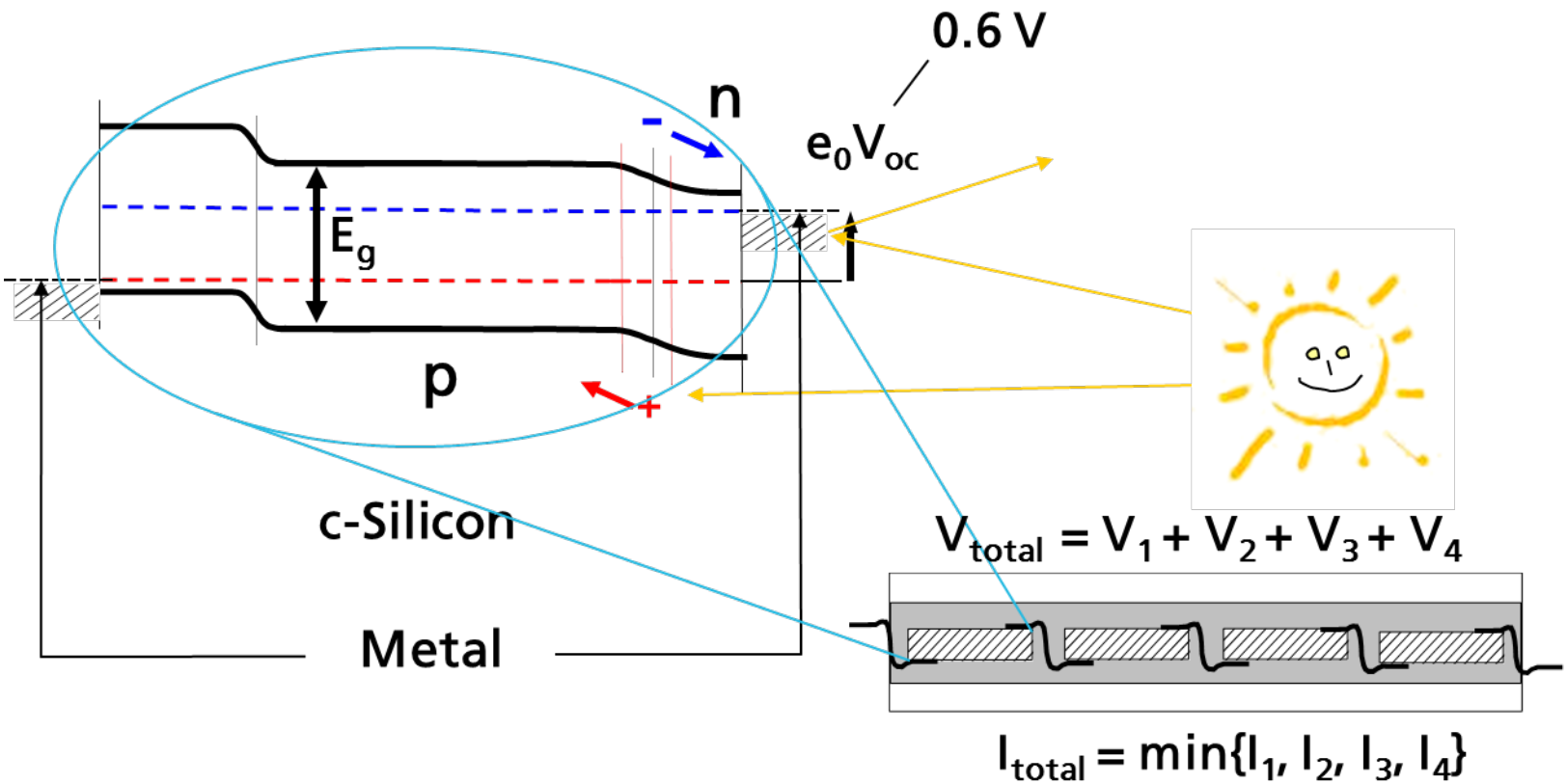
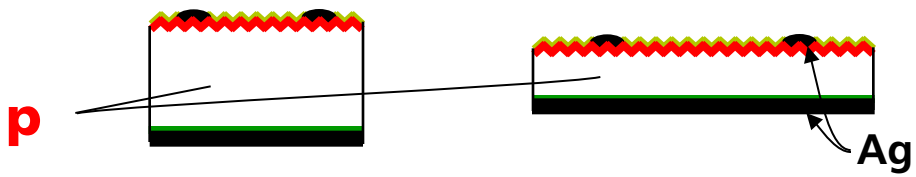
Typical mc-Si Solar Cell and Module Efficiencies 2013



