PV Efficiency: Measurement & Theoretical Limits

Lecture 14 – 10/27/2011
MIT Fundamentals of Photovoltaics
2.626/2.627
Prof. Tonio Buonassisi
Motivation

1. Efficiency is a strong determining factor of cost.
2. Efficiency is tricky to measure accurately.
3. Several new technologies attempt to overcome fundamental efficiency limits of solar cells.
Learning Objectives: PV Efficiency Limits

1. Identify source(s) of record solar cell efficiencies.
2. Identify source(s) of “standard” solar spectra.
3. Describe how to simulate the solar spectrum in the lab: Describe how a solar simulator works.
4. Describe how to accurately measure & report cell efficiency, and how to avoid common pitfalls when attempting to measure cell efficiency.
5. Describe efficiency limitations of a typical solar cell:
   - Blackbody (heat engine) limit
   - Detailed balance model
   - Other (realistic) considerations
6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.
Key Concepts:

Updated record cell and module efficiency tables are published every six months, in the journal “Progress in Photovoltaics.”

Ref to latest version of “Efficiency Tables”:

Table I. Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000W/m²) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

<table>
<thead>
<tr>
<th>Classification</th>
<th>Effic. (%)</th>
<th>Area (cm²)</th>
<th>Vpc (V)</th>
<th>Jsc (mA/cm²)</th>
<th>FF (%)</th>
<th>Test Centre (and date)</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Silicon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Si (crystalline)</td>
<td>25.0 ± 0.5</td>
<td>4.00 (ca)</td>
<td>0.706</td>
<td>42.9</td>
<td>82.8</td>
<td>UNSW PERL [13]</td>
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</tr>
<tr>
<td>Si (multicrystalline)</td>
<td>20.4 ± 0.5</td>
<td>1.02 (ap)</td>
<td>0.664</td>
<td>26.0</td>
<td>80.9</td>
<td>NREL [5/04] [14]</td>
<td></td>
</tr>
<tr>
<td>Si (thin film transfer)</td>
<td>19.1 ± 0.4</td>
<td>3.983 (ap)</td>
<td>0.650</td>
<td>37.8</td>
<td>76.7</td>
<td>FNG-HSE [2/11]</td>
<td>ISH (48 μm thick) [4]</td>
</tr>
<tr>
<td>Si (thin film submodule)</td>
<td>10.5 ± 0.3</td>
<td>94.0 (ap)</td>
<td>0.492</td>
<td>29.7</td>
<td>72.1</td>
<td>FNG-HSE [6/07]</td>
<td>CSG Solar (1-2 μm on glass; 20 cells) [15]</td>
</tr>
<tr>
<td>III-V cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>GaAs (thin film)</td>
<td>28.1 ± 0.8</td>
<td>0.998 (ap)</td>
<td>1.111</td>
<td>29.4</td>
<td>85.9</td>
<td>NREL (3/11) [5]</td>
<td>Alta Devices [5]</td>
</tr>
<tr>
<td>GaAs (multicrystalline)</td>
<td>18.4 ± 0.5</td>
<td>4.011 (l)</td>
<td>0.994</td>
<td>22.2</td>
<td>79.7</td>
<td>NREL [11/55] [16]</td>
<td>RTI, Ge substrate [16]</td>
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<tr>
<td>InP (crystalline)</td>
<td>22.1 ± 0.7</td>
<td>4.02 (t)</td>
<td>0.878</td>
<td>25.5</td>
<td>85.4</td>
<td>NREL [4/90] [9]</td>
<td>Spire, epitaxial [7]</td>
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<tr>
<td>Thin film chalogenide</td>
<td>19.6 ± 0.6</td>
<td>0.996 (ap)</td>
<td>0.713</td>
<td>34.9</td>
