Nanotechnologie na km^2

aneb
o fotovoltaice v perspektivách

A. Fejfar

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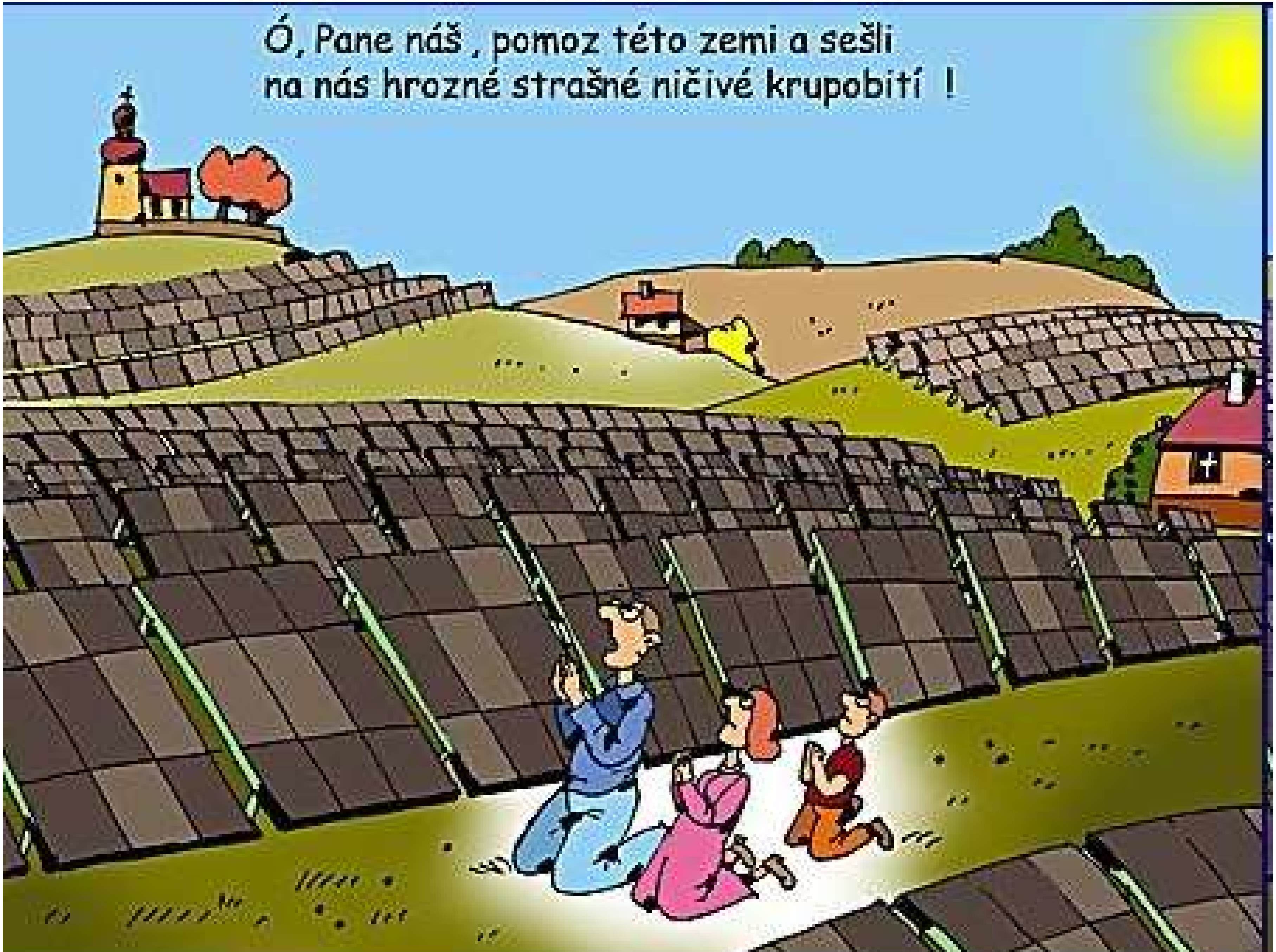
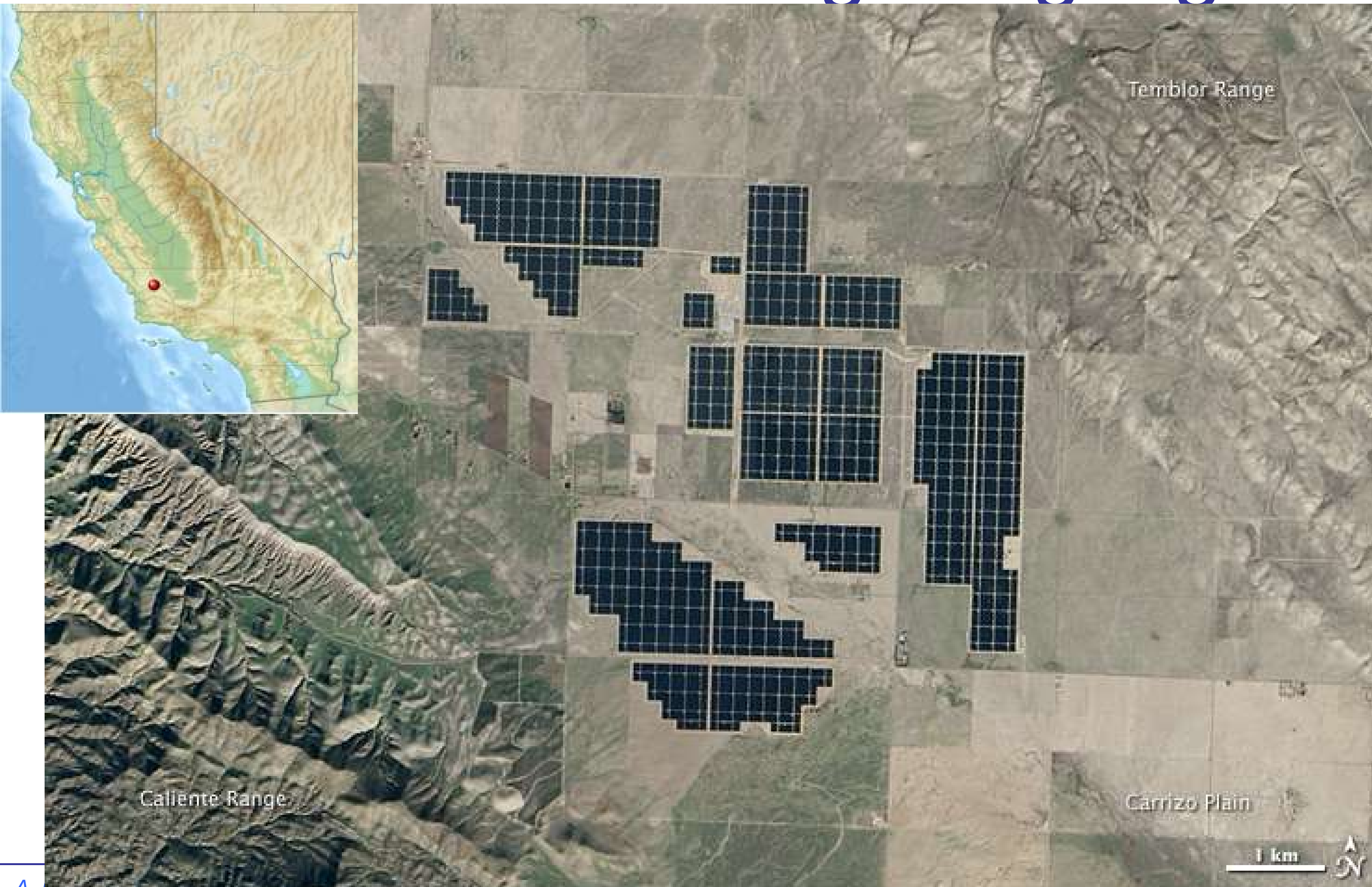
Cukrovarnická 10, 162 53 Praha 6, * e-mail: fejfar@fzu.cz


