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# Classical and new approaches to thin film photovoltaics

Claudio Manfredotti

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# World PV module production

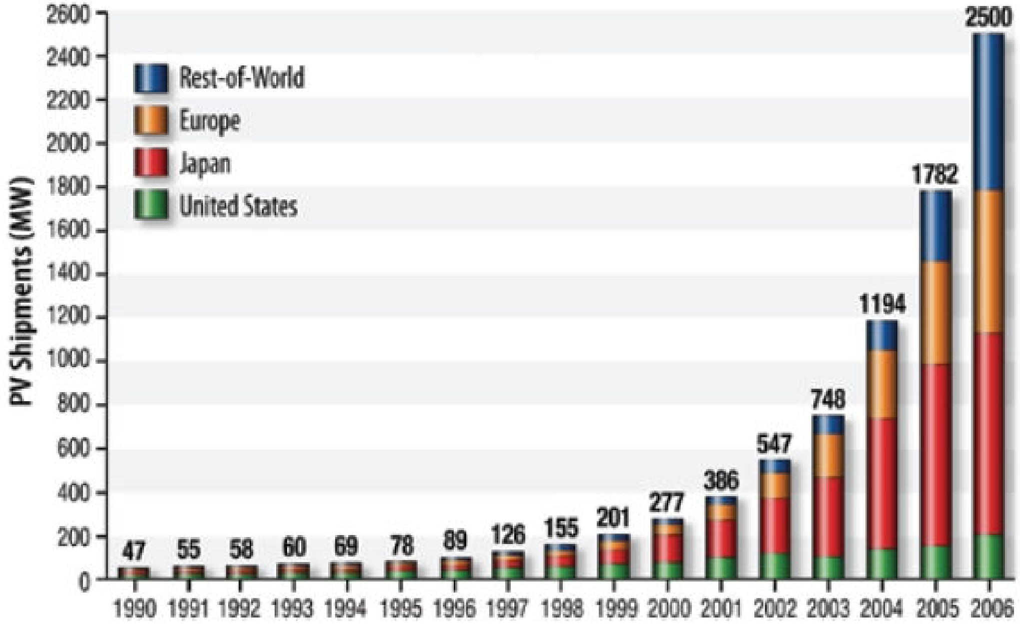


**Figure 1.** World photovoltaic module production (in megawatts), total consumer, and commercial per country (from *PV News*, Paul Maycock, Editor; February 2004). Most of this production is from crystalline or multicrystalline Si solar cells at present.

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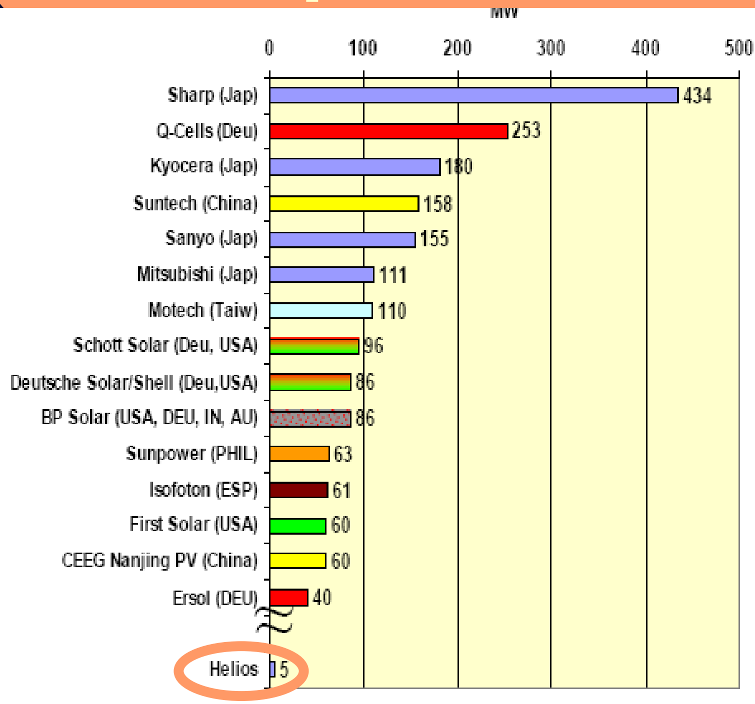
# PV companies in the world




| '06 vs '05 | Posizione '05 |
|---|---|
| 1% | 1 |
| 53% | 2 |
| 27% | 3 |
| 92% | 8 |
| 24% | 4 |
| 11% | 5 |
| 83% | 9 |
| 1% | 6 |
| 11% | 10 & 12 |
| 3% | 7 |
| 173% | NE |
| 15% | 11 |
| 200% | NE |
| 500% | NE |
| 100% | NE |
| 0% | 15 in Europa |

*Figura 6 – I maggiori produttori del mercato fotovoltaico mondiale 2006, i loro incrementi di produzione rispetto all'anno precedente e la posizione che occupavano nel 2005 (Fonte: PV News, Aprile 2007)*

# Public research centres in Italy

*Principali strutture pubbliche di ricerca nel settore fotovoltaico*

| Organizzazione | Aree di Ricerca & Sviluppo |
|---|---|
| ENEA | Tecnologie del silicio cristallino, a film sottile e a eterogiunzione. Sistemi a concentrazione. Qualificazione componenti e sistemi. Integrazione architettonica. Normativa. |
| CESI Ricerca | Tecnologie delle multigiunzioni III-V per applicazioni spaziali e terrestri a concentrazione. Sistemi. Normativa. |
| CNR IMM Bologna | Tecnologie del silicio cristallino a eterogiunzione. |
| CNR Bari | Tecnologie del silicio a film sottile. |
| CNR IMEM Parma | Tecnologie dei materiali III-V. |
| CNR ISOF Bologna | Tecnologie delle celle solari organiche. |
| CNR ISMAC Milano | Tecnologie delle celle solari organiche. |
| CNR IMM Lecce | Tecnologie dei materiali III-V, del silicio a film sottile e del termofotovoltaico. |
| Università di Milano Bicocca | Tecnologie del silicio cristallino e a film sottile. |
| Politecnico di Milano | Integrazione architettonica. |
| Politecnico di Torino | Tecnologia dei convertitori statici di potenza. |
| Università di Ferrara | Tecnologie del silicio cristallino. Celle dye-sensitized. Sistemi a concentrazione. |
| Università di Bologna | Tecnologie delle celle solari organiche. |
| Università di Parma | Tecnologie del CdTe e del CIGS a film sottile. Tecnologie dei materiali III-V. |
| Università di Firenze | Tecnologie per la produzione del silicio. |
| Università di Camerino | Tecnologie dei materiali III-V. |
| Università di Roma 1 | Tecnologie del silicio a film sottile e a eterogiunzione. |
| Università di Roma 2 | Tecnologie delle celle dye-sensitized. |
| Università di Napoli 1 | Tecnologie del silicio cristallino. Modellistica. |
| Università di Salerno | Modellistica e caratterizzazioni. Tecnologia dei convertitori statici di potenza. |
| Università di Palermo | Tecnologia dei convertitori statici di potenza. |
| CCR IES Ispra | Certificazione di moduli fotovoltaici. Normativa. |

Fonte : ENEA

# PV installations in Europe

*Tabella 4 – Potenza complessiva delle nuove installazioni di impianti fotovoltaici nei Paesi europei più impegnati, relativa agli anni 2005 e 2006 (Fonte EurObserv'ER, 2007)*

| Paesi | 2005 | 2006 |
|---|---|---|
| | nuove installazioni in MW | |
| Germania | 866 | 1153 |
| Spagna | 14,5 | 60,5 |
| Italia | 15,6 | 11,6 |
| Francia | 5,3 | 6,4 |
| Austria | 4,8 | 5 |
| Gran Bretagna | 2,7 | 2,7 |
| Belgio | 0,8 | 2,1 |
| Grecia | 0,9 | 1,2 |
| Svezia | 0,4 | 0,6 |
| Cipro | n.d. | 0,5 |
| Portogallo | 0,3 | 0,5 |
| Olanda | 1,7 | 0,4 |
| **Totale** | **913** | **1244,5** |

