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# Cost-effective high-efficiency 1-sun PV modules

Wim Sinke
ECN Solar Energy

IEA PV Roadmap Workshop
Paris
04 02 2014

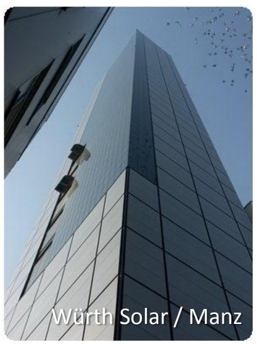
www.ecn.nl

# Cell & module technologies
# *Commercial*



**1 sun: wafer-based silicon (≈90%)**
- monocrystalline
- multicrystalline & quasi mono

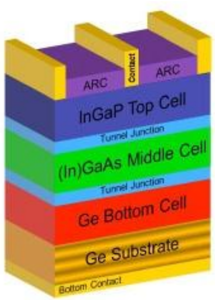
Module efficiencies 14 ~ 22%

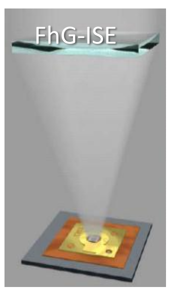





**1 sun : thin films (≈10%)**
- cadmium telluride (CdTe)
- copper-indium/gallium-diselenide/sulphide (CIGSS)
- silicon

Module efficiencies 7 ~ 14%



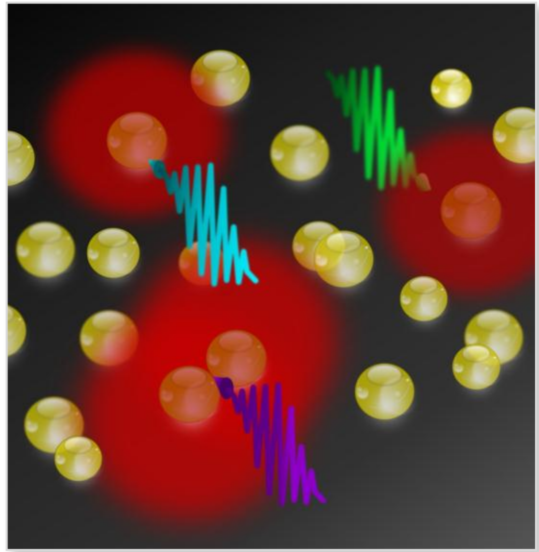


**Concentrator (<1%)**
- multi-junction III-V semiconductors
- silicon

Module efficiencies 25 ~ 33%

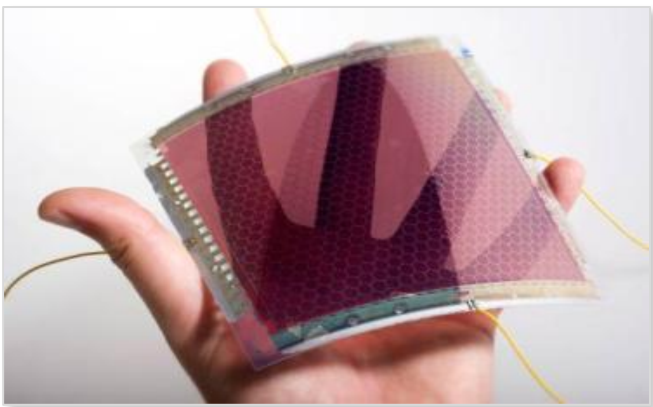
# Concepts & technologies
# *Lab and pilot production* *("nanotechnology at km² scale")*

- **super-high-efficiency concepts**
  (incl. combinations of existing technologies)
  - more complete use of solar spectrum (optimize cell or modify spectrum)
  - advanced light management (incl. macro- and micro-concentration)



*Example:*
spectrum conversion using quantum dots
(Univ. of Amsterdam)

- **super-low-cost concepts**
  (& technologies for new applications)