Ó, Pane náš , pomoz této zemi a sešli
na nás hrozné strašné ničivé krupobití !

Photovoltaics is getting big



Energie

Průměrná americká rodina obklopená barely ropy, které spotřebuje za rok.

Obrázek je z roku 1970.

Dnes by jejich spotřeba byla asi o 40% větší.

A každý chce žít jako Američan.

Terawattová výzva

Průměrná spotřeba lidské civilizace je 15 TW (15000 GW).

Průměrně spotřebuje průměrný občan:

~11 kW / U.S.A

3 – 5 kW / Evropan

~ 1 kW / Číňan

---

2 kW / průměrný obyvatel planety

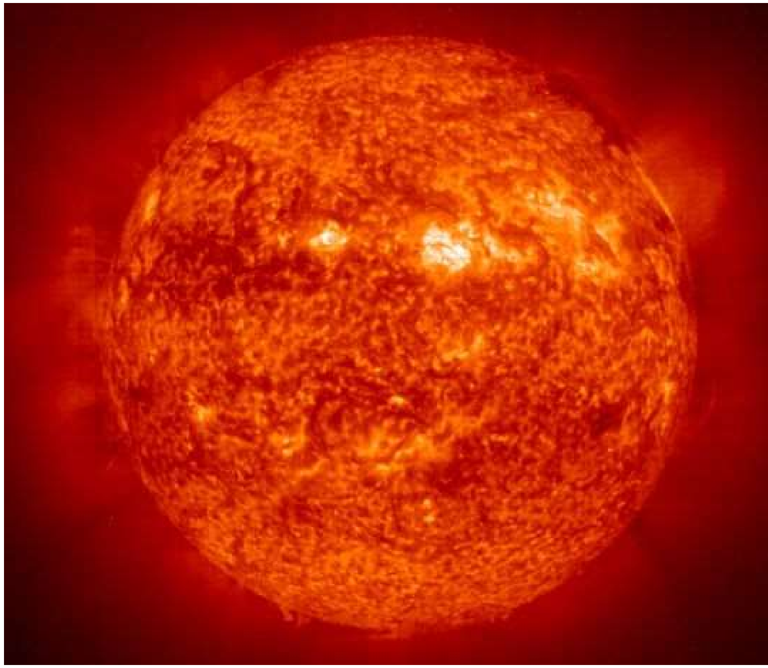
Dobrá zpráva: Počet obyvatel Země se ustálí na cca 10 mld.
Špatná zpráva: většina z nich bude spotřebovávat víc energie.
Při odhadovaných 4 kW / člověka = 40 TW.

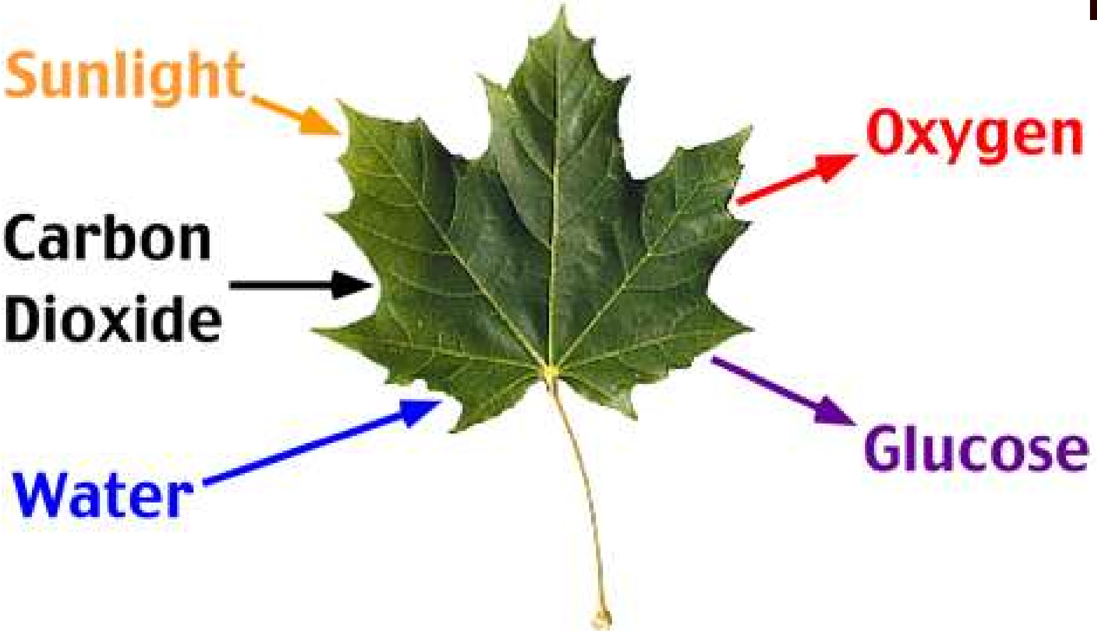
Přidání 10 TW znamená:

- Spuštění 1 GW elektrárny každý den po dobu 27.5 roků

2 MW FV elektrárna
Každých10 minut
po dobu 81 roků

125 000 TW



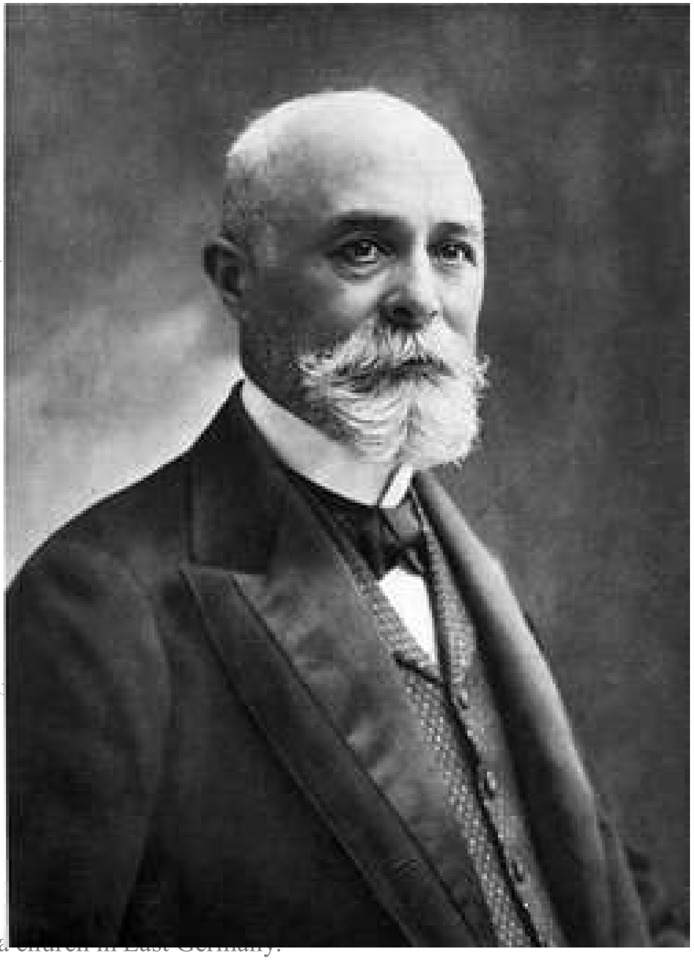

Sunlight
Carbon Dioxide
Water
Oxygen
Glucose


This photograph of Earth was taken by Apollo 17 astronauts in 1972 and

Fotovoltaické (FV) články:

1) Jak se na ně přišlo?
2) Jak fungují?
3) Jak se dělají?
4) Kolik stojí?
5) Stojí to za to?
6) Jak to udělat lépe?

1839 - Alexandre Edmond Becquerel



1839 - Alexandre Edmond Becquerel - PV efekt
1873 - Willoughby Smith - Se
1877 - Charles Fritts - první Se sluneční článek
1887 - Heinrich Hertz - UV fotovodivost
1888 - Edward Weston patent US389124, "Solar cell", and US389125, "Solar cell".
1894 - Melvin Severy patent US527377, "Solar cell", and US527379, "Solar cell".
1897 - Harry Reagan patent US588177, "Solar cell".
1901 - Nikola Tesla the patent US685957, "Apparatus for the Utilization of Radiant Energy", and U
1902 - Philipp von Lenard - vnější fotoefekt v závislosti na barvě světla
1904 - Wilhelm Hallwachs sluneční článek Cu/Cu2O.
1905 - Albert Einstein
1913 - William Coblentz patent US1077219, "Solar cell".
1914 - Sven Ason Berglund patents "methods of increasing the capacity of photosensitive cells".
1916 - Robert Millikan potvrdil Einsteinovo vysvětlení
1916 - Jan Czochralski
1946 - Russell Ohl patent US2402662, "Light sensitive device".
1950s - Bell Lab.
1953 - Gerald Pearson lithium-silicon photovoltaic cells
1954 - AT&T exhibits solar cells at Murray Hill, New Jersey.
1955 - Western Electric licence commercially solar cell technologies.
1957 - Gerald L. Pearson, Daryl M. Chapin, and Calvin S. Fuller (AT&T) patent US2780765, "Sola
1962 - The Telstar satellite
1963 - Sharp Corporation - photovoltaic module of silicon solar cells.
1971 - Salyut 1 is powered by solar cells.
1973 - Skylab is powered by solar cells.
1977 - The Solar Energy Research Institute is established at Golden, Colorado.
1980s - efficient silicon cells are in production.
1989 - efficient concentrator solar cell are in use.
1990 - The Cathedral of Magdeburg installs solar cells on the roof, marking the first installation on a
1991 - President George H. W. Bush directs the U.S. Department of Energy to establish the National Renewable Energy Laboratory
1993 - National Renewable Energy Laboratory
2001 - Helios

1905 Albert Einstein:

1902 - Philipp von Lenard
- Vnější fotoefekt
1916 - Robert Millikan
Experimentání potvrzení Einsteinovy teorie
1921 – Nobelova cena

