Solar Energy (1)

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Outline

1. Why to deploy Solar Energy massively?
2. Photovoltaics Fundamentals
3. Market and Cost Situation for PV Technology
4. Conclusions
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65% of our carbon budget compatible with a 2°C goal already used

Total Carbon Budget:
2900 GtCO₂

Amount Used 1870-2011:
1900 GtCO₂

Amount Remaining:
1000 GtCO₂
65% of our carbon budget compatible with a 2°C goal already used
Energy demand is rising quickly: here electricity

- IEA scenarios for global electricity generation until 2050 (4DS and 2DS scenario)
- High electrification scenario by Professor Christian Breyer, based on IEA figures
- Average of generation scenarios

Own illustration, data from IEA [5] [6]
The renewable potential

Source: Richard Perez & Marc Perez - A FUNDAMENTAL LOOK AT ENERGY RESERVES FOR THE PLANET

Comparing finite and renewable planetary energy reserves (Terawatt-years).
Total recoverable reserves are shown for the finite resources.
CSP versus PV

CSP

Direct Normal Irradiance (DNI) $\rightarrow$ clear sky is necessary

PV

DNI + diffuse radiation $\rightarrow$ PV-Cells als work with cloudy sky

Antireflex - Beschichtung

Sonnenlicht

Halbleit- material

Frontkontakt

Rückkontakt
### Characteristics

<table>
<thead>
<tr>
<th>Resource</th>
<th>Direct and diffuse radiation</th>
<th>Direct radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block size</td>
<td>mWatt up to 100 MW</td>
<td>10 MW up to 100 MW</td>
</tr>
<tr>
<td>Installation:</td>
<td>everywhere (rooftops etc.)</td>
<td>Flat unused land</td>
</tr>
<tr>
<td>Capacity factor:</td>
<td>700 – 2000 full load hours</td>
<td>2000 – 7000 full load hours</td>
</tr>
<tr>
<td>Backup:</td>
<td>External</td>
<td>therm. storage + foss. Backup</td>
</tr>
<tr>
<td>Inst. Power (2015)</td>
<td>227 GW</td>
<td>5 GW</td>
</tr>
<tr>
<td>Electricity price</td>
<td>0.03 – 0.13 €/kWh</td>
<td>0.06 – 0.20 €/kWh</td>
</tr>
</tbody>
</table>
Thermal vs. electric storage

CSP with thermal storage and some fossil co-combustion can provide a secured electricity supply.
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Photoelectric effect

**Photoelectric effect:** emissions of electrons from the atom or atomic group by the action of electromagnetic radiation. The energy distribution of the detached electrons is not determined by the intensity of the incident light, but by its frequency. The electron has the energy of the absorbed photon, which is reduced by the amount liberation energy.
Photovoltaic effect

**Photovoltaic effect:** The effect of an electrical potential difference between two electrodes under light irradiation, i.e. light is directly converted into electrical energy.
Isolator - Semiconductor – Conductor

Energy bands model in solids:

Classification of solids by their bandgap energy

Conduction band

Band gap

Valence band

Isolator

Seminconductor

Conductor
Excitation of Electrons in semiconductors

1. Absorption of light. An electron (blue) is excited with at least the bandgap energy. Generation of an electron-hole pair. \((10^{-15} \text{ s})\)

2. The electron relaxes to the minimum band, the hole (red) to the bandmaximum. \((10^{-12} \text{ s})\)

Electron (hole) "lives" on Band minimum (-maximum). (Up to ms range)

If no band gap were present, the excitation energy would immediately be converted into thermal energy → no metals as PV material
Band gap energy

Planck-Einstein equation for the photon

\[ E_\lambda = \frac{hc}{\lambda} \]

**Material** | **\( E_G \) in eV**
---|---
Ge | 0.7
CulnSe₂ | 1
C-Si | 1.13
GaAs | 1.42
CdTe | 1.45
AlSb | 1.55
CuGaSe₂ | 1.7
a-Si (amorph) | 1.7
Al₅Ge₆Ga₅As | 1.9
GaP | 2.3
CdS | 2.45

\( \lambda_G = 1.78 \mu m \)

\( \lambda_G = 1.13 \mu m \)

\( \lambda_G = 0.51 \mu m \)

\( c = 2.998 \times 10^8 \) m/s
\( h = 6.626 \times 10^{-34} \) Js
1 eV = 1.602 × 10⁻¹⁹ J
Solar Spectrum