**1 % !**

Fonte : ENEA

# PV industrial production in Italy

*Tabella 7 – Capacità produttiva attuale e attesa delle principali compagnie impegnate nella produzione di celle e moduli fotovoltaici in Italia*

| Compagnia | Tecnologia | Capacità attuale (MW/anno) | Capacità attesa (2009) (MW/anno) |
|---|---|---|---|
| Enipower | celle cSi / moduli | 10 | 10 |
| Helios Technology | celle cSi / moduli | 8 | 40 |
| Istar solar | Moduli | 4,5 | 10 |
| Renergies | Moduli | 1,1 | 30 |
| SE Project | Moduli | 10 | 50 |
| Solarday | Moduli | 10 | 25 |
| Omnia Solar | celle cSi | 1 | 30 |
| XGroup | celle cSi / moduli | 1 | 100 |
| Soluxia | Moduli | | 12 |
| Elettrosannio | Moduli | 1 | 3 |
| Blu minipower | Moduli | | 10 |
| Solsonica | celle cSi / moduli | | 30 |
| Arendi | Moduli CdTe | | 18 |
| Totale | | 46,6 | 368 |

Fonte : ENEA

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# PV power in Italy

*Tabella 5 – Potenza cumulata relativa alle diverse tipologie di impianti fotovoltaici installati in Italia*

| Tipologia | 1987 | 1992 | 1997 | 2002 | 2007 (luglio) |
|---|---|---|---|---|---|
| off-grid industriali | 2,3 | 3,7 | 4,8 | 6,4 | 7,7 |
| off-grid domestici | 3,0 | 4,0 | 5,0 | 5,3 | 5,6 |
| on-grid centralizzati | 0,2 | 0,7 | 6,2 | 6,7 | 7,7 |
| on-grid distributi | 0,0 | 0,1 | 0,7 | 3,6 | 49,2 |
| Totale | 5,5 | 8,5 | 16,7 | 22,0 | 70,2 |
| Crescita media annuale | | 11% | 20% | 6% | 44% |

Fonte : ENEA

# Progress in PV energy conversion efficiency

NREL

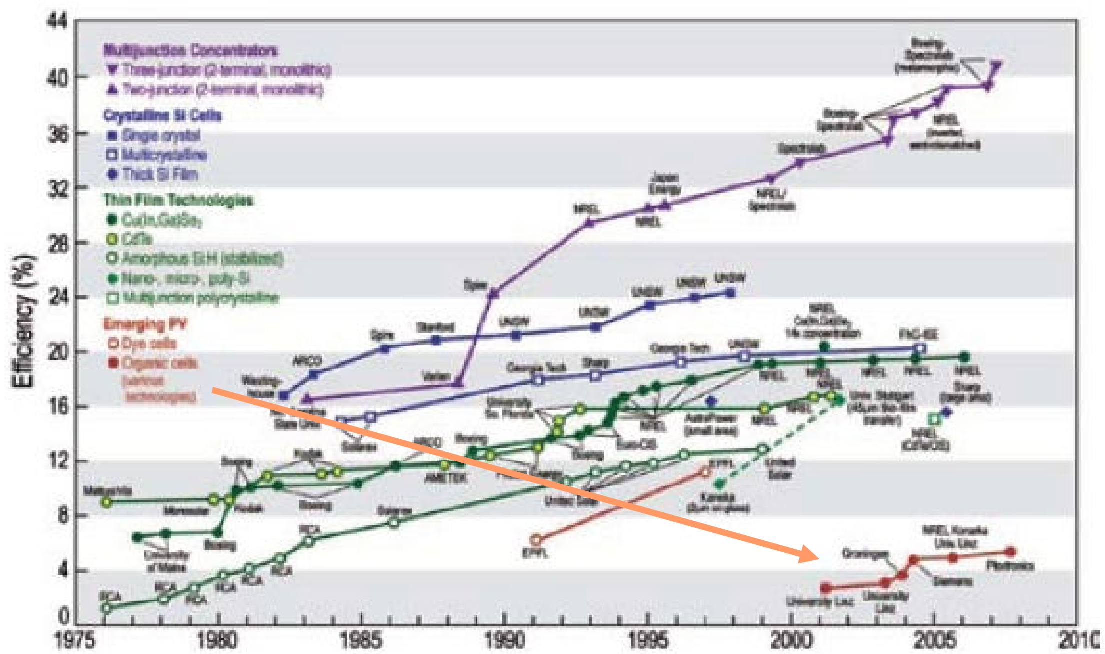


**Figure 3.** Progress of research-scale photovoltaic device efficiencies, under AM1.5 simulated solar illumination for a variety of technologies (as compiled by Larry Kazmerski, National Renewable Energy Laboratory).

- EFFICIENCY ?
- STABILITY ?
- COST ?

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# New technologies or just reducing the cost ?

SOLAR DAILY
one cell at a time

June 16, 2008

SolarDaily Advertising Kit

SOLARCELL

## Solar Cells Cost Could Fall Below One Dollar Per Watt By 2020

Dublin, Ireland (SPX) Jun 16, 2008
Conditions within the power industry have changed significantly in recent years. The rising cost of natural gas has made this an expensive source of power, while concern about global warming and the introduction of limits on CO2 emissions will have a profound effect on the use of coal for power generation, at least in the developed world. In consequence nuclear power has its best chance of ...
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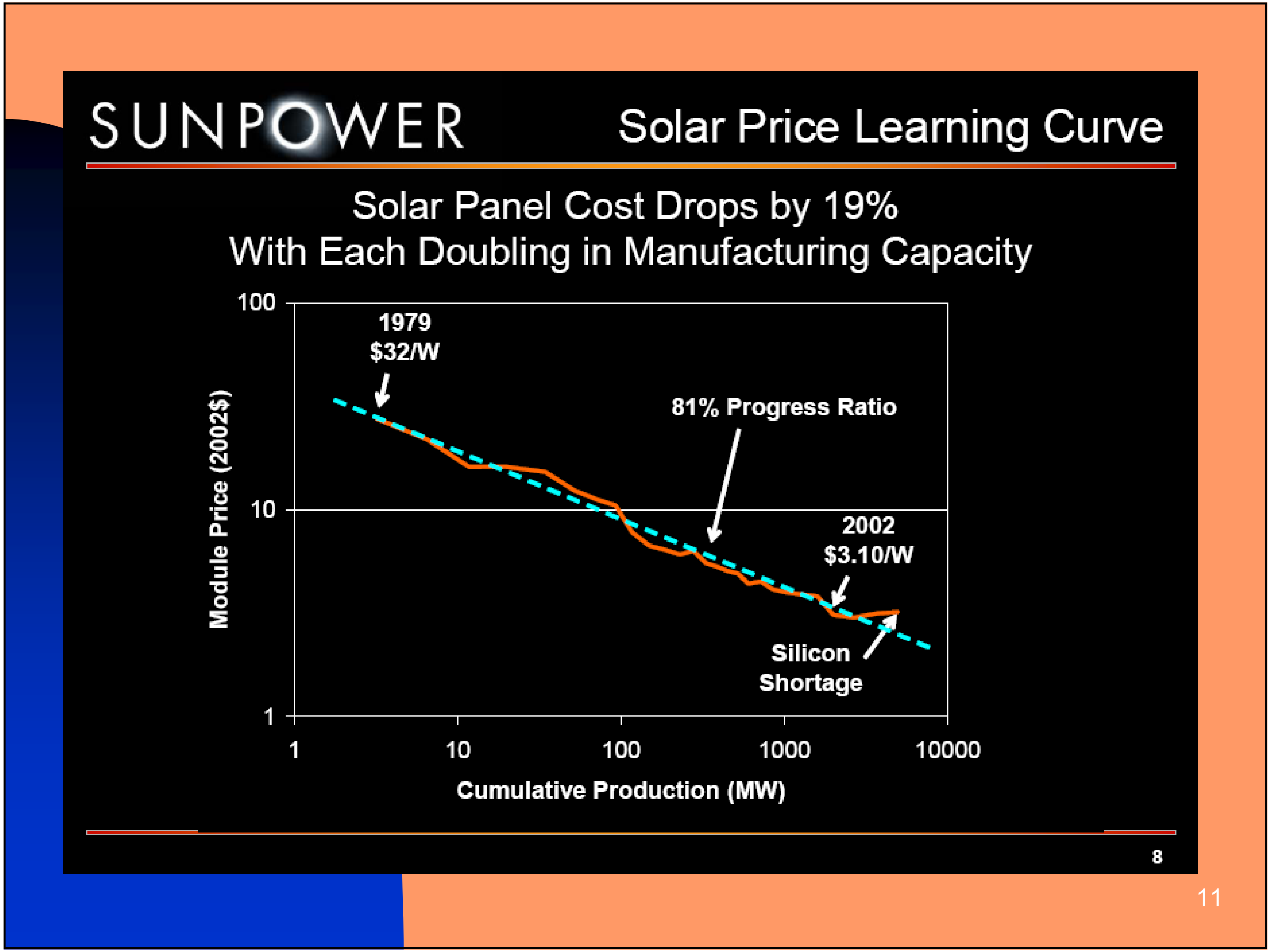
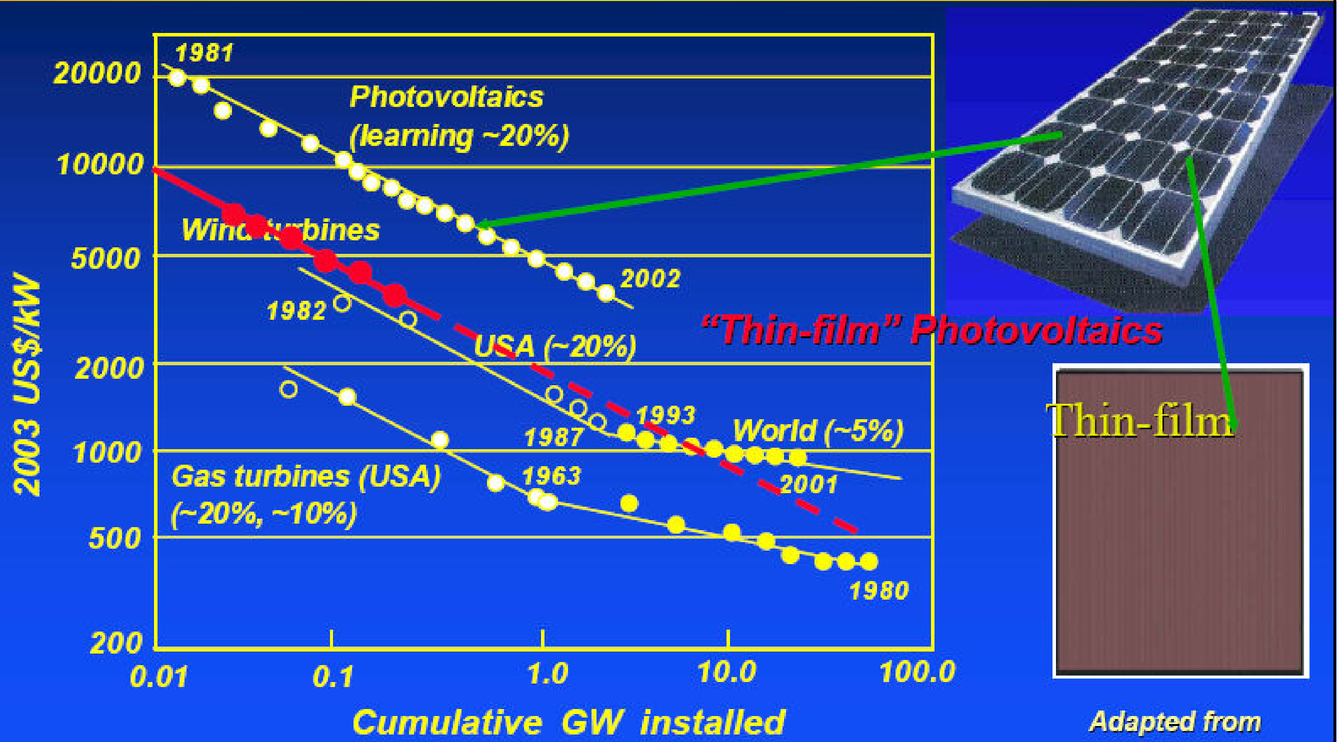
TERRA.WIRE