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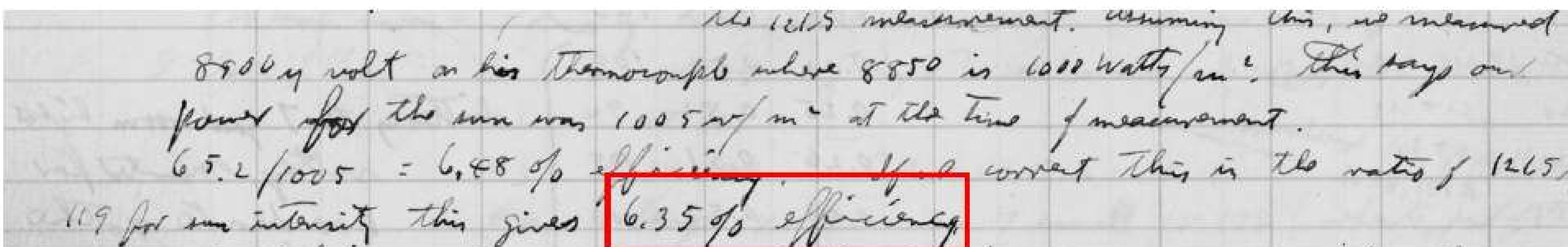
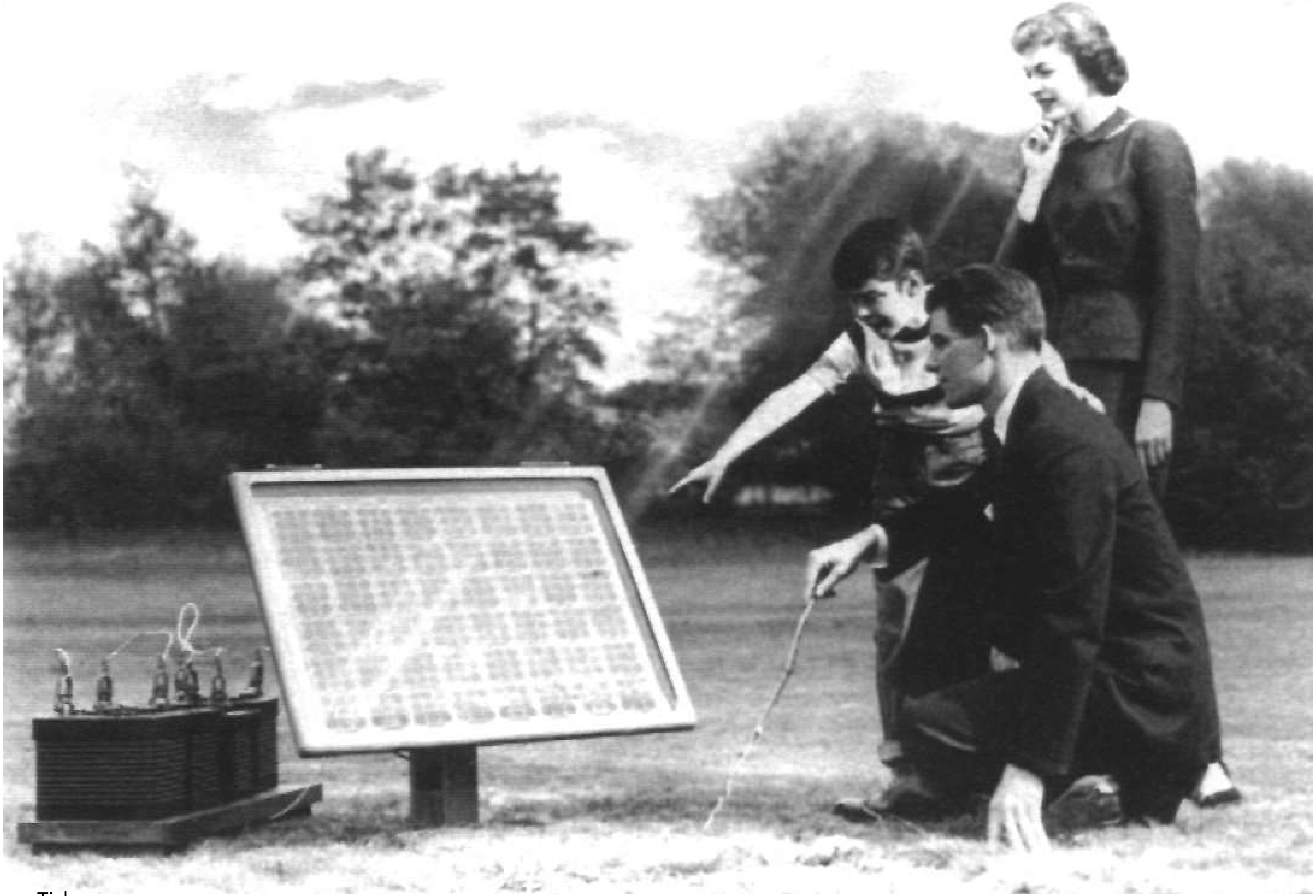
Začátek „doby sluneční“:

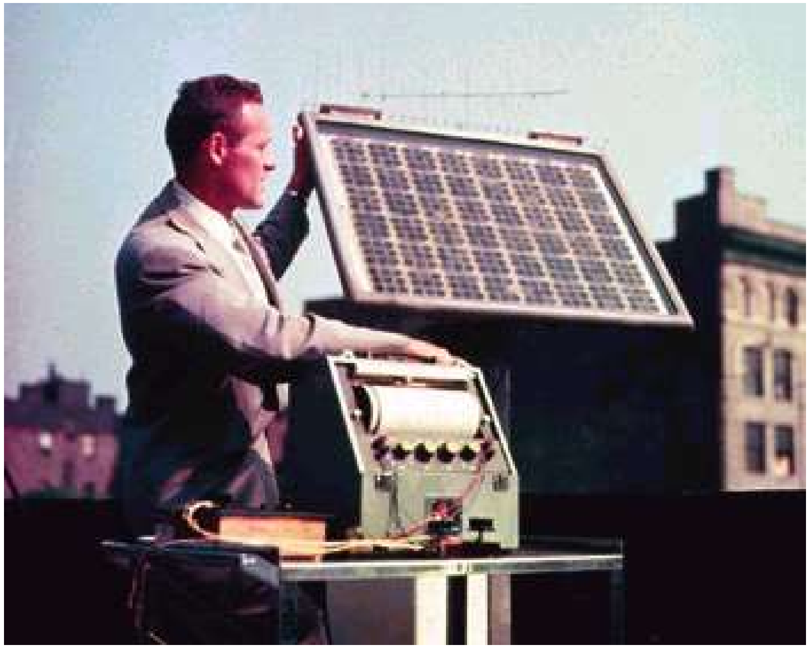
1953 - 4 G. Pearson, D. Chapin, C. Fuller (Bellovy laboratoře):
První sluneční článek s účinností 6%
arsenem dopovaná Si deska dopovaná bórem na PN přechod

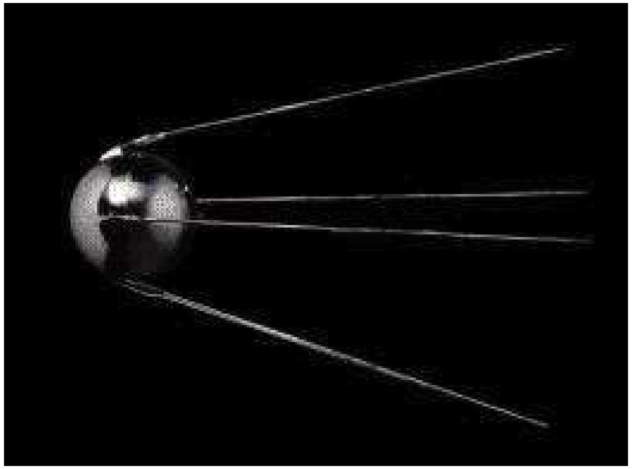




Tisk:
„počátek nové éry využití neomezené energie Slunce” (Times)
„jednoho dne mohou sluneční články vyrobit více energie než zdroje založené na uhlí, ropě či jádru” (New York Times).

Americus, Georgia: První testy Bellovských slunečních baterií





4. října 1957: Sputnik
83 kg na oběžná dráha 250 km

Vanguard I.