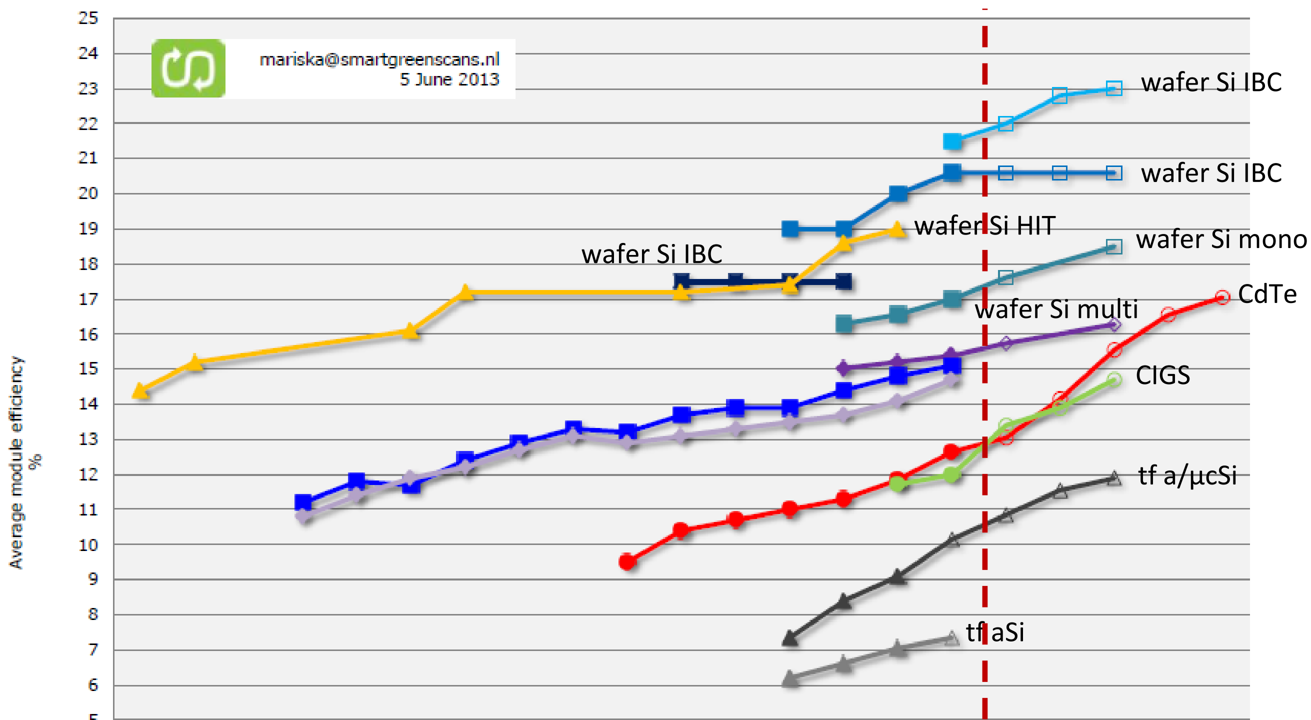


*Example:*
polymer solar cell (Solliance)

# Commercial module efficiencies (selection) ECN

# *History + short-term projections (announced)*

M.J. de Wild-Scholten
SmartGreenScans
(June 2013)




| | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013e | 2014e | 2015e | 2016e | 2017e |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sunpower, X-series | | | | | | | | | | | | | | | | 21.5 | 22.0 | 22.8 | 23.0 | | |
| Sunpower, E-series | | | | | | | | | | | | | 19.0 | 19.0 | 20.0 | 20.6 | 20.6 | 20.6 | 20.6 | | |
| Sunpower, 1st generation | | | | | | | | | | | 17.5 | 17.5 | 17.5 | 17.5 | | | | | | | |
| HIT, Sanyo/Panasonic | 14.4 | 15.2 | | | | 16.1 | 17.2 | | | | 17.2 | | 17.4 | 18.6 | 19.0 | | | | | | |
| Mono-Si n-type PANDA, Yingli, CN | | | | | | | | | | | | | | 16.3 | 16.6 | 17.0 | 17.6 | | 18.5 | | |
| Multi-Si, Yingli, CN | | | | | | | | | | | | | | 15.0 | 15.2 | 15.4 | 15.7 | | 16.3 | | |
| Mono-Si (Photon Int Feb 2013) | | | | 11.2 | 11.8 | 11.7 | 12.4 | 12.9 | 13.3 | 13.2 | 13.7 | 13.9 | 13.9 | 14.4 | 14.8 | 15.1 | | | | | |
| Multi-Si (Photon Int Feb 2013) | | | | 10.8 | 11.4 | 11.9 | 12.2 | 12.7 | 13.1 | 12.9 | 13.1 | 13.3 | 13.5 | 13.7 | 14.1 | 14.7 | | | | | |
| CdTe, First Solar | | | | | | | | | | 9.5 | 10.4 | 10.7 | 11.0 | 11.3 | 11.9 | 12.7 | 13.1 | 14.2 | 15.6 | 16.6 | 17.1 |
| CIGS, Solar Frontier, JP | | | | | | | | | | | | | | | 11.7 | 12.0 | 13.4 | 13.9 | 14.7 | | |
| μc/a-Si, Oerlikon Solar Fabs | | | | | | | | | | | | | 7.4 | 8.4 | 9.1 | 10.2 | 10.9 | 11.6 | 11.9 | | |
| a-Si, TSolar, ES | | | | | | | | | | | | | 6.20 | 6.63 | 7.05 | 7.35 | | | | | |

# Commercial module efficiencies (selection)

ECN

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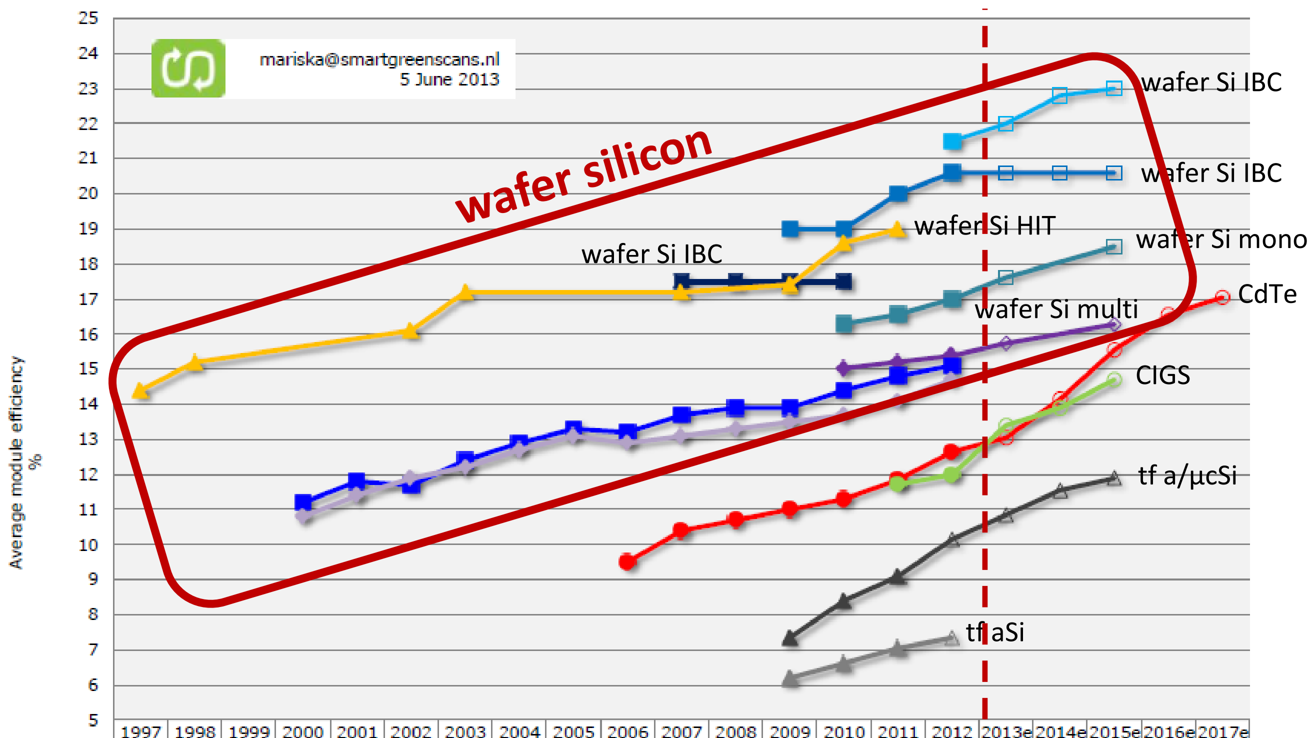