<td>79.2</td>
<td>NREL [4/09] [18]</td>
<td>NREL, CIGS on glass [18]</td>
</tr>
<tr>
<td>CIGS (cell)</td>
<td>16.7 ± 0.4</td>
<td>16.0 (ap)</td>
<td>0.661</td>
<td>33.6</td>
<td>75.1</td>
<td>FNG-HSE [3/03]</td>
<td>U.ppsala, 4 serial cells [19]</td>
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<tr>
<td>CIGS (submodule)</td>
<td>16.7 ± 0.9</td>
<td>1.032 (ap)</td>
<td>0.845</td>
<td>26.1</td>
<td>75.5</td>
<td>NREL [6/01] [19]</td>
<td>NREL, mes on glass [20]</td>
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<tr>
<td>CdTe (cell)</td>
<td>10.1 ± 0.3</td>
<td>1.063 (ap)</td>
<td>0.886</td>
<td>16.7</td>
<td>67.0</td>
<td>NREL [7/06] [21]</td>
<td>Oerlikon Solar Lab, Neuchatel [21]</td>
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<tr>
<td>CdTe (amorphous)</td>
<td>10.1 ± 0.2</td>
<td>1.199 (ap)</td>
<td>0.539</td>
<td>24.4</td>
<td>76.6</td>
<td>JOA (12/6) [22]</td>
<td>Kaneka (2 μm on glass) [22]</td>
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<tr>
<td>Amorphous/nanocrystalline Si</td>
<td>10.9 ± 0.3</td>
<td>1.008 (da)</td>
<td>0.736</td>
<td>21.7</td>
<td>68.0</td>
<td>AIST (1/11) [23]</td>
<td>Sharp [6]</td>
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<tr>
<td>Organic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organic polymer</td>
<td>8.3 ± 0.3</td>
<td>1.031 (ap)</td>
<td>0.816</td>
<td>14.4</td>
<td>70.0</td>
<td>NREL (11/10) [24]</td>
<td>Konarka [24]</td>
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<tr>
<td>Organic (submodule)</td>
<td>3.5 ± 0.3</td>
<td>208.4 (ap)</td>
<td>8.020</td>
<td>0.847</td>
<td>48.3</td>
<td>NREL (7/06) [25]</td>
<td>Solameter [25]</td>
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<tr>
<td>Multijunction devices</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaInP/Ge/GaAs/Ge</td>
<td>32.0 ± 1.5</td>
<td>3.989 (t)</td>
<td>2.022</td>
<td>14.37</td>
<td>85.0</td>
<td>Spectrolab (monolithic)</td>
<td></td>
</tr>
<tr>
<td>GaN/AlGaAs (thin film)</td>
<td>25.8 ± 1.3</td>
<td>4.00 (t)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>NREL (11/60) [26]</td>
<td>Kopin/Boeing (four terminal) [26]</td>
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<tr>
<td>a-Si:nc-Si:nc-Si (thin film)</td>
<td>12.4 ± 0.7</td>
<td>1.059 (ap)</td>
<td>1.936</td>
<td>8.96</td>
<td>71.5</td>
<td>NREL (3/11) [27]</td>
<td>United Solar [7]</td>
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<tr>
<td>a-Si:nc-Si (thin film cell)</td>
<td>11.9 ± 0.6</td>
<td>1.227 (ap)</td>
<td>1.346</td>
<td>12.9</td>
<td>68.5</td>
<td>NREL [6/10] [28]</td>
<td>Oerlikon Solar Lab, Neuchatel [27]</td>
</tr>
<tr>
<td>a-Si:nc-Si (thin film submodule)</td>
<td>11.7 ± 0.4</td>
<td>1.049 (ap)</td>
<td>1.423</td>
<td>5.462</td>
<td>2.99</td>
<td>71.3 AIST (9/04) [29]</td>
<td>Kaneka (thin film) [28]</td>
</tr>
<tr>
<td>Organic (two-cell tandem)</td>
<td>8.3 ± 0.3</td>
<td>1.087 (ap)</td>
<td>1.733</td>
<td>8.03</td>
<td>59.5</td>
<td>FNG-HSE [10/10]</td>
<td>Helltek [29]</td>
</tr>
</tbody>
</table>

*CGS: CuxGa2-xGaAs; a-Si: amorphous silicon/germanium alloy.