17.3.1958

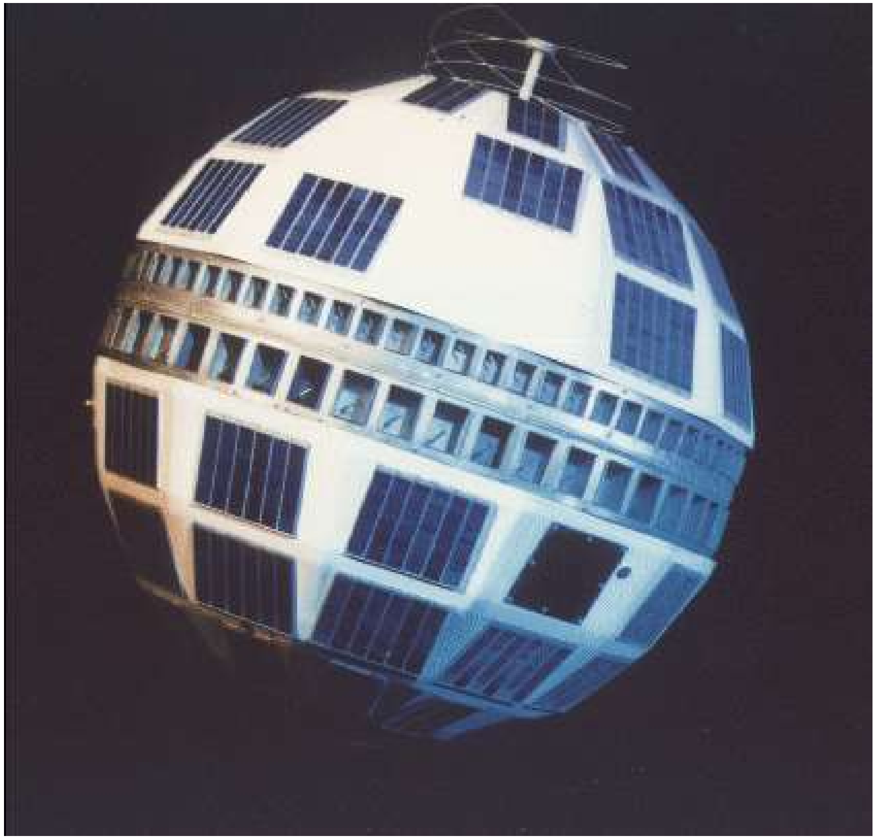
1.47 kg

Grapefruit satellite [Nikita Khruschev]

The Vanguard TV3 was launched on December 6, 1957 at Cape Canaveral Kennedy Space Center. It was the first attempt by the United States to put a satellite into orbit around Earth. However, the rocket only rose a few feet before crashing violently back onto the launchpad.

Derided by press as a "kaputnik" in the *Daily Express*, a "flopnik" in the *Daily Herald*, a "puffnik" in the *Daily Mail* and a "stayputnik" in the *News Chronicle*.[

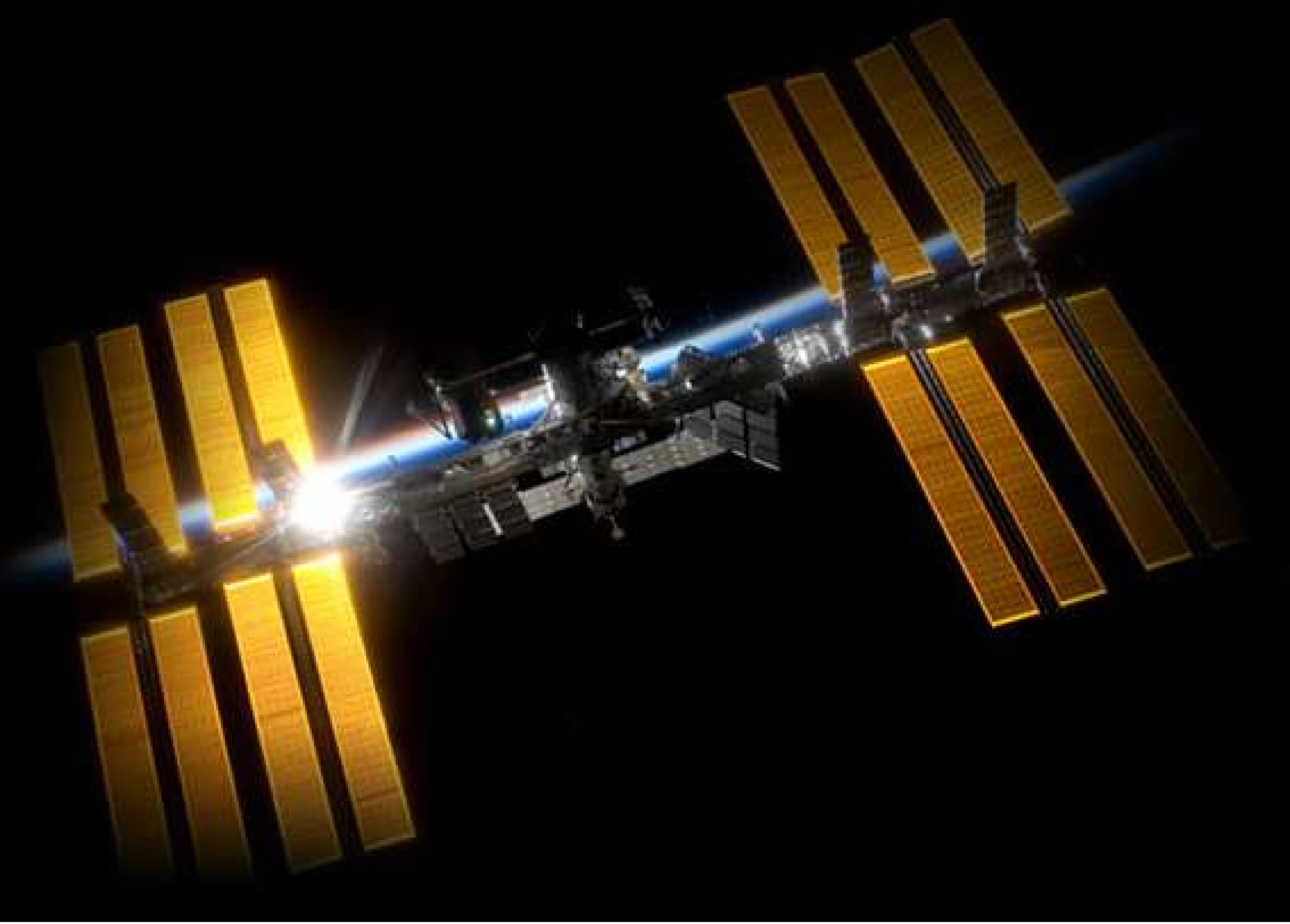
1962 Bell solar cells powered Telstar



Telstar 1 was launched on July 10, 1962 into a 514 x 3051 nmi. orbit by a Delta launch vehicle. The spacecraft weighed 171 pounds (the Delta capability was for a maximum payload of 180 pounds). The shape was a faceted sphere with a diameter of a little over 34 inches. Of six spacecraft built, two were launched. The solar cells provided just under 15 watts.