M.J. de Wild-Scholten
SmartGreenScans
(June 2013)

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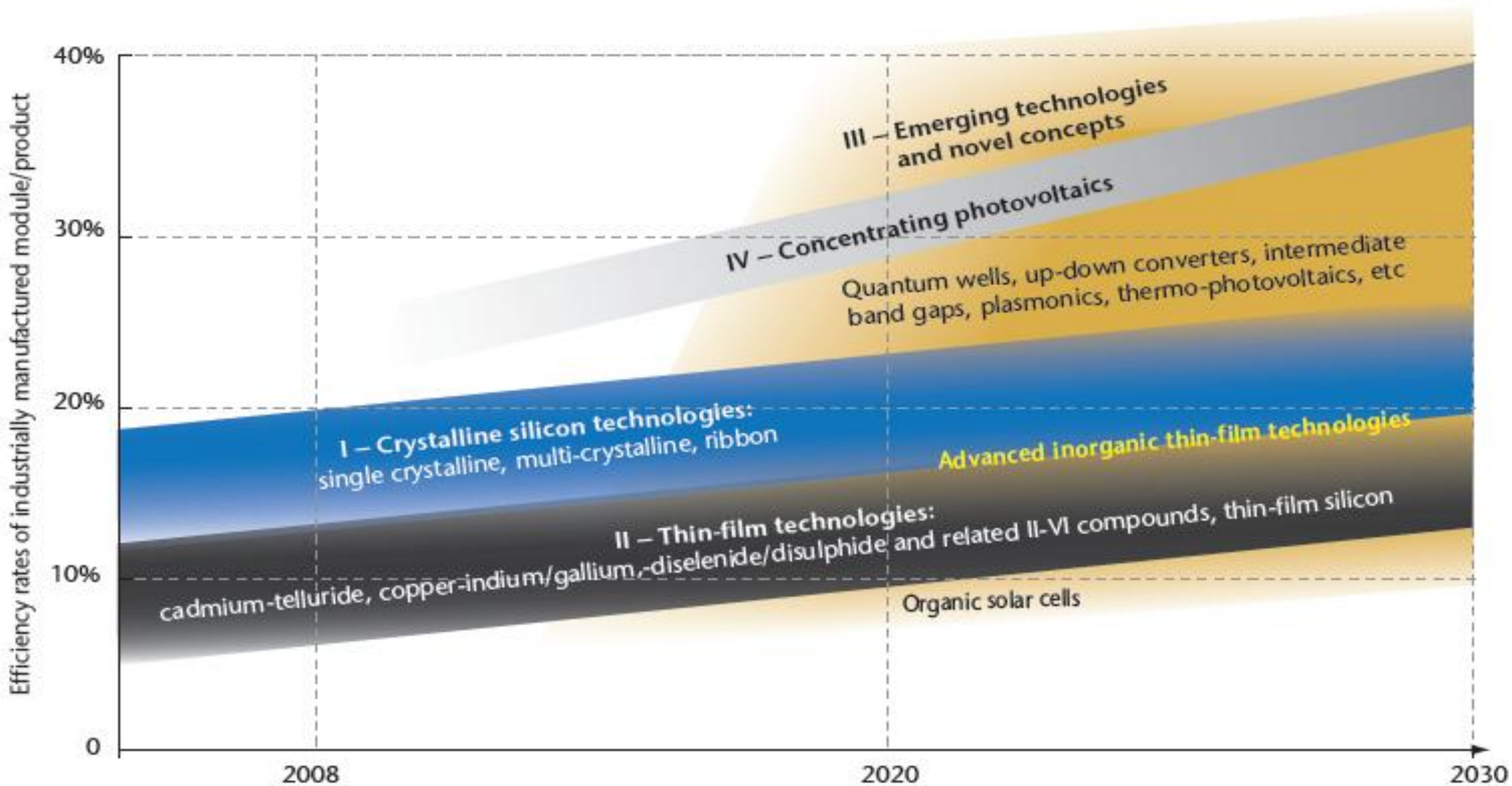
# Commercial module efficiencies

## *History + long-term projections* *(simplified estimates)*




*Source*: IEA PVPS.