The solar radiation is often approximated with the radiation of a black body (BB) of 5780 or 5800 K.
Fractional Function

\[ F_{\lambda_1 - \lambda_2} = \frac{\int_{\lambda_2}^{\lambda_1} e_{\lambda b}(\lambda) \, d\lambda}{\int_{0}^{\infty} e_{\lambda b}(\lambda) \, d\lambda} = \frac{1}{\sigma T^4} \int_{\lambda_1}^{\lambda_2} e_{\lambda b}(\lambda) \, d\lambda \]

Distribution for black body temperature \( T_{BB} \)

Band-Emission for interval \( \lambda_1 - \lambda_2 \)

Emission of whole spectrum = \( \sigma T^4 \)
Types of solar cells

- Thick film solar cells
  - Mono crystalline silicon (c-Si)
  - Multi crystalline silicon (mc-Si)
- Thin film solar cells
  - amorphous silicon (a-Si)
  - Micro crystalline silicon (c-Si)
  - CdTe
  - GaAs
  - CIGS
- Dye solar cells (Grätzel-Zelle)
- Organic solar cells
Silicon crystal structure

Si-atoms has 4 covalent bonds.

Incident photons excite electrons from valence band to conduction band

Electrons & wholes move in the crystal lattice until they recombine.
Silicon lattice doping

The semiconductor material is contaminated with atoms of another element group to provide n-type and p-type crystals.

Excess electrons (or holes) move freely in n-type crystals (or p-type crystals).

IMPORTANT: Both doped materials are electrically neutral!
pn-junction – 1/4

Neutral charge, but extra (nonbonded) electrons free on n-type side.

Extra holes in p-type side.
pn-junction – 2/4

When p and n are joined, electrons move from n-side to fill holes on p-side.

Positive charge begins to build on the n-side of the junction because of the loss of electrons.

Negative charge begins to build on the p-side as electrons fill bond vacancies (holes).
pn-junction – 3/4

Near the junction, most of the free electrons on the n-side have moved to the p-side, creating a large positive charge at the junction.

Large negative charge is created at the junction because of the transfer of electrons to the p-side to fill holes.

Symbols:
- Electron
- Hole
- Negative Charge Buildup
- Positive Charge Buildup
- Silicon Atom
- Donor Atom
- Acceptor Atom
- Normal Bond with 2 Electrons
- Bond Missing an Electron (i.e., a Hole)
- Bond with Extra Electron from Donor Atom

Quelle: NREL, Basic Photovoltaic Principles and Methods, 1981
er pn-junction – 4/4

Once the junction has fully formed, it presents a barrier to additional crossover of electrons to p-side.

Once the junction has fully formed, it presents a barrier to the possible transfer of holes from p-side to n-side.

Electron
Hole
− Negative Charge Buildup
+ Positive Charge Buildup
Silicon Atom
Donor Atom
Acceptor Atom
Normal Bond with 2 Electrons
Bond Missing an Electron (i.e., a Hole)
Bond with Extra Electron from Donor Atom

Quelle: NREL, Basic Photovoltaic Principles and Methods, 1981
PN-diode: Space charge region
Energy Band Modell

- p-Gebiet
- Raumladungszone
- n-Gebiet

Diffusion

Ladungsverteilung

Quelle: Volker Quaschning, Regenerative Energiesysteme
Absorption – practical application – 1/6

Reflection on the surface
Let us first consider Photon 1. It is reflected in spite of the antireflection layer and does not contribute to energy conversion.
Absorption – practical application – 2/6

Absorption in the emitter
Let us consider Photon 2. It is absorbed within the highly doped emitter. Due to the high doping, the diffusion length is extremely small, so the generated hole most probably recombines before reaching the space charge zone.
Absorption in the space charge zone

The absorption of the photon takes place here within the space charge zone. The field prevailing in the space charge zone separates the generated electron-hole pair and drives the two charge carriers in different directions. The electron is driven to the n-domain and then to the minus contact of the solar cell.
Absorption within the diffusion length of the electrons
Photon 4 is only absorbed deep into the solar cell. The generated electron is not in an electric field but diffuses "aimlessly" through the crystal. If it happens to arrive near the n-side it can flow to the contact.
Absorption – practical application – 5/6

Absorption outside the diffusion length of the electrons
A real loser is Photon 5, which is absorbed only in the lower region of the solar cell. The electron diffuses through the p-base, but recombines with a hole before it could reach the space charge zone.
Absorption – practical application – 6/6

Transmission
Finally, photon 6 is not absorbed at all in the thickness of the solar cell and transmitted without having formed an electron-hole pair.
Shockley-Queisser Limit – 1/2

Theoretical limit for photovoltaic cells, calculated in 1961 by William Shockley and Hans Queisser.