http://www.beatriceco.com/bti/porticus/bell/telstar.html

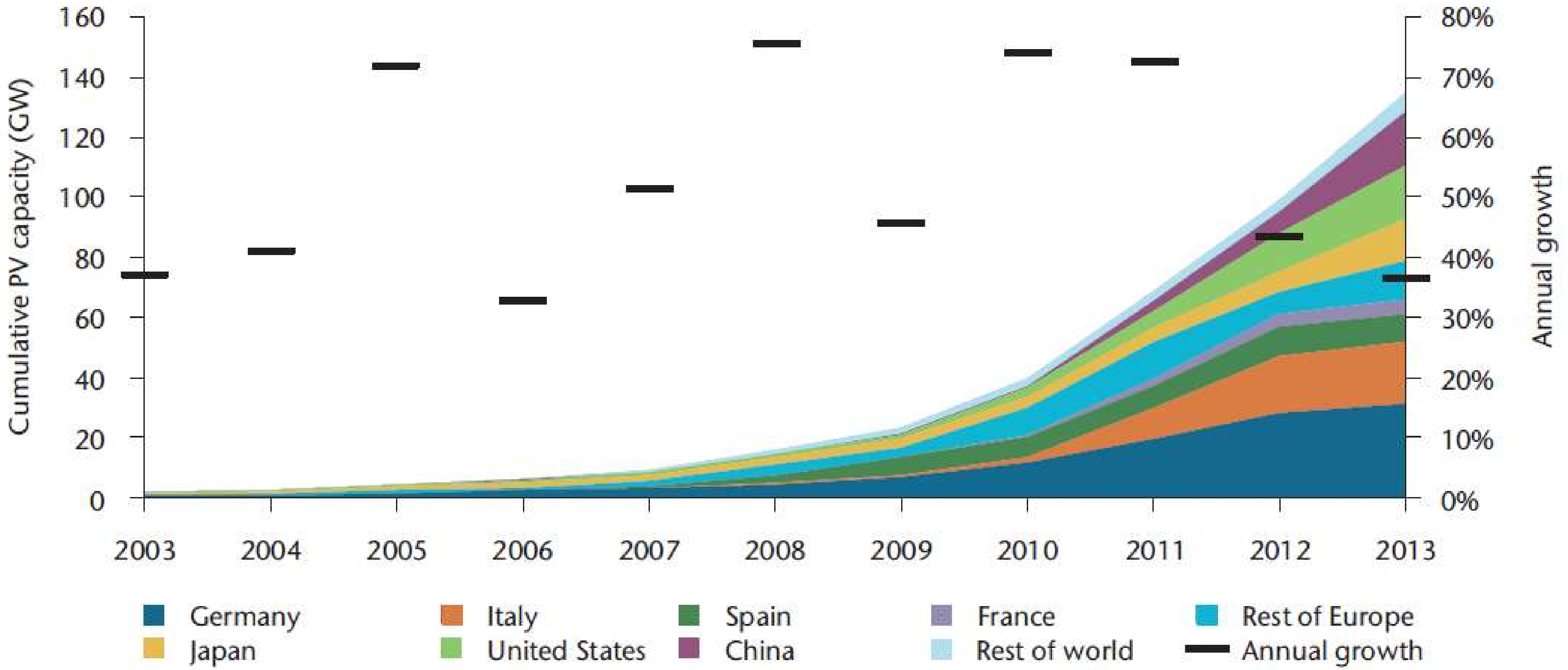
AT&T's Telstar was not only a tremendous technical success, but the international reaction was spectacular. A U.S. Information Agency poll showed that Telstar was better known in Great Britain than Sputnik had been in 1957. Rather than launching a useless bauble, the Americans had put into orbit a satellite that promised to tie together the ears and eyes of the world. Interestingly, the world saw Telstar as an undertaking of the United States (U.S. Information Agency publicity may have helped). President Kennedy hailed Telstar as "our American communications satellite" and "this outstanding symbol of America's space achievements."(Cunniffe, pg. 29)



PAST
Niche Markets

IEA Technology Roadmap: Solar Photovoltaic Energy - 2014 edition

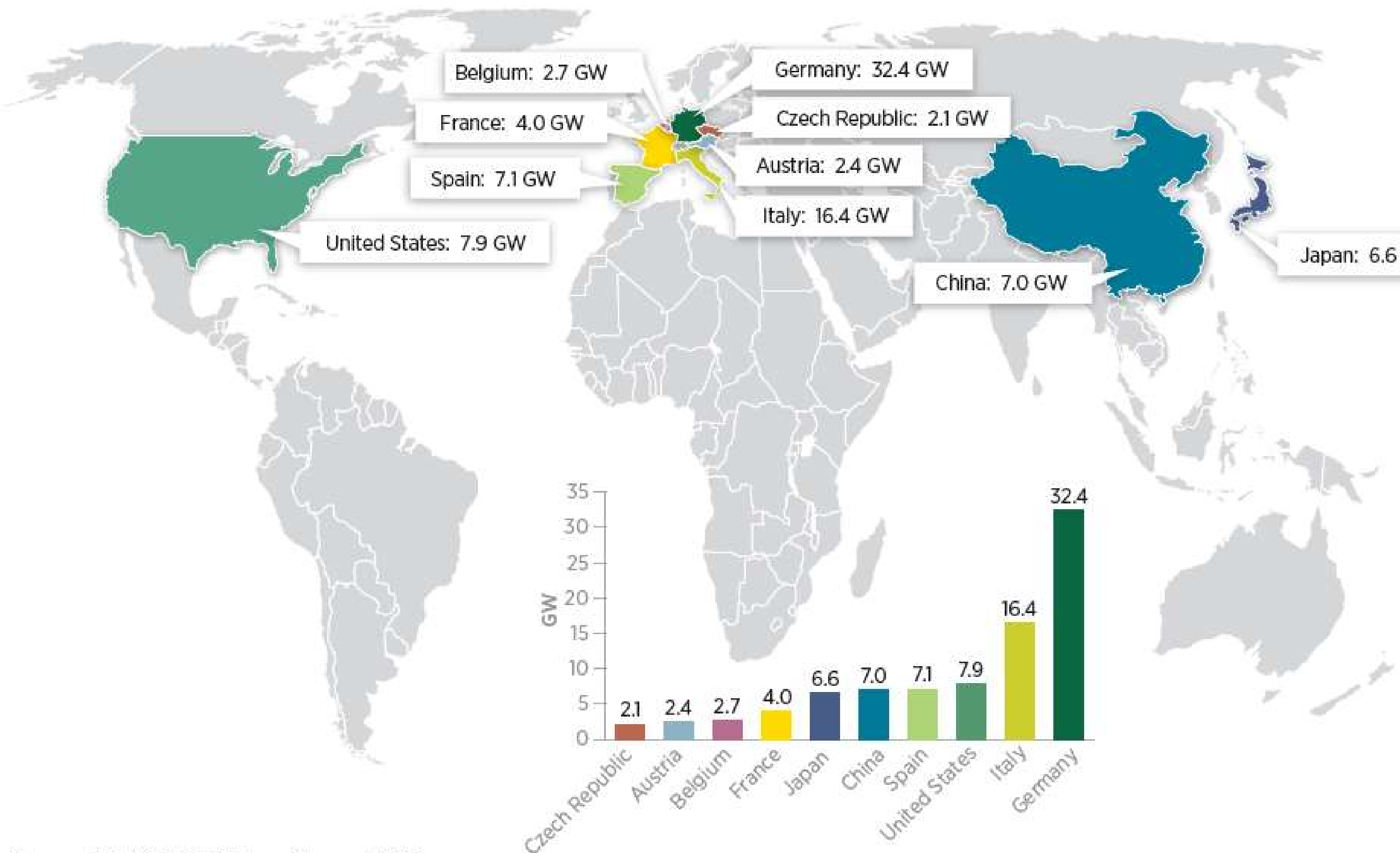
Figure 1: Global cumulative growth of PV capacity