- Flood ravaged Iowa cleans up as waters recede
- US envoy says no 'G8 solution' to climate change
- Thousands evacuated as rains lash China quake region
- Radioactive traces found in Italy hospital waste: reports
- Food, environment to dominate G8 summit: Japan PM
- Losing just 15 buildings rips heart out of flooded Iowa town
- Climate change threatening coral reef fish: Australian researchers
- Flash floods, mudslides kill 25 in India's northeast
- China starts to evacuate up to 70,000 from quake zone over rain: report
- China starts to evacuate up to 70,000 from quake zone: report


SUNPOWER
Solar Price Learning Curve
Solar Panel Cost Drops by 19%
With Each Doubling in Manufacturing Capacity
1979
$32/W
81% Progress Ratio
2002
$3.10/W
Silicon
Shortage
Module Price (2002$)
100
10
1
1
10
100
1000
10000
Cumulative Production (MW)
8
11

# Cost reduction

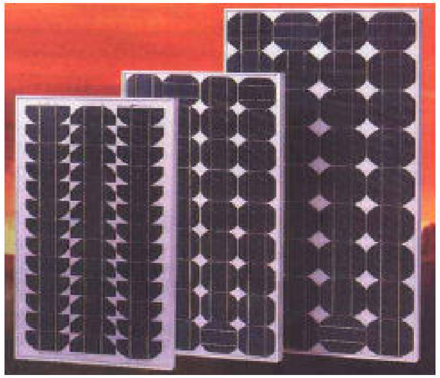


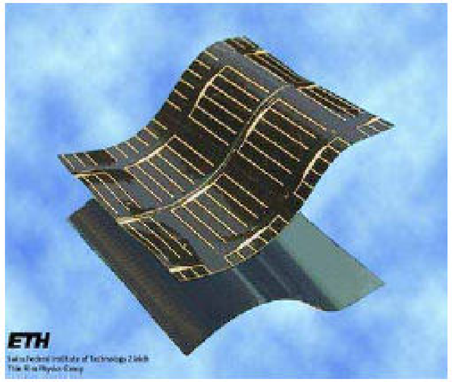

Adapted from
Grübler et al.,1999

UNSW

Photovoltaics - Electricity from Sunlight

## Solar cell technologies

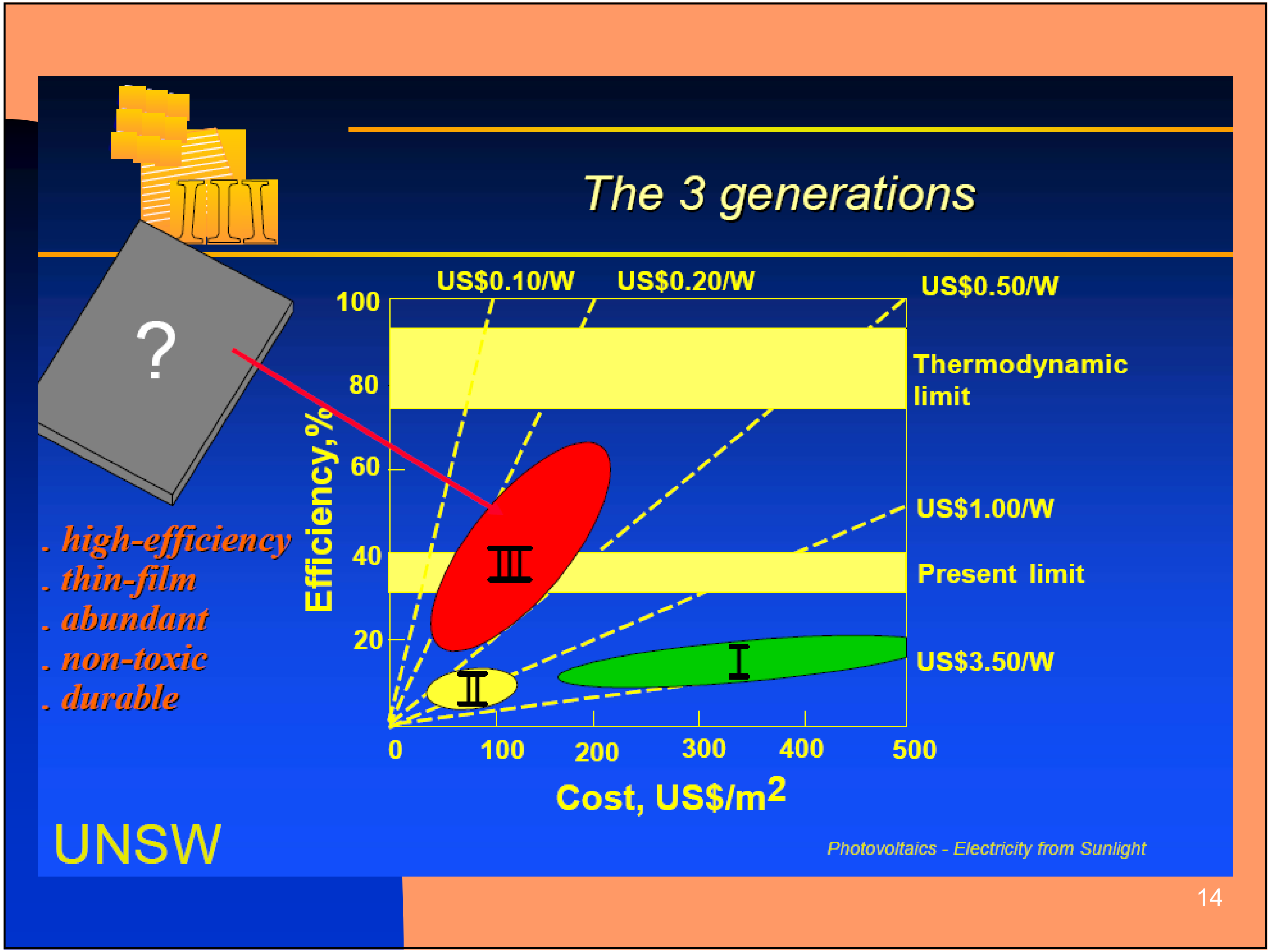


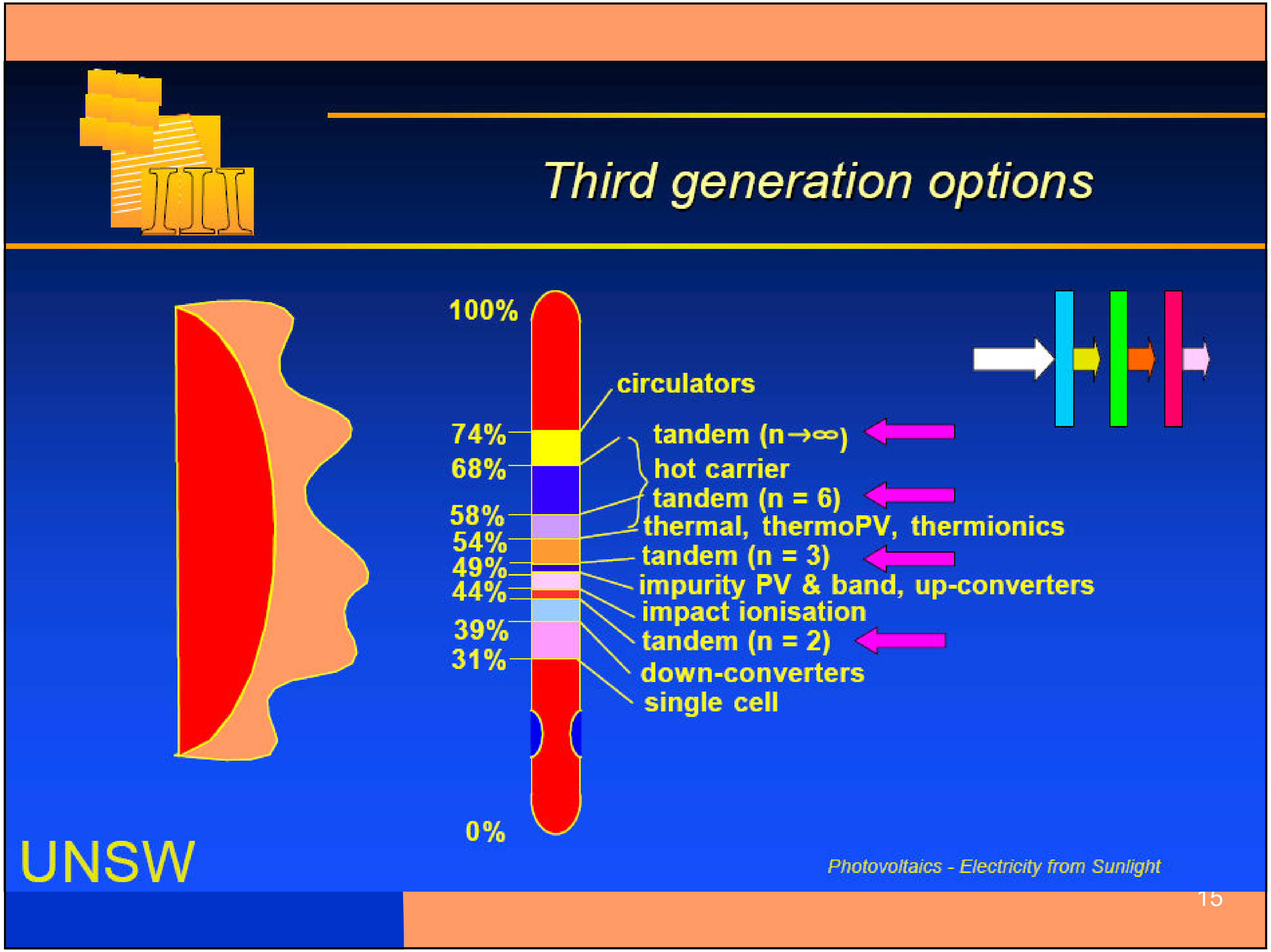



| 1st Generation | 2nd Generation | 3rd Generation |