# Commercial module efficiencies (selection) ECN

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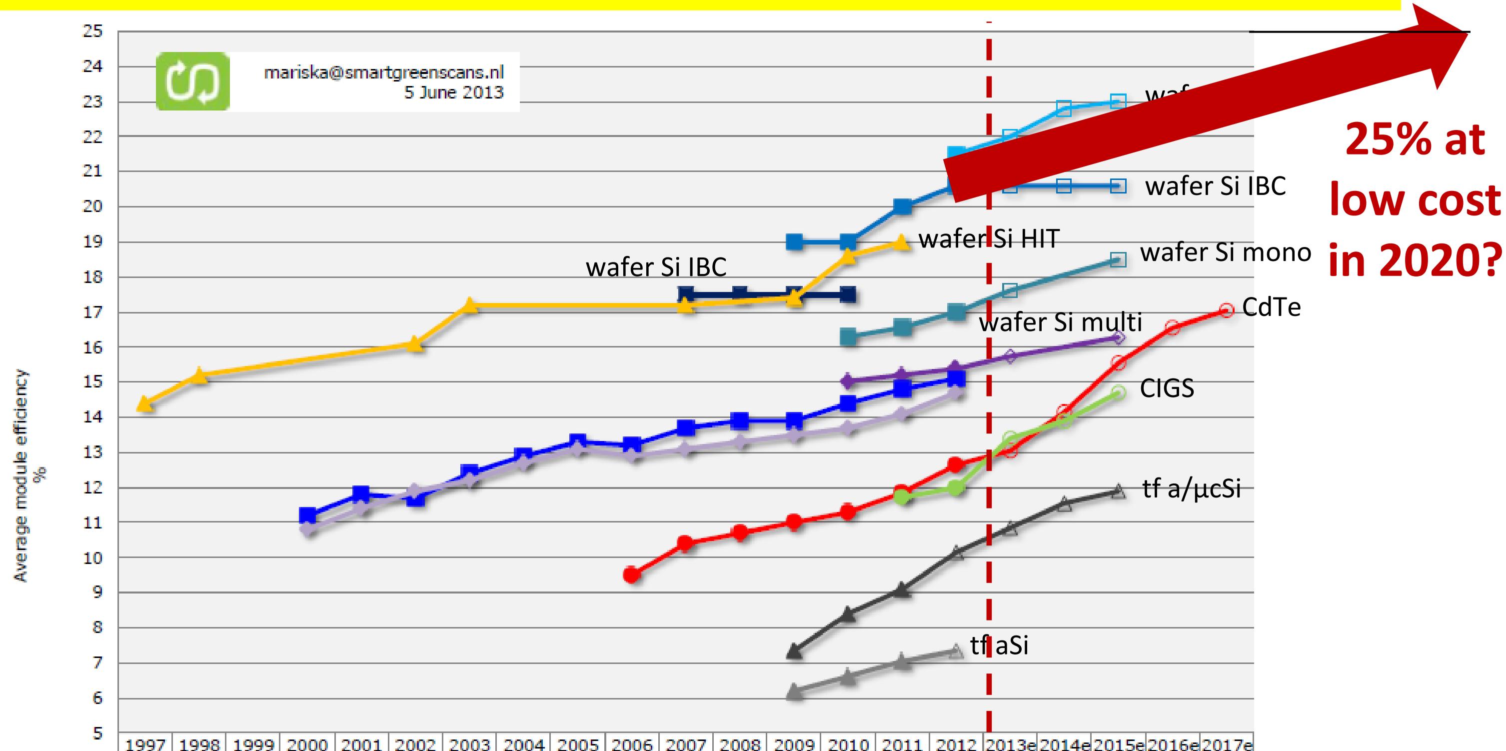


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M.J. de Wild-Scholten
SmartGreenScans
(June 2013)

# Towards and beyond 25% 1-sun module efficiency at competitive cost

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- Bring wafer-silicon technology to perfection (to 25%) – ST/MT
  - reduce process complexity and cost of current high-end technologies
  - combine key features of current high-end technologies (e.g. rear hetero-junction, rear contact)
  - use ultra-thin wafers + advanced light management
- Combine the best of two worlds (beyond 25%) - MT
  - high-efficiency wafer-silicon + wide-gap thin-film technology (2- or 4-terminal one-sun tandem)
- Novel routes (to and beyond 25%) - MT/LT
  - high-efficiency wafer-silicon + spectrum converters
  - other multi-gap approaches (bulk, quantum dots, nanowires, etc.)
  - other high-efficiency approaches ( multi carrier, hot carrier, intermediate band, etc.)

# Wafer-based silicon technologies: *a variety of options (selection)*

| Conductivity type | Crystal type | Contact geometry | Junction geometry | Junction type | Light collection | Identity |
|---|---|---|---|---|---|---|
| | | Front & rear | Front | Homo | Front | **Today's workhorse: monofacial** |
| | Multi | | | | Front & rear | **Today's workhorse: bifacial version** |
| P-type | | | | Hetero | Front | **HJT / HIT** *(today's high end)* |
| | | | | | Front & rear | |
| | Quasi-mono | | Rear | | | - |
| | | Rear | Front | Homo | Front | **Metal Wrap-Through (MWT)** *(emerging)* |
| N-type | | | | | Front & rear | |
| | | | | Hetero | Front | **HJ-MWT** *(novel)* |
| | | | | | Front & rear | |
| | Mono | | Rear | Homo | Front | **Interdigitated Back Contact (IBC)** *(today's high end)* |
| | | | | | Front & rear | |
| | | | | Hetero | Front | **HJ-IBC** *(novel)* |
| | | | | | Front & rear | - |

