Materials challenges for terawatt-scale photovoltaics (PV)

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Content

• Thinking big

• The materials and technologies toolbox

• Towards ultra-high efficiencies and new applications

• Economics and market

• One size (no longer) fits all

• A view on the future
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Bold thinking is needed: *multi-terawatts a.s.a.p.*
What is needed for impact?

- World primary/final energy consumption (rounded): 19/12 TW

- PV power expressed as power @ 1 sun (= 1000 W/m²) e.g. at 25% module efficiency: 250 Wp/m²

- Typical ratio average/peak power (= capacity factor) of PV systems (globally): 0.2

  PV “24/7” power: 50 W/m²

→ Covering 1% of current global energy requires ≈5000 km² module area (including conversion and storage losses)
Multi-terawatt deployment needed and possible

Terawatt-scale photovoltaics: Trajectories and challenges

By Nancy M. Haegel, Robert Margolis, Tonio Buonassisi, David Feldman, Armin Froitzheim, Raffi Garabedian, Martin Green, Stefan Glunz, Hans-Martin Henning, Burkhard Holder, Izumi Kaizuka, Benjamin Kroposki, Koji Matsubara, Shigeru Niki, Keiichiro Sakurai, Roland A. Schindler, William Tumas, Eike R. Weber, Gregory Wilson, Michael Woodhouse, Sarah Kurtz

NREL (US), FhG-ISE (DE) & AIST (JP)
The first terawatt is in sight now

- Projected growth in installed PV capacity

Nearly 1 TW total installed solar power possible by 2021
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Best research-cell efficiencies: the foundation of module efficiency improvement

www.nrel.gov/ncpv/images/efficiency_chart.jpg

Interactive version on: http://spectrum.ieee.org/static/interactive-record-breaking-pv-cells
Maximizing efficiency
Selected record cell architectures

Commercial PV technologies

The common view
Commercial PV technologies

Current situation

**Standard (“flat plate”) use:** wafer-based crystalline silicon

Module efficiencies 16 ~ 22%

**Standard (“flat plate”) use:** thin films (CdTe, CIGS, Si)

Module efficiencies 8 ~ 17%

**Concentrator use (sun tracking):** III-V tandems and Si

Module efficiencies 25 ~ 35%
Today’s commercial workhorse

Simplicity is difficult to beat in cost

≈180 μm
PV technology market shares

About 75* GWp PV module production in 2016

*2016 production numbers reported by different analysts vary between 70 and 82 GWp. We estimate that total PV module production is realistically around 75 GWp for 2016.

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE AG 2017
PV technology market shares

Production 2016 (GWp)
- Thin film: 4.9
- Multi-Si: 57.5
- Mono-Si: 20.2

Data: from 2000 to 2010. Navigant; from 2011: IHS (Mono-/Multi- proportion from cell production). Graph: PSE AG 2017
PV technology market shares

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Commercial module efficiencies
Gradual but robust increase

Innovations + Blood, Sweat & Tears

- Silicon - high-end mono
- Silicon - standard mono
- Silicon - standard multi
- Thin-film CIGS
- Thin-film CdTe
- Thin-film aSi/μcSi
- Thin-film aSi
Striving for perfection

Record cells compared

Albert Polman, Mark Knight, Erik C. Garnett, Bruno Ehrler, Wim C. Sinke
Science 15 Apr 2016: Vol. 352, Issue 6283, DOI: 10.1126/science.aad4424
http://subsites.amolf.nl/lmpv/shockley-queisser/
Striving for perfection
Record cells compared

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Towards high module efficiencies

The first step: closing the lab/fab gap
Striving for perfection

Record cells compared
Towards high module efficiencies

The first step: closing the lab/fab gap

### Practical Limit for Single-Material Modules

![Graph showing module efficiency over years for different materials: silicon, thin films, and various silicon types.](image)

- **Silicon**
  - High-end mono
  - Standard mono
  - Standard multi

- **Thin-films**
  - CIGS
  - CdTe
  - aSi/µcSi
  - aSi

The graph illustrates the module efficiency (%) over years from 2000 to 2020, highlighting the practical limit for single-material modules.
Developments in the lab

- Very-high efficiency concepts
- Very low-cost concepts & and technologies for new applications

Example: tandem solar cell

Example: PV window (UCLA; USA)

Example: solar foil (HyET Solar; NL)
Towards high module efficiencies

The next step: tandems?