|---|---|---|
| Silicon wafer | Thin-film on glass | Thin film – on plastic |
| • Thickness: > 250 μm | • Thickness: < 3 μm | • Thickness: < 3 μm |
| • Area limited by wafer size | • Large area deposition | • Large area possible |
| • Rigid | • Rigid | • Flexible |
| • Complex module integration | • Monolithic module integration | • Easy module integration |
| ⇒ Expensive | ⇒ Low cost potential | ⇒ Low cost potential |

Si wafer

1. Amorphous Si; 2. CdTe; 3. CIGS


The 3 generations
?
. high-efficiency
. thin-film
. abundant
. non-toxic
. durable
US$0.10/W
US$0.20/W
US$0.50/W
Thermodynamic limit
US$1.00/W
Present limit
US$3.50/W
Efficiency, %
100
80
60
40
20
0
100
200
300
400
500
Cost, US$/m2
III
II
I
UNSW
Photovoltaics - Electricity from Sunlight
14


Third generation options
100%
74%
68%
58%
54%
49%
44%
39%
31%
0%
circulators
tandem (n→∞)
hot carrier
tandem (n = 6)
thermal, thermoPV, thermionics
tandem (n = 3)
impurity PV & band, up-converters
impact ionisation
tandem (n = 2)
down-converters
single cell
UNSW
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# Possible future scenarios

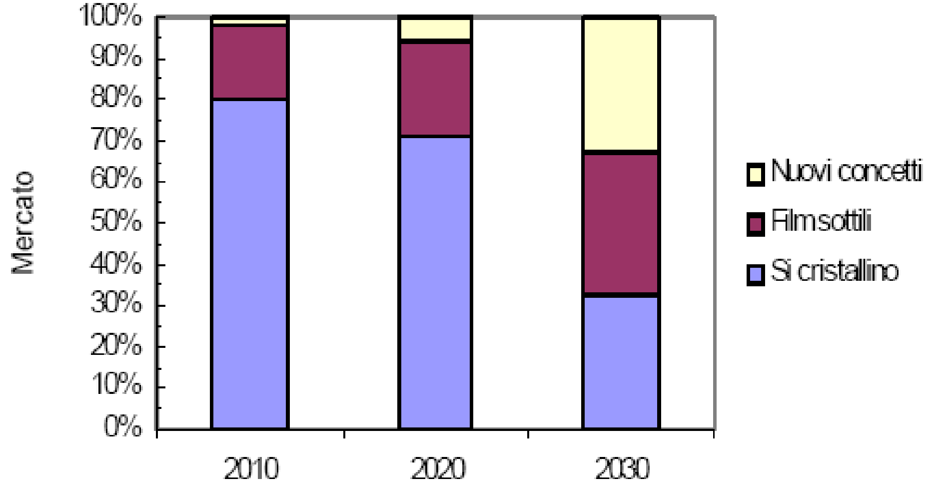
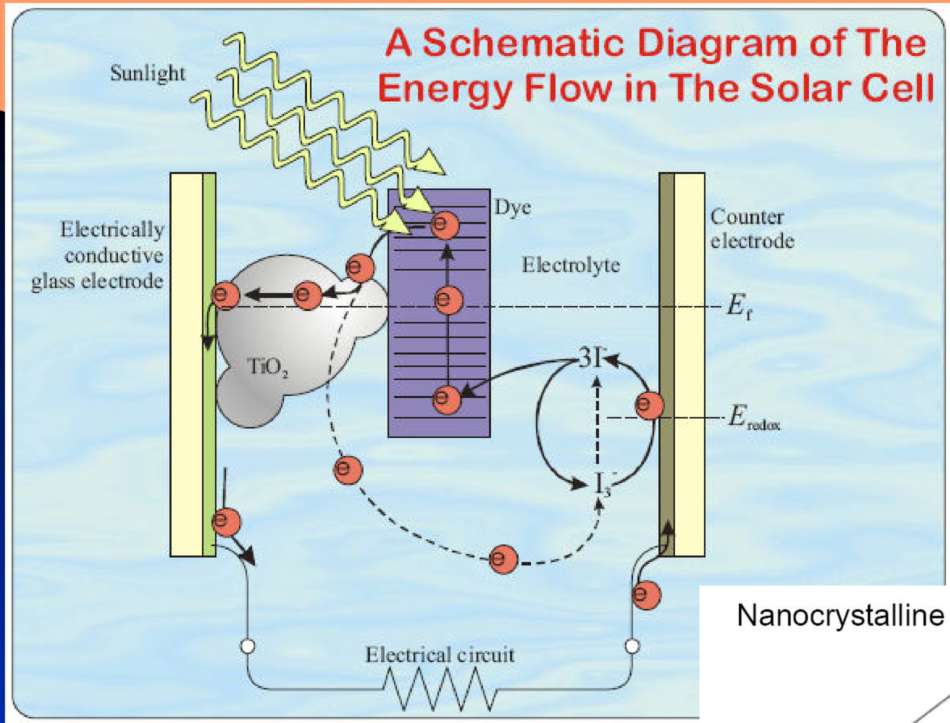