# Example: combine strengths of current high-end silicon technologies

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## Current Best Si Cells

| Maker (notes) | Efficiency | $V_{oc}$ (mV) | $J_{sc}$ (mA/cm$^2$) | FF | Source |
|---|---|---|---|---|---|
| Sanyo (HIT, 98 µm) | 24.7% | 750 | 39.6 | 83.2% | 39th IEEE PVSC (2013). |
| UNSW (diffused, 300 µm) | 25.0% | 706 | 42.7 | 82.8% | Zhou, *et. al.* APL **73,** (1998). |
| Best of: | 26.6% | 750 | 42 .7 | 83.2% | |

Maintain high $V_{oc}$ and $J_{sc}$

Bonna Newman - AMOLF (Dec. 2013) 6

# Advanced light management for high efficiency silicon cells

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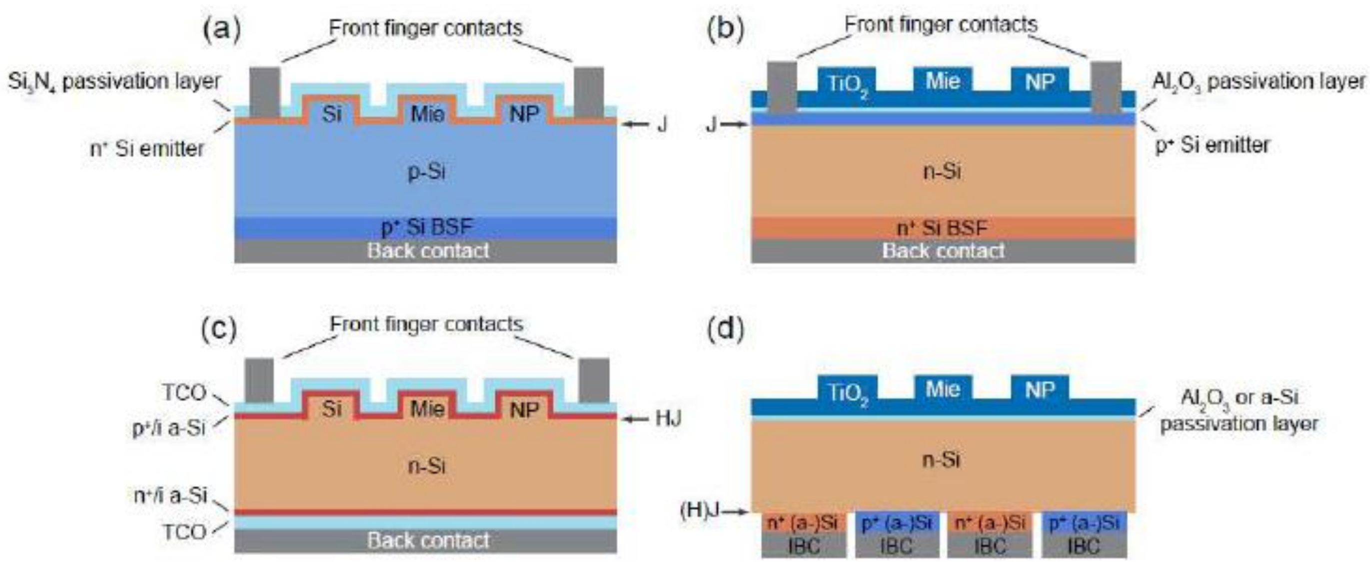
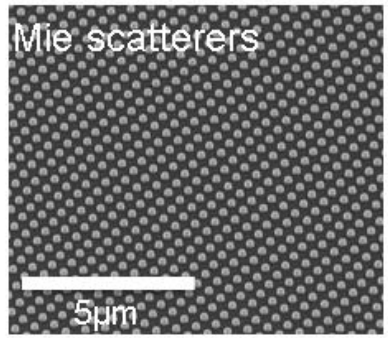
## Nanopatterned Si solar cell designs








Mie scatterer designs: slightly lower current than standard texture but higher voltage → opportunity to beat the 25% efficiency record

FOM Institute AMOLF

*Piero Spinelli, Bonna Newman*

# Towards and beyond 25% 1-sun module efficiency at competitive cost

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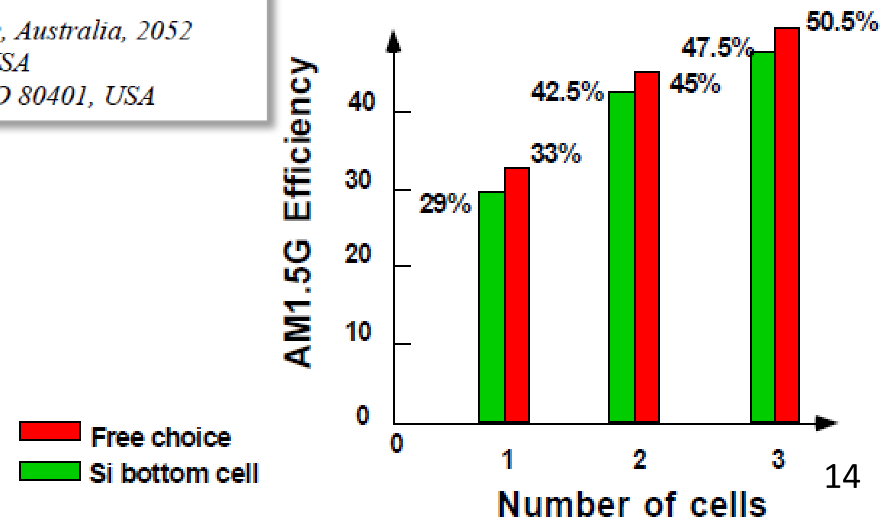
# Silicon wafer based tandems