Source: Unless otherwise indicated, all tables and figures derive from IEA data and analysis.

KEY POINT: Cumulative PV capacity grew at 49%/yr on average since 2003.

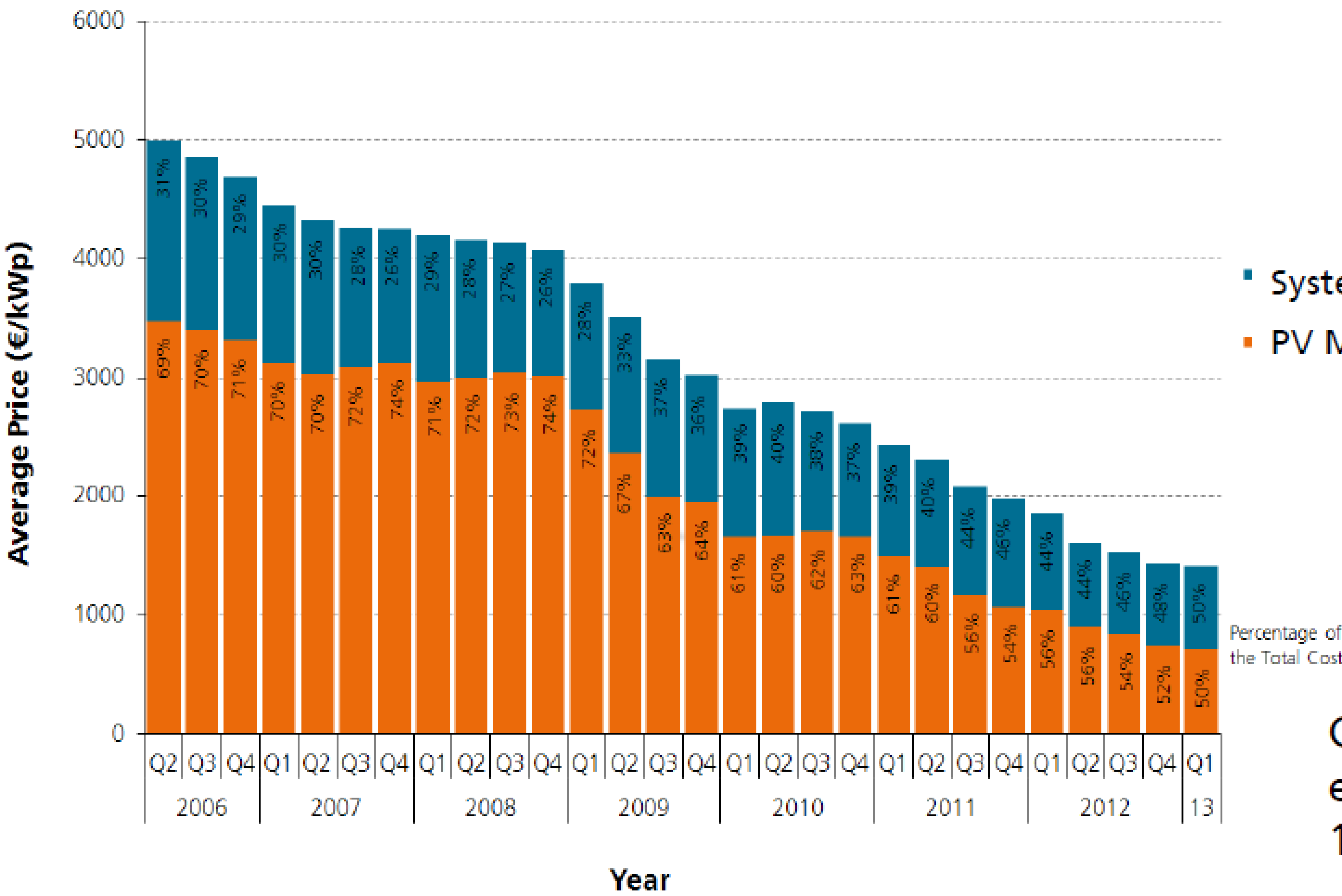
Solar Electricity Installed Capacity (2012) – Select Countries