*Figura 4 – Previsioni della ripartizione del mercato per tecnologie a breve, medio e lungo termine. Tra i nuovi concetti, oltre alle tecnologie emergenti è compreso il fotovoltaico a concentrazione (Fonte: EPIA, 2007)*

Fonte : ENEA



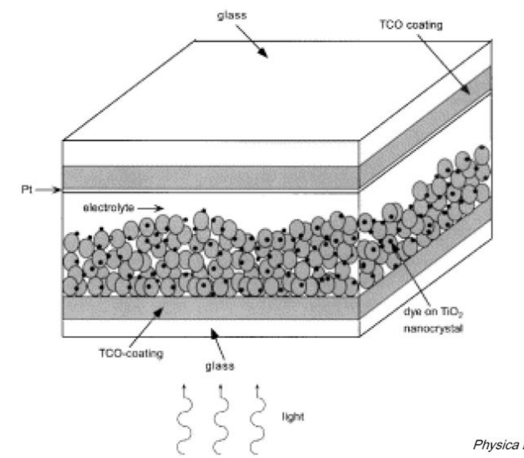

*DSSC*

Dye Sensitized

Solar

Cells

Nanocrystalline $TiO_2$ dye-sensitised solar cell




*Physica E 14 (2002) 11 – 17*

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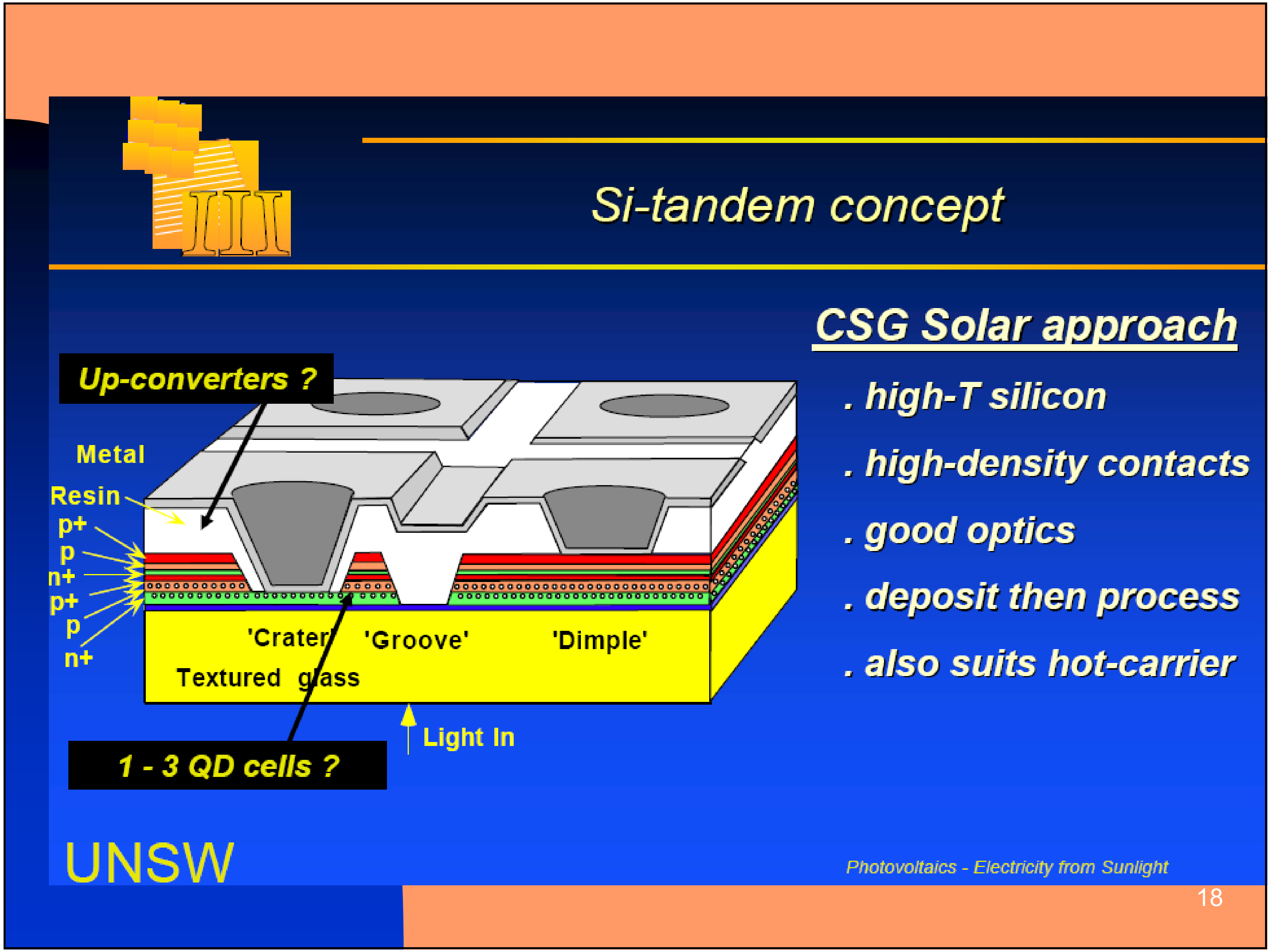

Si-tandem concept
CSG Solar approach
. high-T silicon
. high-density contacts
. good optics
. deposit then process
. also suits hot-carrier
Up-converters ?
Metal
Resin
p+
p
n+
p+
p
n+
'Crater'
'Groove'
'Dimple'
Textured glass
Light In
1 - 3 QD cells ?
UNSW
Photovoltaics - Electricity from Sunlight
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# High efficiency Si solar cells