28th European Photovoltaic Solar Energy Conference and Exhibition

**SILICON WAFER-BASED TANDEM CELLS:**
**THE ULTIMATE PHOTOVOLTAIC SOLUTION?**

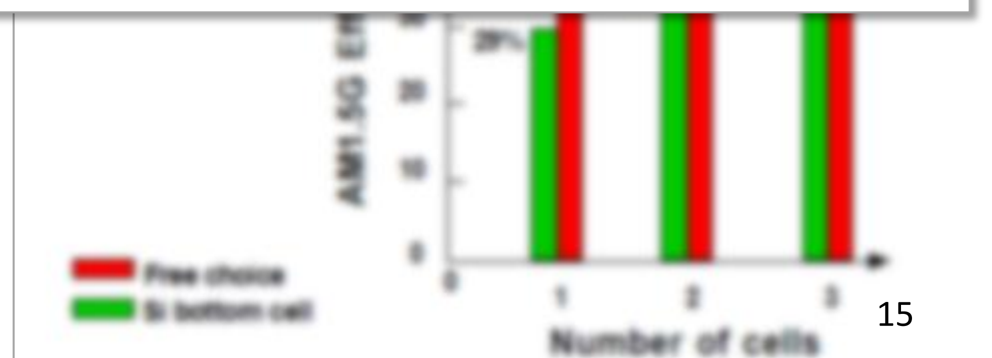
Martin A. Green[1] (Phone: +(61-2) 9385-4018; Fax: +(61-2) 9662-4240; Email: m.green@unsw.edu.au)
Xiaojing Hao[1]; Stephen Bremner[1]; Gavin Conibeer[1]; Ibraheem Al Mansouri[1]; Ning Song[1]; Ziheng Liu[1];
Steven A. Ringel[2]; J.A. Carlin[2]; T.J. Grassman[2]; B. Galiana[2]; A.M. Carlin[2]; C. Ratcliff[2]; D. Chmielewski[2];
L. Yang[2]; M.J. Mills[2]; Glenn Teeter[3]; Matthew Young[3]

[1] *Australian Centre for Advanced Photovoltaics, University of New South Wales, Sydney, Australia, 2052*
[2] *Ohio State University, 2015 Neil Avenue, Columbus, OH 43210-1272, USA*
[3] *National Renewable Energy Laboratory, 15013 Denver West, Parkway, Golden, CO 80401, USA*