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Table II. Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at a cell temperature of 25°C (IEC 60904-3: 2008, ASTM G-173-03 global).

<table>
<thead>
<tr>
<th>Classification</th>
<th>Effic. (%)</th>
<th>Area (cm²)</th>
<th>V_{oc} (V)</th>
<th>I_{sc} (A)</th>
<th>FF (%)</th>
<th>Test Centre (and date)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si (crystalline)</td>
<td>22.9 ± 0.6</td>
<td>778 (da)</td>
<td>5.60</td>
<td>3.97</td>
<td>80.3</td>
<td>Sandia (9/96)</td>
<td>UNSW/Gochermann [32]</td>
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<tr>
<td>Si (large crystalline)</td>
<td>21.4 ± 0.6</td>
<td>15780 (ap)</td>
<td>68.6</td>
<td>6.293</td>
<td>78.4</td>
<td>NREL (10/09)</td>
<td>SunPower [33]</td>
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<tr>
<td>Si ( multicrystalline)</td>
<td>17.8 ± 0.4</td>
<td>14920 (ap)</td>
<td>38.86</td>
<td>9.04</td>
<td>75.7</td>
<td>ESTI (2/11)</td>
<td>Q-Cells (60 serial cells) [8]</td>
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<tr>
<td>Si (thin film polycrystalline)</td>
<td>8.2 ± 0.2</td>
<td>661(ap)</td>
<td>25.0</td>
<td>0.320</td>
<td>68.0</td>
<td>Sandia (7/02)</td>
<td>Pacific Solar (1–2 μm on glass) [34]</td>
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<tr>
<td>GaAs (crystalline)</td>
<td>21.1 ± 0.6</td>
<td>921 (ap)</td>
<td>12.69</td>
<td>1.98</td>
<td>77.1</td>
<td>NREL (4/11)</td>
<td>Alta Devices [5]</td>
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<td>CIGS</td>
<td>15.7 ± 0.5</td>
<td>9703 (ap)</td>
<td>28.24</td>
<td>7.254</td>
<td>72.5</td>
<td>NREL (11/10)</td>
<td>Miasole [35]</td>
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<tr>
<td>CIGSS (Cd free)</td>
<td>13.5 ± 0.7</td>
<td>3459 (ap)</td>
<td>31.2</td>
<td>2.18</td>
<td>68.9</td>
<td>NREL (8/02)</td>
<td>Showa Shell [36]</td>
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<tr>
<td>CdTe</td>
<td>12.8 ± 0.4</td>
<td>6687 (ap)</td>
<td>94.1</td>
<td>1.27</td>
<td>71.4</td>
<td>NREL (1/11)</td>
<td>PrimeStar monolithic [9]</td>
</tr>
<tr>
<td>a-Si/a-SiGe/a-SiGe (tandem)</td>
<td>10.4 ± 0.5</td>
<td>905 (ap)</td>
<td>4.353</td>
<td>3.285</td>
<td>66.0</td>
<td>NREL (10/98)</td>
<td>USSC [37]</td>
</tr>
</tbody>
</table>

* a-CIGSS, CuInGaSSe; a-Si, amorphous silicon/hydrogen alloy; a-SiGe, amorphous silicon/germanium/hydrogen alloy.
* Effic., efficiency.
* (ap), aperture area; (da), designated illumination area.
* FF, fill factor.
* Recalibrated from original measurement.
* Spectral response and current–voltage curve reported in present version of these Tables.
* Spectral response reported in Version 37 of these Tables.