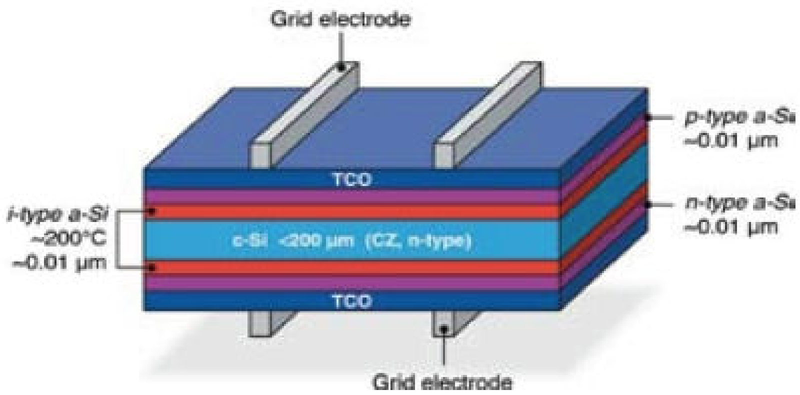
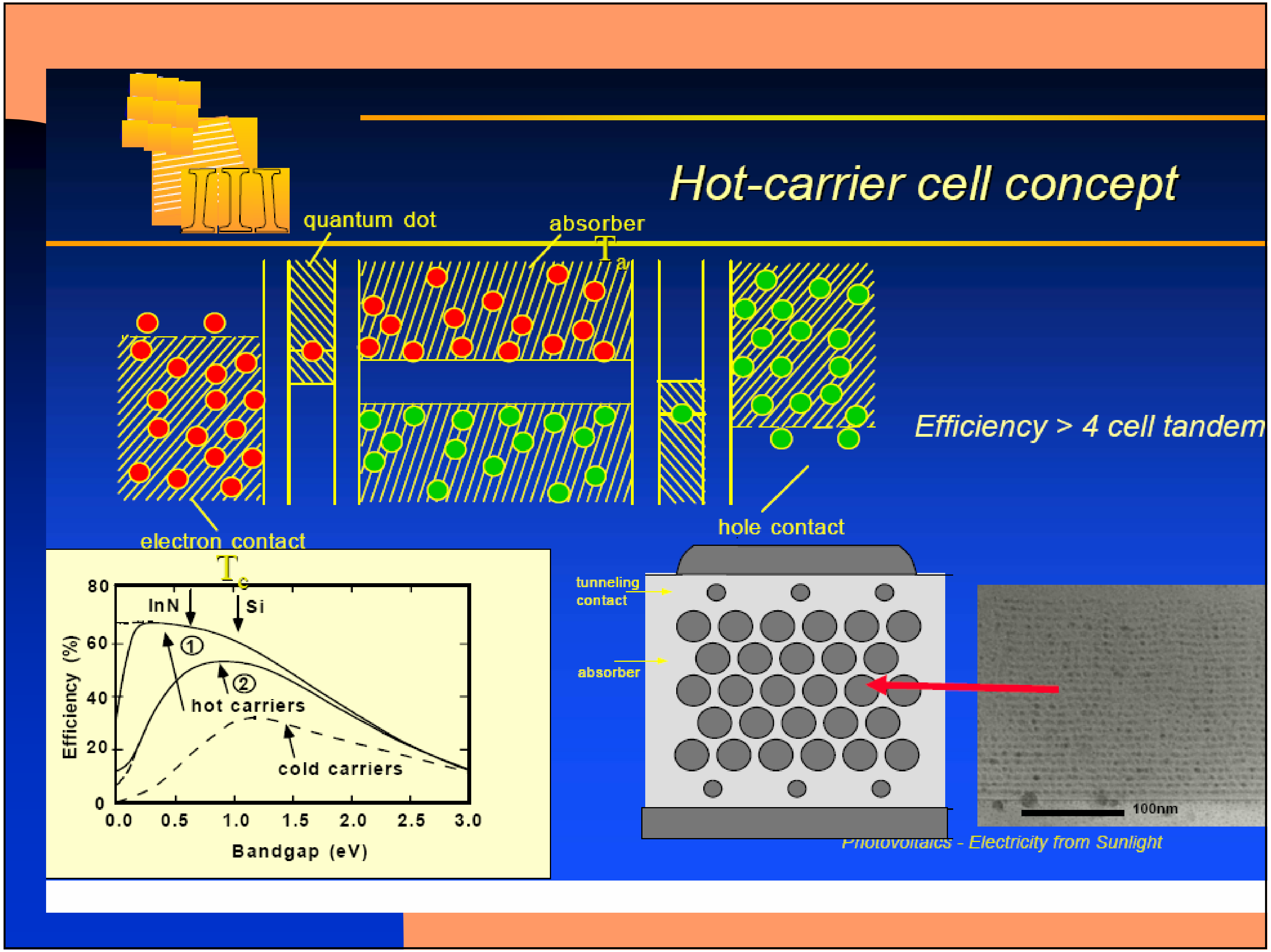



**Figure 2.** Illustration of the Sanyo heterojunction with intrinsic thin layer (HIT) cell that is based on crystalline Si and has demonstrated a 22% efficiency. TCO means transparent conducting oxide, typically used as a contact, and CZ indicates Czochralski-grown, which means pulled from the melt as a single crystal. The three types of amorphous silicon (a-Si) included in the cell differ in the types of dopants (or impurities) that have been added: *i*-type (or intrinsic) is undoped, *n*-type contains a dopant (such as phosphorous) that increases the number of free negative charge carriers (i.e., electrons), and *p*-type contains a dopant (such as boron) that increases the number of free positive charge carriers (i.e., holes). The types and amounts of impurities in the silicon affect its conductivity and other properties.



Hot-carrier cell concept
quantum dot
absorber
$T_a$
electron contact
$T_c$
hole contact
Efficiency > 4 cell tandem
Efficiency (%)
Bandgap (eV)
InN
Si
①
②
hot carriers
cold carriers
tunneling contact
absorber
100nm
Photovoltaics - Electricity from Sunlight

# Quantum Dots Solar Cells ( Nozik, NREL )

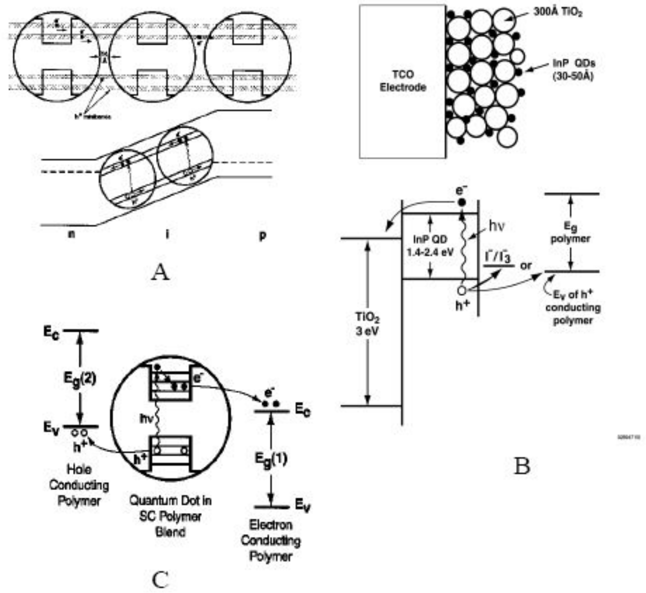



Fig. 1. Configurations for quantum dot solar cells. (A) a QD array used as a photoelectrode for a photo-electrochemical or as the i-region of a p-i-n photovoltaic cell; (B) QDs used to sensitize a nanocrystalline film of a wide bandgap oxide semiconductor (viz. $TiO_2$) to visible light. (C) QDs dispersed in a blend of electron- and hole-conducting polymers.

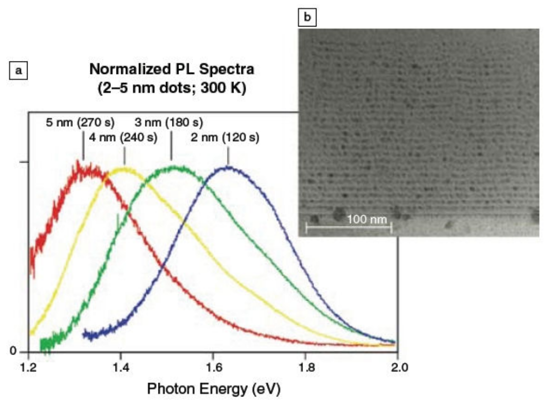



**Figure 12.** Silicon quantum dots in an oxide material (micrograph) and resulting photoluminescence (PL) spectra as a function of quantum dot diameter. (a) Different particle sizes and associated PL wavelengths and (b) high-resolution transmission electron microscope image of the 5-nm particles for illustration. Numbers in parentheses represent lifetime in microseconds.

# Multi-exciton generation (MEG)

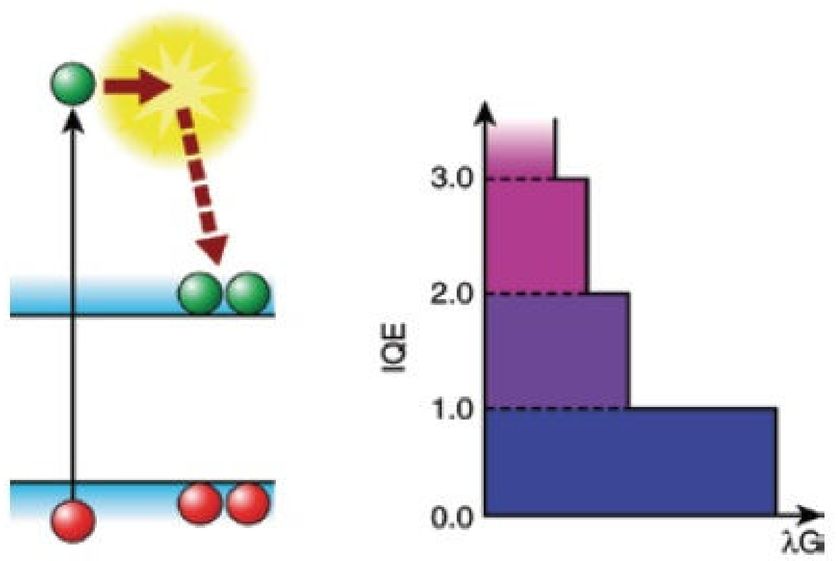



**Figure 15.** Impact ionization whereby more than one carrier pair is created by an incident photon (left), leading to the ideal internal quantum efficiency (IQE) as a function of excitation wavelength (λG) (right).