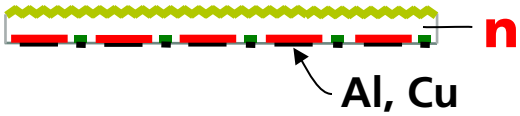
Cell efficiency 17.5%

Module efficiency 15%

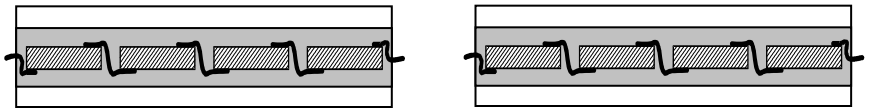
c- Si Technology Development Roadmap

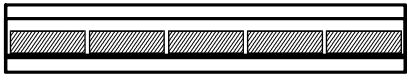


Next Generation c-Si Technologies



	1980	2005	2020
Cell Thick-ness [µm]	400	200	100
Kerf Loss [µm]	400	200	100
Edge Length [cm]	10	15	15
$\overline{\eta}_{cell(m)}$ [%]	10 (8)	15 (13)	20 (19)
Si [g/W_p]	30	10	3
MW_p/Line	10	100	1000

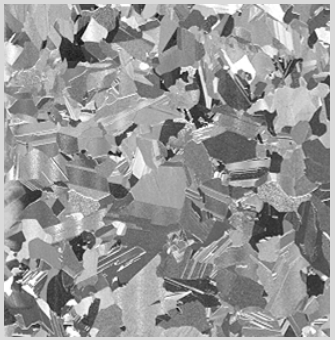




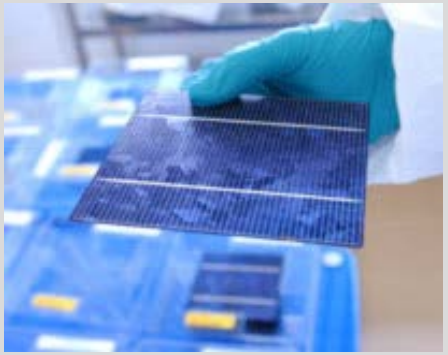
Module ~ Cell Efficiency

Value Chain of c-Si Photovoltaics

Si-Rohstoff -> Kristall



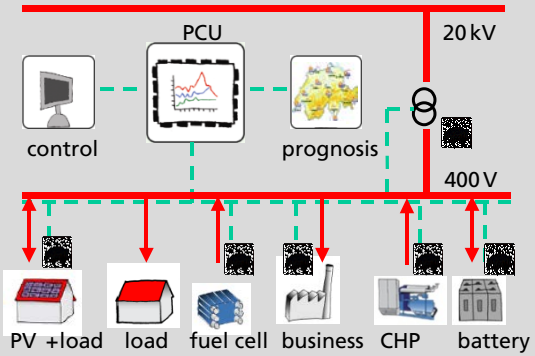
Si-Scheibe



Solarzelle

Module & System

Wechselrichter



Stromnetz

Quelle: Dr. G. Ebert, Fraunhofer ISE, 2012

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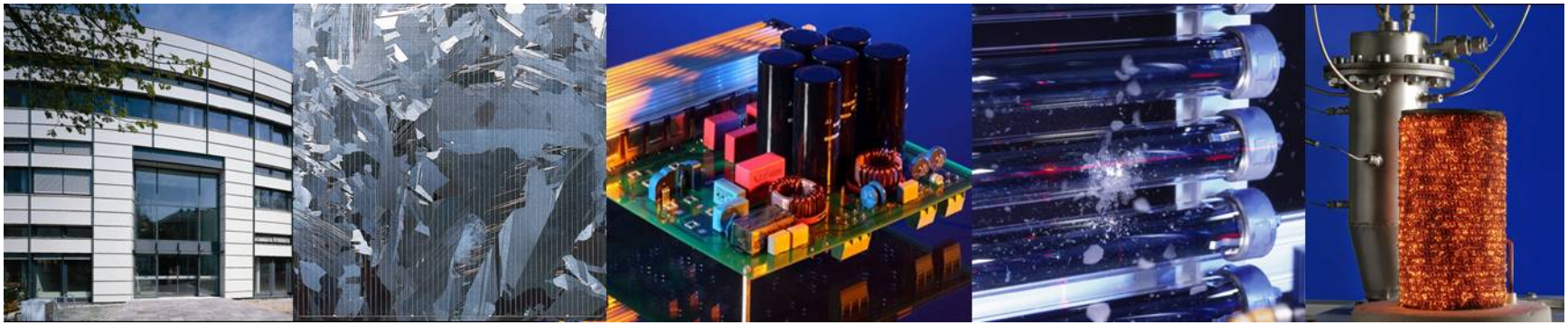
Summary…

- PV at Fraunhofer ISE
- 2001 – 2100: century of renewable energies
- Solar energy has the largest potential (WBGU 2003)
- Advantages and disadvantages of c-Si PV technology
- Best c-Si lab solar cell efficiency
  - multicrystalline 20.4%
  - single crystalline 25.0%
- Typical industrial solar cell (module) efficiency
  - multicrystalline 17.5% (15.0%)
  - single crystalline 18.5% (16.0%)
- Best industrial solar cell (module) efficiency
  - single crystalline 24.2% (21.0%)

Many thanks for your attention!



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