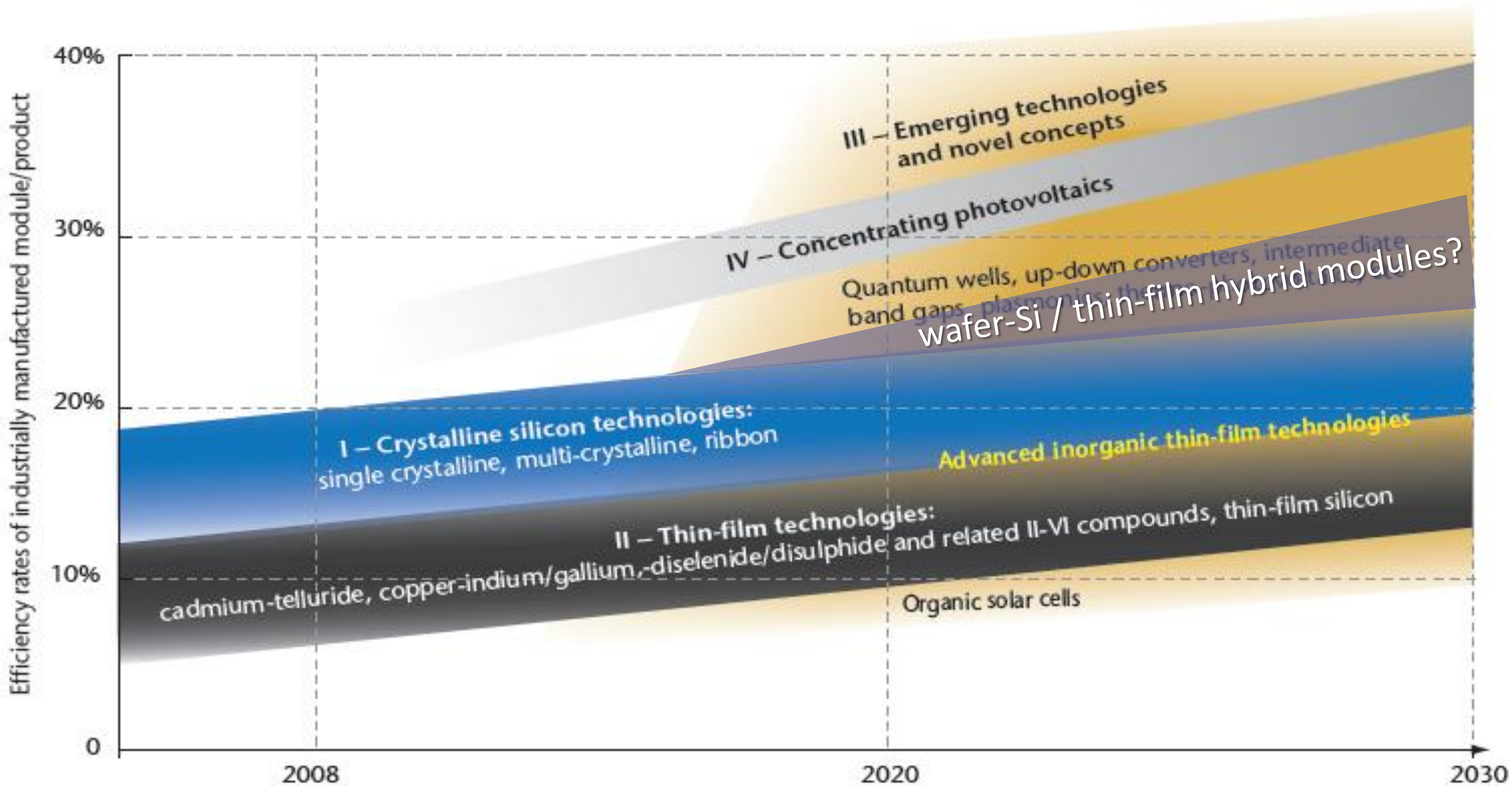
# Silicon wafer based tandems

ABSTRACT: On-going price reductions with wafer-based cells is making silicon technology increasing difficult to dislodge. With market leaders expected to be manufacturing modules above 16% efficiency at $0.36/Watt by 2017, even the cost per unit area ($60-$70/m$^2$) will be difficult for thin-film technologies to significantly undercut. This may make dislodgement likely only by appreciably higher energy conversion efficiency approaches. A silicon wafer-based cell able to capitalize on on-going cost reductions within the mainstream industry but with an appreciably higher than present efficiency might therefore provide the ultimate PV solution. With average selling prices of 156 mm quasi-square monocrystalline Si wafers recently approaching $1 (per wafer), wafers now provide clean, low cost templates for overgrowth of thin, wider bandgap high performance cells, nearly doubling silicon's ultimate efficiency potential. The range of Si-based tandem approaches are reviewed together with recent results and ultimate prospects.



# Commercial module efficiencies

## *History + long-term projections (simplified estimates)*




*Source*: IEA PVPS.

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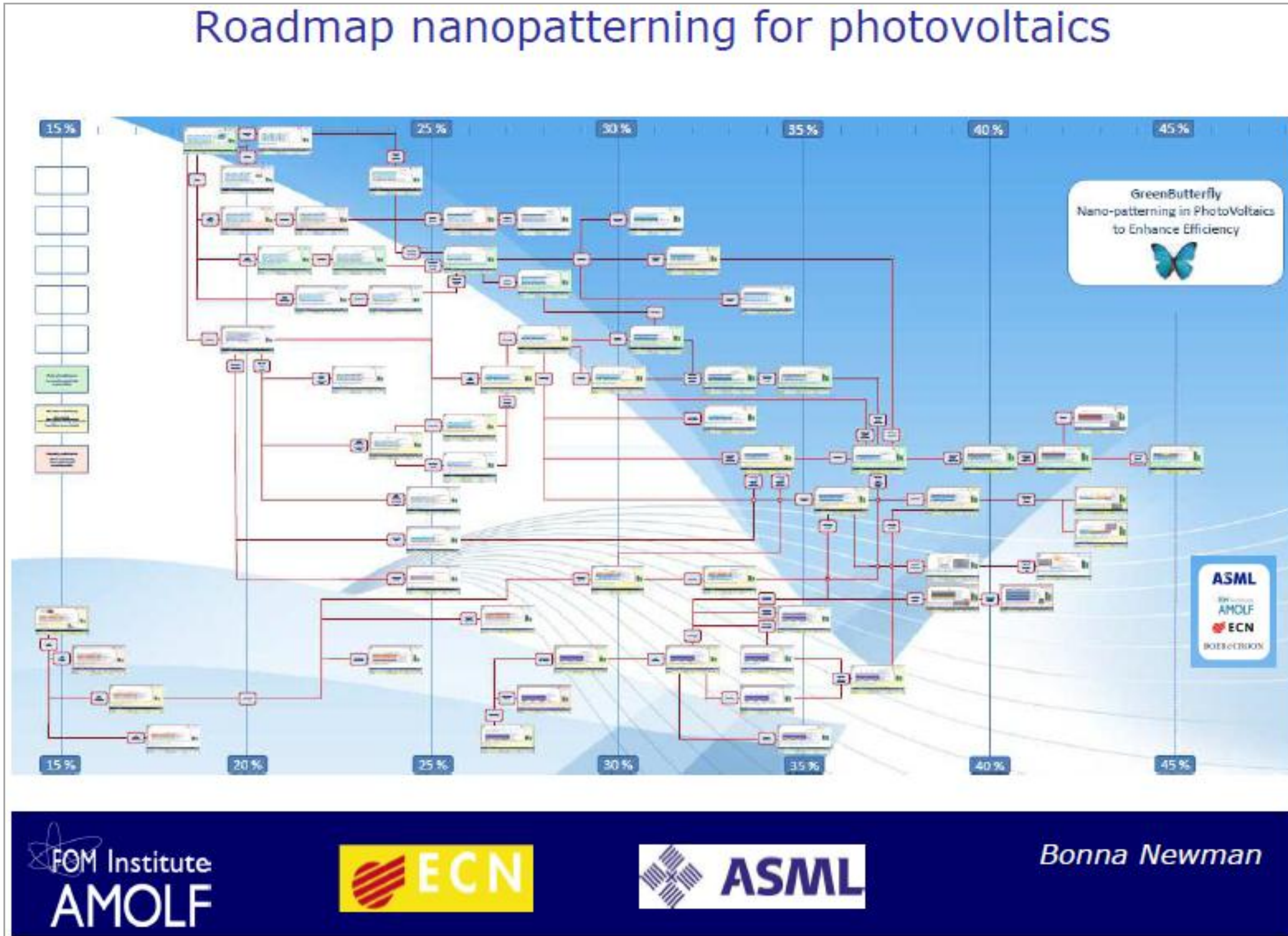
# Nanotechnology for high-efficiency PV: ECN
*finding the way in a jungle of options*