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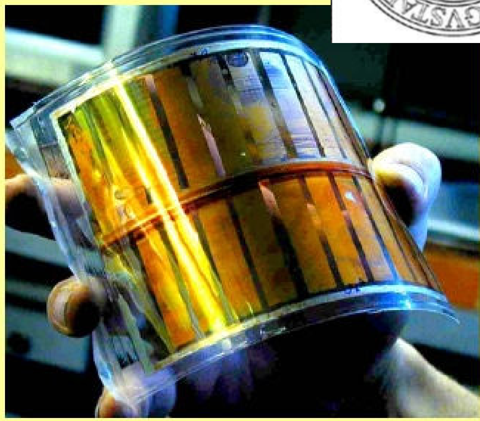
WWW.SKIRAMA.IT

TRENTINO ITALIA

FOLGARIA - LAVARONE SCIARE

CENTRO FONDO Passo Coe



# First European School on Thin Film Photovoltaics

Folgaria ( Tn)

12 -17 january 2009


24

# 2007 market

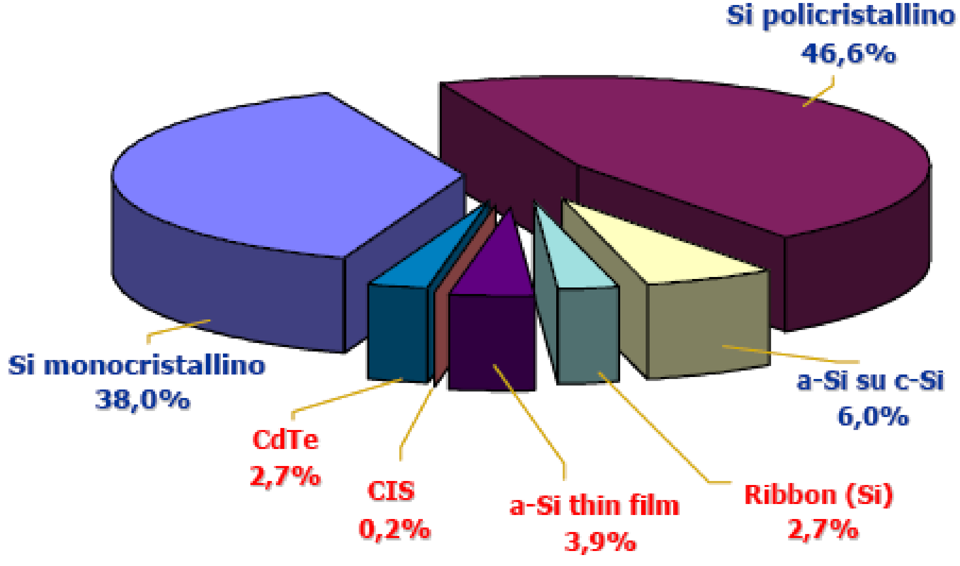
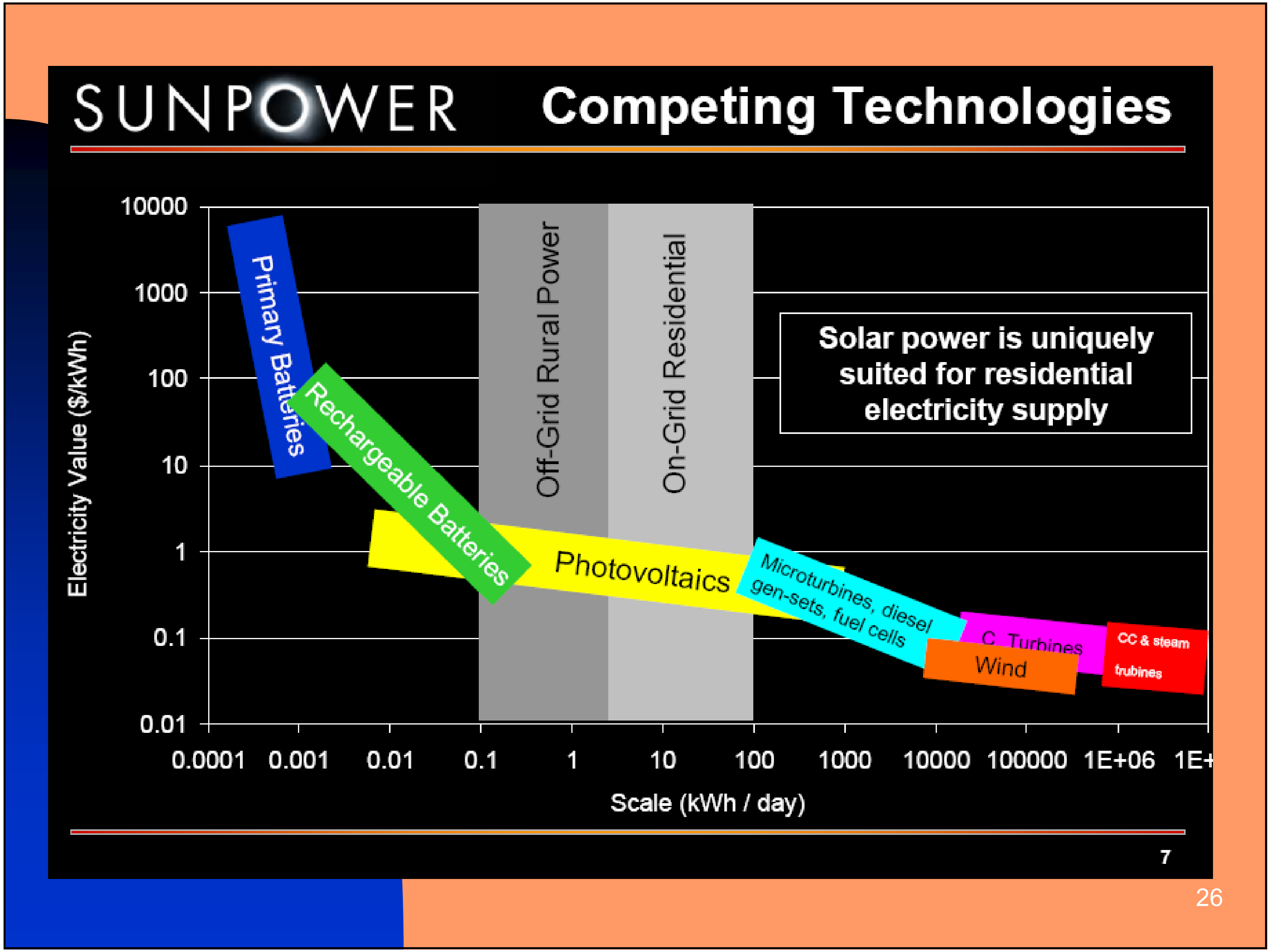



*Figura 1 – Ripartizione per tecnologie della produzione fotovoltaica mondiale (Fonte: PV News, Aprile 2007)*

Fonte : ENEA


SUNPOWER
Competing Technologies
Electricity Value ($/kWh)
10000
1000
100
10
1
0.1
0.01
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
100000
1E+06
1E+
Scale (kWh / day)
Primary Batteries
Rechargeable Batteries
Off-Grid Rural Power
On-Grid Residential
Photovoltaics
Microturbines, diesel gen-sets, fuel cells
C. Turbines
Wind
CC & steam trubines
Solar power is uniquely suited for residential electricity supply
7
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# Multi-junction solar cells

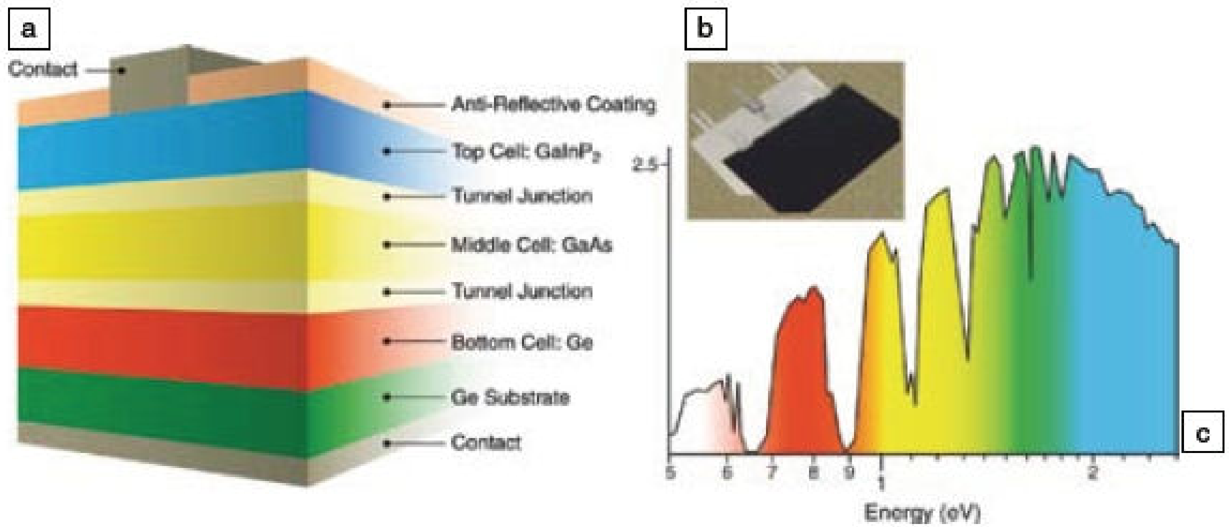


**Figure 8.** (a) Schematic of a possible configuration for a three- (triple-) junction device and (b) picture of a GaInP/GaAs/GaInAs cell with a demonstrated 31.3% efficiency. (c) Solar spectrum illustrating the basic approach for spectrum splitting by a multijunction cell. A four-junction device with bandgaps of 1.8 eV, 1.4 eV, 1.0 eV, and 0.7 eV would have a theoretical efficiency of >52%.