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Record module efficiencies typically 2–7% lower than record cell

M.A. Green, Prog. Photovolt: Res. Appl. 19 (2011) 565
NOTE: These are record cell efficiencies under ideal conditions (25°C, ~1000 W/m²)! Actual commercially-available silicon solar cells are typically 14-17% efficient. Modules are typically around 11-13%.
Learning Objectives: PV Efficiency Limits

1. Identify source(s) of record solar cell efficiencies.
2. Identify source(s) of “standard” solar spectra.
3. Describe how to simulate the solar spectrum in the lab: Describe how a solar simulator works.
4. Describe how to accurately measure & report cell efficiency, and how to avoid common pitfalls when attempting to measure cell efficiency.
5. Describe efficiency limitations of a typical solar cell:
   - Blackbody (heat engine) limit
   - Detailed balance model
   - Other (realistic) considerations
6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.
Please see the lecture 14 video to see Prof. Buonassisi explaining how to use NREL’s Solar Spectra website (linked to below).

http://rredc.nrel.gov/solar/spectra/
The receiving surface is defined in the standards as an inclined plane at 37° tilt toward the equator, facing the sun (i.e., the surface normal points to the sun, at an elevation of 41.81° above the horizon)

The specified atmospheric conditions are:

a) the 1976 U.S. Standard Atmosphere b with temperature, pressure, aerosol density (rural aerosol loading), air density, molecular species density specified in 33 layers
   b) an absolute air mass of 1.5 (solar zenith angle 48.19° s)
   c) Angstrom turbidity (base e) at 500 nm of 0.084 c
   d) total column water vapor equivalent of 1.42 cm
   e) total column ozone equivalent of 0.34 cm
   f) surface spectral albedo (reflectivity) of Light Soil as documented in the Jet Propulsion Laboratory ASTER Spectral Reflectance Database (http://speclib.jpl.nasa.gov.)

Source: http://rredc.nrel.gov/solar/spectra/am1.5/
Standard Solar Spectra

Source: http://pveducation.org/pvcdrom/appendicies/standard-solar-spectra

Courtesy of PVCDROM. Used with permission.
Measuring Global/Direct Insolation

Please see the lecture 14 video, or follow the link below to see solar irradiance measurement equipment.

http://www.nrel.gov/data/pix/searchpix_visual.html
Change is the Only Constant...

Evolution of the Solar Constant

Learning Objectives: PV Efficiency Limits

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6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.
Simulating Solar Spectra in the Lab (Solar Simulator)

Diagram removed due to copyright restrictions.
See the video for lecture 14, or Fig. 2 at the link referenced below.

Solar Simulator Properties

Uniformity

Spectral Fidelity

Temporal Stability


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Attempts to Simulate Solar Spectra: Light Sources

Non-ideal matches: QTH, Hg, M-Halide...

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Better matches: Xe lamps with air mass filters
Solar Simulator Standards

Standard IEC 904-9: Requirements for solar simulators for crystalline Si single-junction devices

<table>
<thead>
<tr>
<th></th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral match (ratio of the actual</td>
<td>0.75-1.25</td>
<td>0.6-1.4</td>
<td>0.4-2.0</td>
</tr>
<tr>
<td>percentage of total irradiance to the</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>required percentage specified for</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>each wavelength range)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-uniformity of irradiance</td>
<td>&lt; ±2%</td>
<td>&lt; ±5%</td>
<td>&lt; ±10%</td>
</tr>
<tr>
<td>Temporal Instability*</td>
<td>&lt; ±2%</td>
<td>&lt; ±5%</td>
<td>&lt; ±10%</td>
</tr>
</tbody>
</table>

For more info on PV testing standards, see: [http://photovoltaics.sandia.gov/docs/pvstndrds.htm](http://photovoltaics.sandia.gov/docs/pvstndrds.htm)

Other common standards:
- ASTM E927-05: [http://www.astm.org/Standards/E927.htm](http://www.astm.org/Standards/E927.htm)
- JIS C 8912-1989