hybrid tandems?
(silicon with dedicated thin film)
Top cell candidate: methyl ammonium lead halide perovskite

$\text{CH}_3\text{NH}_3\text{PbI}_3$
Silicon technology generations

- **Gen1**
  - Limited by (a.o.) extrinsic Si material quality:
    - Multi → mono, HP multi; p → n

- **Gen2**
  - Limited by surface & interface quality:
    - Advanced surface passivation; passivating contacts; heterojunctions

- **Gen3**
  - Limited by intrinsic Si material quality:
    - Thin wafers + light trapping (to SQ)

- **Gen4**
  - Limited by Si bandgap
    - Tandems (beyond SQ)
Silicon technology generations

• Gen1
  – Limited by (a.o.) extrinsic Si material quality:
    – Multi $\rightarrow$ mono, HP multi; $p \rightarrow n$

• Gen2
  – Limited by surface & interface quality:
    – Advanced surface passivation; passivating contacts; heterojunctions

• Gen3
  – Limited by intrinsic Si material quality:
    – Thin wafers + light trapping (to SQ)

• Gen3?
  – Limited by Si bandgap
    – Tandems (beyond SQ)
Commercial PV technologies: an alternative view
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From cell to module: current approach

$\approx 300 \text{ watt-peak (Wp)}$
Price-experience curve PV modules

Combined effects of volume and innovation
Price of roof systems (Germany)

(Bron: Fraunhofer ISE)
Efficiency matters

Cost structure electricity generation

- Costs of cells or cell layers
- Costs of cells to modules
- Area-related system costs
- Power-related and fixed system costs
- Operation and maintenance costs
- Cost of capital
Efficiency matters

Cost structure electricity generation

- Costs of cells or cell layers
- Costs of cells to modules
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- Cost of capital

Higher efficiency
Spectacular development in generation cost

Solar Could Beat Coal to Become the Cheapest Power on Earth

by Jessica Shankleman and Chris Martin
January 3, 2017, 1:00 AM GMT+1 Updated on January 3, 2017, 1:16 PM GMT+1

- Global average solar cost may fall below coal within 10 years
- Countries from Saudi Arabia to Mexico planning auctions
Game-changing price reduction of solar energy

www.bloomberg.com/news (29 October 2014)
Power Purchasing Agreement (PPA) price offers

Lowest ever solar bids submitted in Abu Dhabi

2.4 – 3.6 €/kWh
Global cumulative capacity (in GWp)

PV now supplies ≈2% of all electricity

Source: IEA PVPS.
Installed capacity NL (in MWp)

PV now supplies ≈2% of NL electricity
Contribution of PV to electricity use per country

<table>
<thead>
<tr>
<th>Country</th>
<th>Percentage</th>
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<tbody>
<tr>
<td>Honduras</td>
<td>12.5%</td>
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<td>Greece</td>
<td>7.4%</td>
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<td>Italy</td>
<td>7.3%</td>
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<td>Finland</td>
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Source: IEA PVPS (2017)
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Volume by and with diversity
Freedom of shape

Julianadorp, NL
Photo Paul Pex

http://energieanders.nl/trienergia-driehoek-paneel-100wp-detail
Aesthetic quality

Exasun

Heijmans/AERspire
Flexibility & light weight

HyET Solar (NL) / BrummenEnergie
Solar energy meets Dutch Design
Solar modules made to your liking

ECN, UNStudio, TS Visuals, Aldowa, Design Innovation Group and Hogeschool van Amsterdam; project Dutch Solar Design.
Solar energy meets Dutch Design

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ECN, UNStudio, TS Visuals, Aldowa, Design Innovation Group and Hogeschool van Amsterdam; project Dutch Solar Design.
Solutions for ‘B’ and ‘C’ locations

*Shade-linear modules*

Prototype of shade-linear module (ECN)
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Selected challenges in materials research for terawatt-scale photovoltaics

Stable, high-quality, low-cost, sustainable:

• Wide (& narrow) bandgap absorbers for tandem PV

• Selective IR and UV absorbers for PV windows

• Transparent and non-metal conductors and carrier-selective contacts

• Low-dimensional materials for new optoelectronic properties

• Encapsulants, anti-soiling coatings, support structures

+ closing materials cycles (design for sustainability)
The (solar) energy transformation

we, now

solar energy era

solar energy era

Use of fossil fuels

Year

-2000  0  2000  4000  6000
Thank you for your attention!