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used
applications
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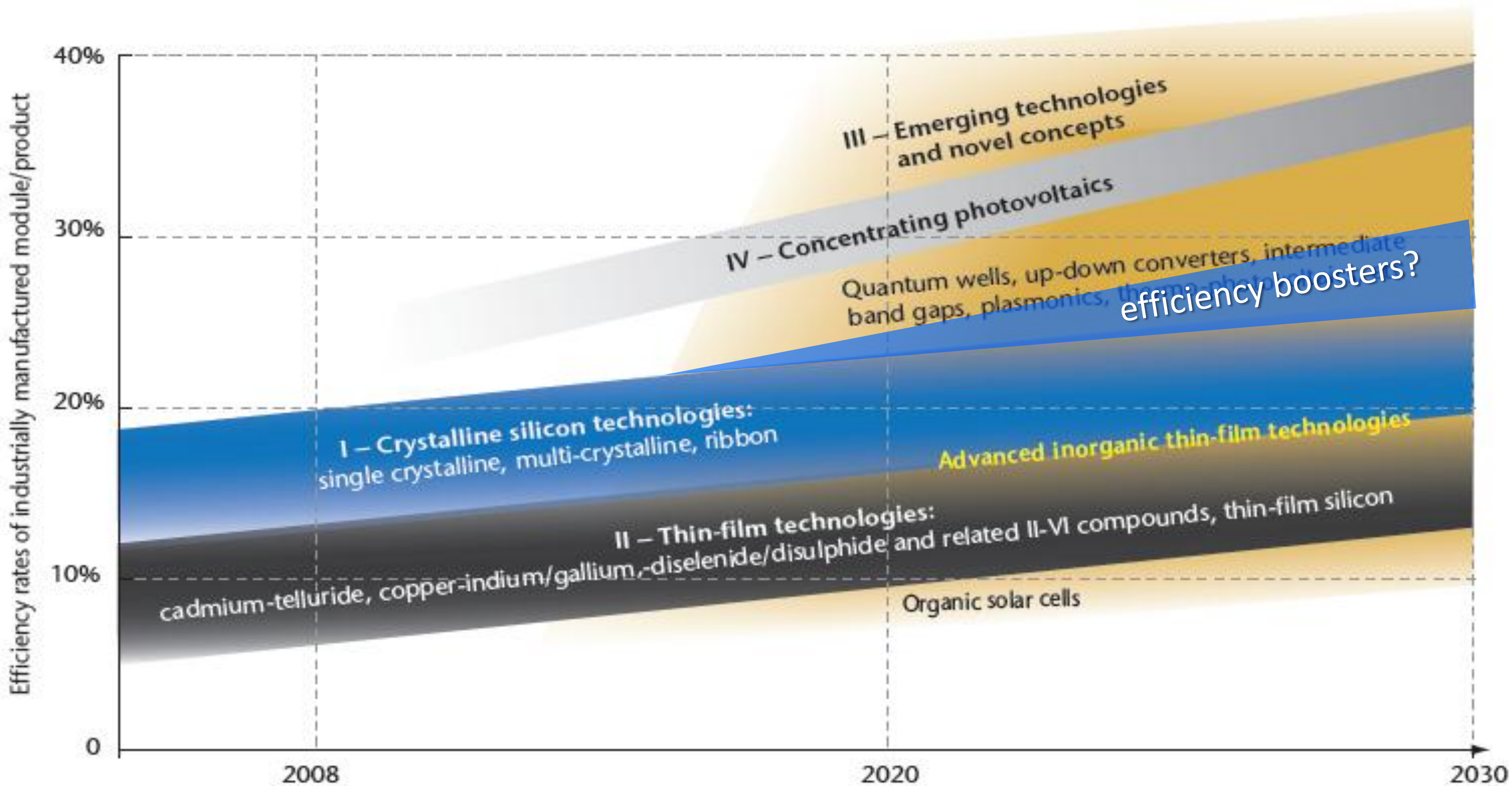
potential
solar
concerns
matter


WikiWorld® by Greg Williams
DISRUPTIVE TECHNOLOGY
is a technological innovation,
product or service that
eventually overturns the
existing dominant technology
or status quo product in the
market. For example,
automobiles displaced
horses for transport.
Early roads were designed
for horses, not cars.
Nevertheless, the potential
for greater convenience,
reliability and speed
offered by the motor car
meant that the road
system was eventually
redesigned in its favor.
The Eight Track marginalized the Record Player.
The Eight Track gave the ability to have music travel with you in the car.
The Compact Disc displaced the Cassette Tape, giving higher quality and cheaper production costs.
The Cassette Tape displaced the Eight Track, giving longer play times, a smaller size of player and media, and more functionality.
The Digital Audio Player is displacing the Compact Disc. From 15-20 songs per CD to hundreds and thousands of songs in a smaller form factor, with content that can be transferred effortlessly through the Internet.
Text excerpted from the Wikipedia article Disruptive technology.
21 May 2007


Breakthrough
Technology

# Commercial module efficiencies

## *History + long-term projections* *(simplified estimates)*




*Source*: IEA PVPS.

# Summary for discussion

- Compared to IEA PV Roadmap 2010:
  - wafer-based silicon technologies offer more possibilities for continued improvement
  - development and market introduction of “disruptive” technologies (even) tougher than expected – they are long-term options
  - the “end game” is between technologies with module efficiencies 25-50% and manufacturing costs 0.25-0.5 $/Wp, allowing system prices (incl. sustainable margins) well below 1 $/Wp

City of the Sun, Municipality Heerhugowaard, NL (photo Kuiper Compagnons)