*requires temporal instability of ≤ ±1% for Class A
Learning Objectives: PV Efficiency Limits

1. Identify source(s) of record solar cell efficiencies.
2. Identify source(s) of “standard” solar spectra.
3. Describe how to simulate the solar spectrum in the lab: Describe how a solar simulator works.
4. Describe how to accurately measure & report cell efficiency, and how to avoid common pitfalls when attempting to measure cell efficiency.
5. Describe efficiency limitations of a typical solar cell:
   - Blackbody (heat engine) limit
   - Detailed balance model
   - Other (realistic) considerations
6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.
Practical Considerations when Measuring Efficiency

Obtain & use an NREL-certified calibration (reference) cell.

Avoid extraneous light. (*A light-tight curtain works well.*)

Ensure 25°C measurement conditions. Remember: $V_{oc}$ can change by up to 0.25–1% / °C. Ideal chucks contain active heating/cooling, and independent temperature verification at the site of measurement (*i.e.*, not under the chuck).

Choose probe location judiciously to avoid series resistance losses.

Account for spectral mismatch between calibration cell and your solar cell.

Please see the lecture 14 video for a visual of example efficiency measurement equipment.

NB: Spectral response mismatch

**Warning:** Different PV materials are sensitive to different parts of the solar spectrum. You may be over/under estimating your performance, if the solar simulator calibration cell is made of a different material to the cells you are testing.

ASTM E973 - 10 Standard Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell

http://www.astm.org/Standards/E973.htm
Best Practices

When making a record efficiency claim, get the cell certified by NREL (FhISE, or other certified testing facility). This avoids controversies. This is challenging, however, for materials that degrade quickly.

Please see the lecture 14 video for paper extracts.
1. Identify source(s) of record solar cell efficiencies.
2. Identify source(s) of “standard” solar spectra.
3. Describe how to simulate the solar spectrum in the lab: Describe how a solar simulator works.
4. Describe how to accurately measure & report cell efficiency, and how to avoid common pitfalls when attempting to measure cell efficiency.
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   - Detailed balance model
   - Other (realistic) considerations
6. Describe the effects of temperature, illumination intensity, and lateral inhomogeneity on solar cell efficiency.
Max Solar Heat Engine (Blackbody) Efficiency: 86%

\[ P_o = \frac{\sigma \cdot T^4}{4\pi R_{sun}^2} \]

\[ P_{Earth} = \frac{R_{sun}^2}{D^2} \cdot P_o \]

\( T_{Sun} = \sim 6000 \text{ K} \)

\( T_{Earth} = \sim 300 \text{ K} \)

Theoretical Efficiency Calculations

First Paper: Prince

Key contribution: Efficiency in a single-junction device varies as a function of bandgap.

Fig. 2. Maximum converted power density in bright sunlight as a function of energy gap of semiconductor.
“Detailed Balance” Limit

Seminal Paper: Shockley-Queisser efficiency limit

Key contribution: “Detailed balance limit”: Light absorption is balanced (counteracted) by radiative recombination. Works for materials with large minority carrier lifetimes.

“Detailed Balance” Limit

Fig. 3. Dependence of the ultimate efficiency $u(x_g)$ upon the energy gap $V_g$ of the semiconductor.