Part of the limitation is the spectral efficiency

$$\eta_\lambda = \frac{\Delta W_G}{E_{\text{solar}} \cdot h \cdot c} \times \int_0^\lambda G E_\lambda(\lambda) \cdot \lambda \cdot d\lambda$$

spectral loss of silicon PV cell
Multijunction PV-Cells

• Multiple pn junctions with tuned bandgaps, which absorb the irradiation over a broader spectrum → higher efficiency
• Shockley-Queisser Limit only valid for a single pn-junction \[^1\]
  • 1-jct. (Shockley-Queisser Limit): 30%
  • 2-jct.: 42%
  • 3-jct.: 49%
  • \(\infty\)-jct.: 68%

• Higher cost per area for multi-junction cells
Wirkungsgrad \[ \eta = \frac{P_{el}}{P_{solar}} = \frac{P_{MPP}}{E_{solar} \times A_{cell}} = \frac{FF \times U_L \times I_K}{E_{solar} \times A_{cell}} \]
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Global PV capacity

CAGR 2000-2013
50%

Cumulative installed PV capacity in GW

increase of installed power by a factor of 15 within six years

Scenarios for global PV deployment

<table>
<thead>
<tr>
<th>Scenario</th>
<th>5% CAGR</th>
<th>7.5% CAGR</th>
<th>10% CAGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed in 2050</td>
<td>4,300 GW</td>
<td>7,900 GW</td>
<td>14,800 GW</td>
</tr>
<tr>
<td>Cum. production</td>
<td>5,600 GW</td>
<td>9,600 GW</td>
<td>16,700 GW</td>
</tr>
</tbody>
</table>

% of IEA WEO: 13% 24% 44%

CAGR: Compound Annual Growth Rate

* CAGR = Compound Annual Growth Rate, ** Suggested market growth by year: 2014-2020: ~20%; 2020-2030: 14%; 2030-2040: 8%; 2040-2050: 4%; Considered by applying the S-curve approach to all scenarios
Cost structure of PV systems

Total: ~1000 €/kWp

~550

Module and inverter: ~ 550 EUR/kWp [world market]

~110

Balance of System cost

~340

“BOS” (= “Any other components”)
- Mounting system
- Installation
- Cable (DC)
- Infrastructure
- Transformer
- Grid connection
- Planning and documentation
Learning rate for PV modules

Notes: Orange dots indicate past module prices; purple dots are expectations. The oval dots correspond to the deployment starting in 2025, comparing the 2DS (left end of oval) and 2DS hi-Ren (right end).
The efficiency of a solar cell is one key driver for cost reduction.

Cell efficiency has a major impact on BOS cost

Effect of higher module efficiency:
- Less modules to install
- Less weight to transport
- Less structures to build
- Less surface to use

Today:
(-15% module efficiency)

- ~2 football fields

~2x efficiency
~50% surface

2050:
(~30% module efficiency)

- ~1 football fields


* Football field (Fifa) = 7140 m²
Learning curve for inverter

Historical learning curve only for inverters < 20 kW. Adaptation for inverters > 500 kW by shift of -25% according to 2013 prices.

Historical learning rate: 18.9%

Scenario 1: 40 EUR/kwp
Scenario 3: 30 EUR/kwp
Scenario 4: 20 EUR/kwp
Historical development of German feed-in tariff

*Nominal values, Feed-in tariff applicable at first of January each year, value 2015 excl. adjustment of 0.4 ct/kWh for direct marketing.
Expected cost development of PV electricity

- North America (1.5 – 5.8)
- Australia (1.6 – 4.9)
- India (1.6 – 3.7)
- Mena (1.6 – 3.7)

1.5% to 5.8% real values EUR 2014, full load hours based on [27], investment cost bandwidth based on different scenarios of market, technology and cost development; assuming 5% (real) weighted average cost of capital.
PV research in Germany addresses disruptive concepts

Theoretical thermodynamic limit for PV: 86%

Kostengünstige und hocheffiziente Tandemzellen
Durch c-Si / Pervoskite
Perovskite: A tandem partner for SI and CIGS

Target:
Efficiency > 30%
stable – environmentally friendly - scalable

Efficiency: 19.9 %

S. Albrecht et al.,
Energy & Env. 2016
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• PV Cells use the photoelectric effect to excite electrons and convert light into electricity
• The energy (wavelength) of the photon needs to be sufficient to overcome the bandgap in a semiconductor material
  ▪ PV cells consist of a junction of differently doped semi-conductors to separate the excited charge carriers
• PV electricity has reduced its cost dramatically over the last 20 years and is today one of the lowest cost electricity producer
• This is driven but scaled automated manufacturing and efficiency improvements in the semiconductor
• Further cost reduction is expected