# Thermodinamic limits

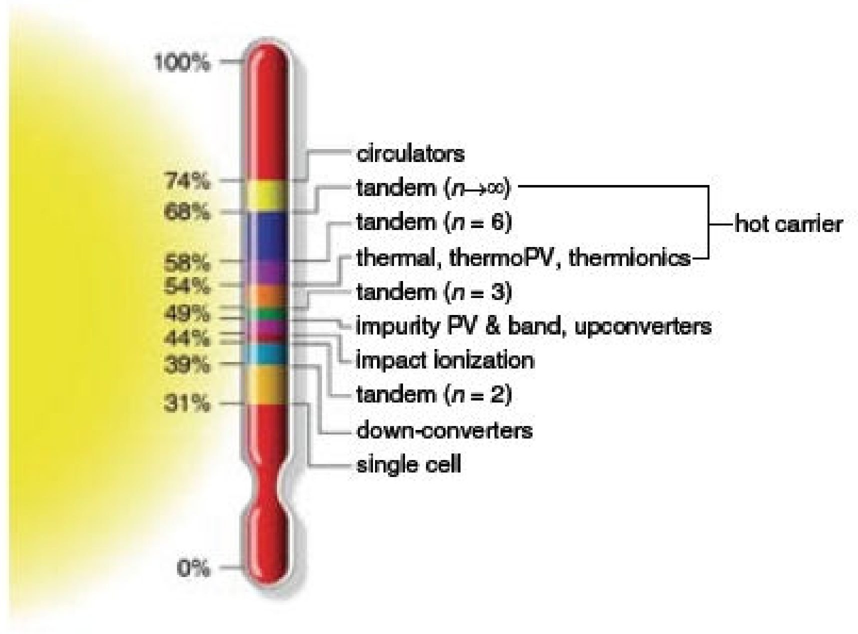


**Figure 13.** Third-generation options and thermodynamic limits on their efficiency. Upconverters include multi-excitonic approaches. *Note: n* is the number of cells in the stack.

# Hot carriers approach

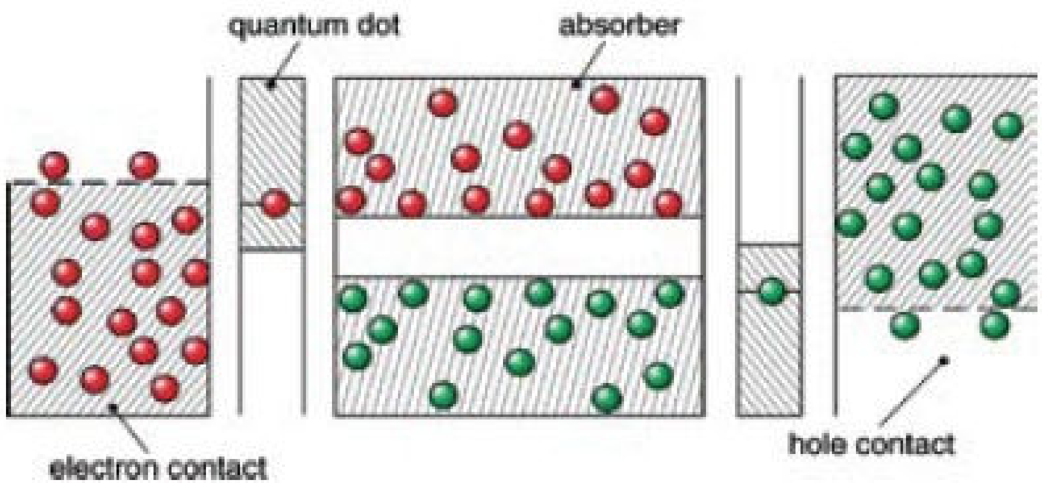


**Figure 14.** Hot-carrier cell schematic. Special properties are required for both the absorption volume and the carrier collection contacts.

# CdTe and CIGS solar cells

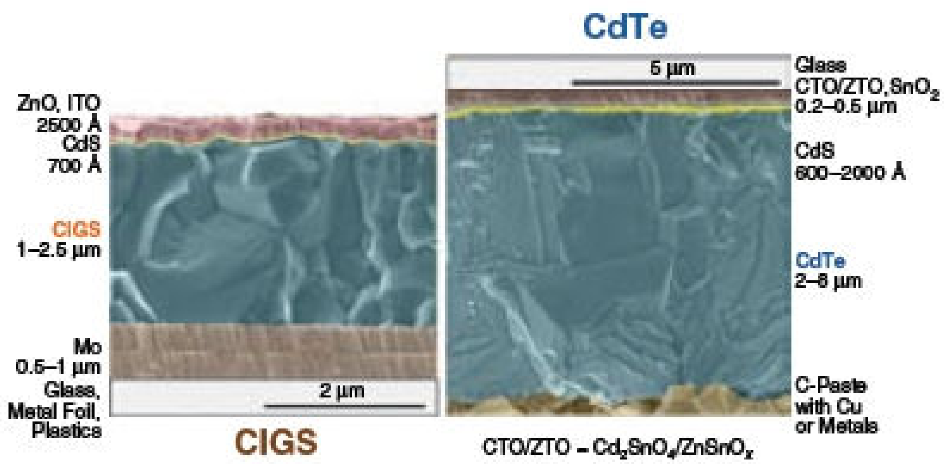


**Figure 11.** Cross-sectional scanning electron microscopy images of a Cu(InGa)$Se_2$ (CIGS) solar cell (left) and a CdTe cell (right). The absorber layers are 1–2.5 and 2–8µm thick, respectively. CTO (cadmium tin oxide) and ZTO (zinc tin oxide) are transparent conducting oxides used as transparent electrical contacts to the solar cell.

# Projected costs of PV modules

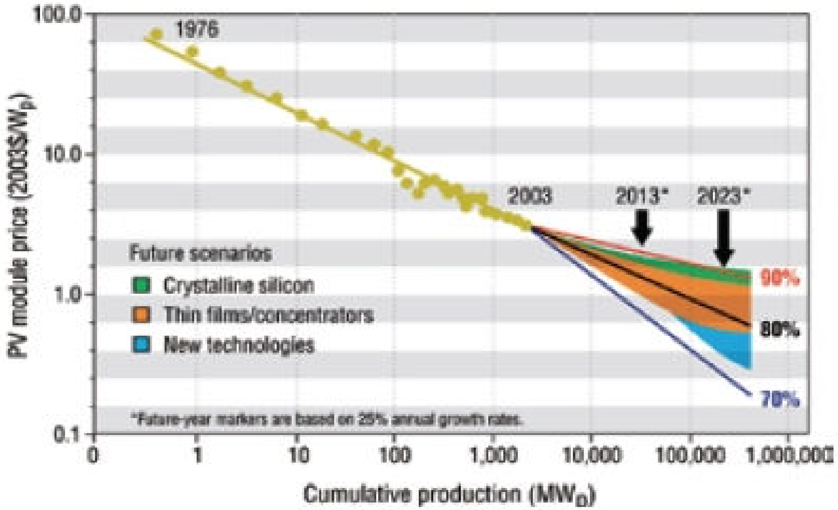


**Figure 4.** Historical and projected costs for wafer and film c-Si photovoltaic modules versus their cumulative production (in megawatts). Extrapolations for future technologies are also shown (from References 5 and 6). The 70%, 80%, and 90% curves represent learning curves for the technology; the lower the percentage, the more rapid the learning, and the more rapid the price decrease with increasing production.

# Flexible solar cells