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"Detailed Balance" Limit

Fig. 6. Efficiency $\eta$ for a solar cell at temperature $T_e=300^\circ$K exposed to a blackbody sun at temperature $T_s=6000^\circ$K. Curve (f) is the detailed balance limit of efficiency, assuming the cell is a blackbody (i.e., $t_s=t_e=1$). Curve (j) is the semiempirical limit, or limit conversion efficiency of Prince (see footnote 3). $\dagger$ represents the "best experimental efficiency obtained to date" for Si (see footnote 6). Curves (g), (h), and (i) are modified to correspond to 90% absorption of radiation (i.e., $t_s=t_e=0.9$) and 100-mw incident solar energy. The values for the $f$ quantities discussed in Sec. 6 are: (f) $f=1.09\times10^{-5}$ ($f_\omega=2.18\times10^{-5}$, $f_e=1$) $t_s=t_e=1$; (g) $f=0.68\times10^{-5}$ ($f_\omega=1.36\times10^{-5}$, $f_e=1$) $t_s=t_e=0.9$; (h) $f=0.68\times10^{-8}$ ($f_\omega=1.36\times10^{-8}$, $f_e=10^{-3}$) $t_s=t_e=0.9$; (i) $f=0.68\times10^{-11}$ ($f_\omega=1.36\times10^{-8}$, $f_e=10^{-6}$) $t_s=t_e=0.9$.

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Key Assumptions of the “Detailed Balance” Limit

• All photons with \( E > E_g \) are absorbed, and create one electron-hole pair.

• Electron and hole populations relax to band edges to create separate distributions in quasi thermal equilibrium with the lattice temperature, resulting in quasi Fermi levels separated by \( \Delta \mu \).

• Each electron is extracted with a chemical potential energy \( \mu \), such that \( qV = \Delta \mu \). Requires constant quasi Fermi levels throughout, i.e., carriers have infinite mobility.

• The only loss mechanism is radiative recombination (a.k.a., spontaneous emission).
“Detailed Balance” Limit

- Home discovery: Walk through the derivation of “detailed balance limit” yourself:
Theoretical Maximum Efficiency as a Function of Bandgap Energy

http://www.pveducation.org/pvcdrom/solar-cell-operation/detailed-balance

Courtesy of PVCDROM. Used with permission.
Modifications to Detailed Balance Calculations: Realistic Effects

- Bulk recombination (*e.g.*, Auger).
- Absorption losses (free-carrier absorption, continuously-varying absorption coefficient).

Image by MIT OpenCourseWare.

Modifications to Detailed Balance Calculations: Finite Carrier Transport

Lower carrier mobility = Lower efficiency limit!

FIG. 2. Radiative efficiency (no nonradiative recombination) vs band gap energy $E_g$. The absorption coefficient is $\alpha=\alpha_0$, the normalized thickness is $\alpha_0 d=10$, and the front surface is textured. All

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Another Approach

Following analysis in P. Würfel’s *Physics of Solar Cells*, p. 183–185:

Assume all efficiency losses derive from:

- **Non-absorption of light** ($E_{ph} < E_g$): 0.74
- **Thermalization of charge carriers** ($E_{ph} > E_g$): 0.67
- **Thermodynamic losses**: 0.64
- **Fill factor losses** (practical solar cell operation): 0.89

Resulting Efficiency Limit: $(0.74) \times (0.67) \times (0.64) \times (0.89) = 0.28$
Representation of Maximum Power: Single Junction


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Evolution of Efficiency Limit Calculations

Figure 1. Progress in calculated limit efficiencies. AM0 efficiencies have been adjusted to AM1 by adding 10% relative.

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From "APPROACHING THE 29% LIMIT EFFICIENCY OF SILICON SOLAR CELLS"
Realistic Limit of Crystalline Si

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APPROACHING THE 29% LIMIT...
Buonassisi (MIT) 2011
Generic silicon solar cell with its loss mechanisms. The losses subtract from the 29% limit efficiency, and are expressed as percentages of incident power (100 mW/cm², standard test conditions).
Good Readings on Efficiency Limits

- *Theoretical Limits of Photovoltaic Conversion*

- *Physics of Solar Cells*
  By Peter Würfel, in Library Reserve.

- *The Physics of Solar Cells*
  By Jenny Nelson, in Library Reserve.

- *Solar Cells*
  By Martin Green, Chapters 5 and 8.
2.627 / 2.626 Fundamentals of Photovoltaics
Fall 2013

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