Sources: SEIA/GTM, REN21, Larry Sherwood/IREC

* Includes PV and CSP

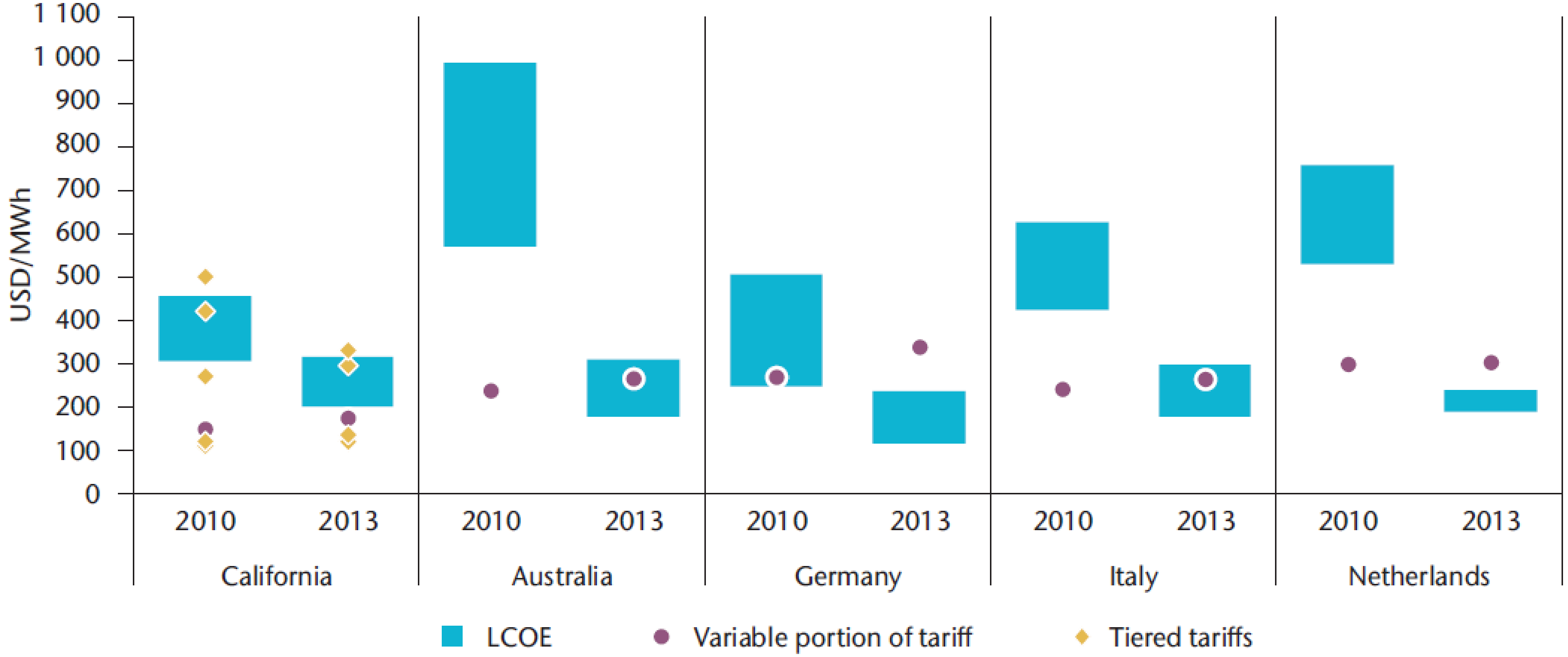
Average price for PV rooftop systems in Germany



Cost of PV electricity: 10 ct/kWh

IEA Technology Roadmap: Solar Photovoltaic Energy - 2014 edition

Figure 4: Grid parity was reached in 2013 in various countries

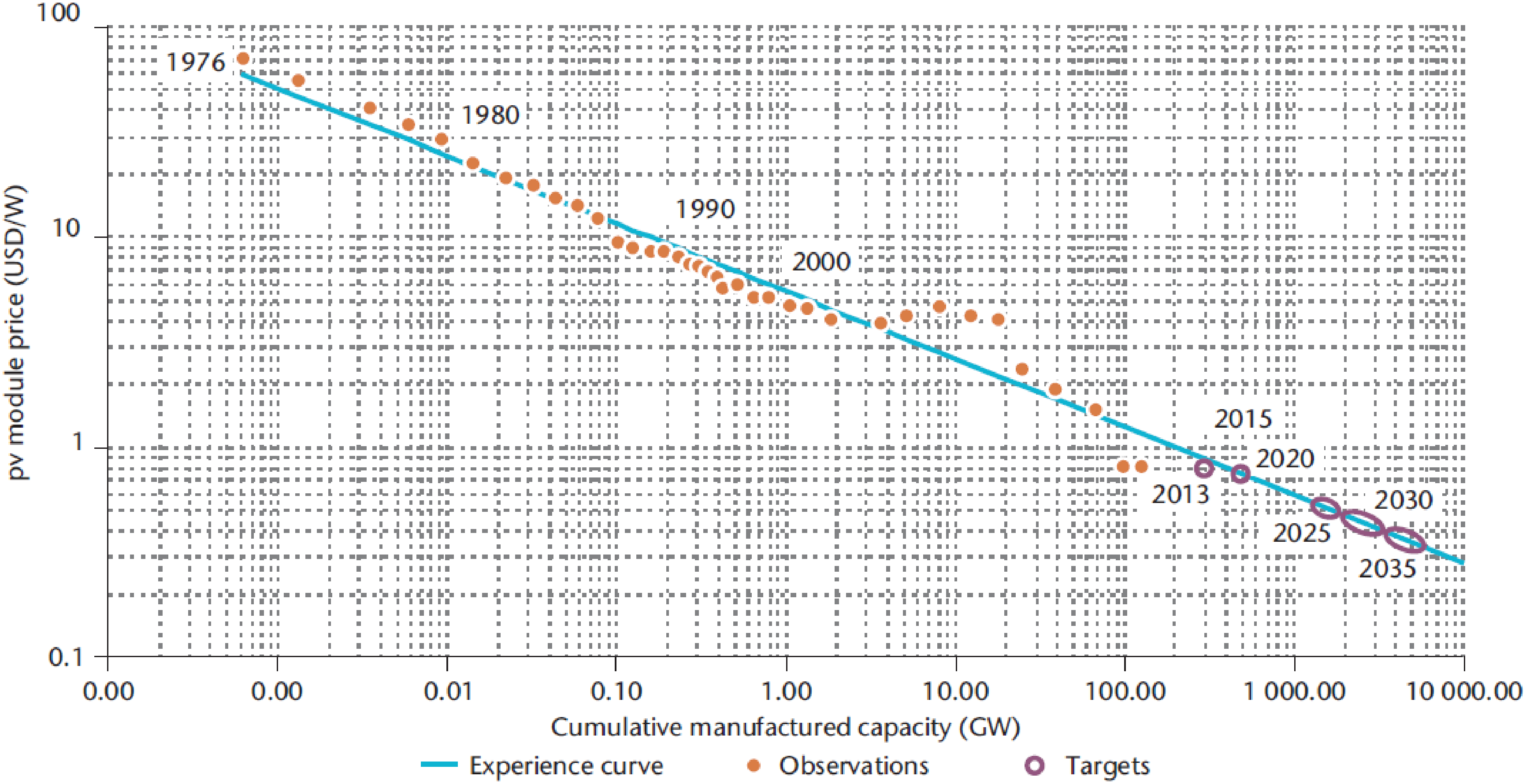


Note: Household electricity tariffs exclude fixed charges. LCOEs are calculated using average residential system costs (including value-added tax and sales tax in where applicable, and investment tax credit in California); ranges mostly reflect differences in financing costs. The tiered tariffs in California are those of Pacific Gas and Electric. Tiers 3 to 4 or 5 are tariffs paid on monthly consumption when it exceeds given percentages of a set baseline. All costs and prices are in 2012 USD.

KEY POINT: Grid parity underpins PV self-consumption in Germany, and net metering in California.

IEA Technology Roadmap: Solar Photovoltaic Energy - 2014 edition

Figure 10: Past modules prices and projection to 2035 based on learning curve

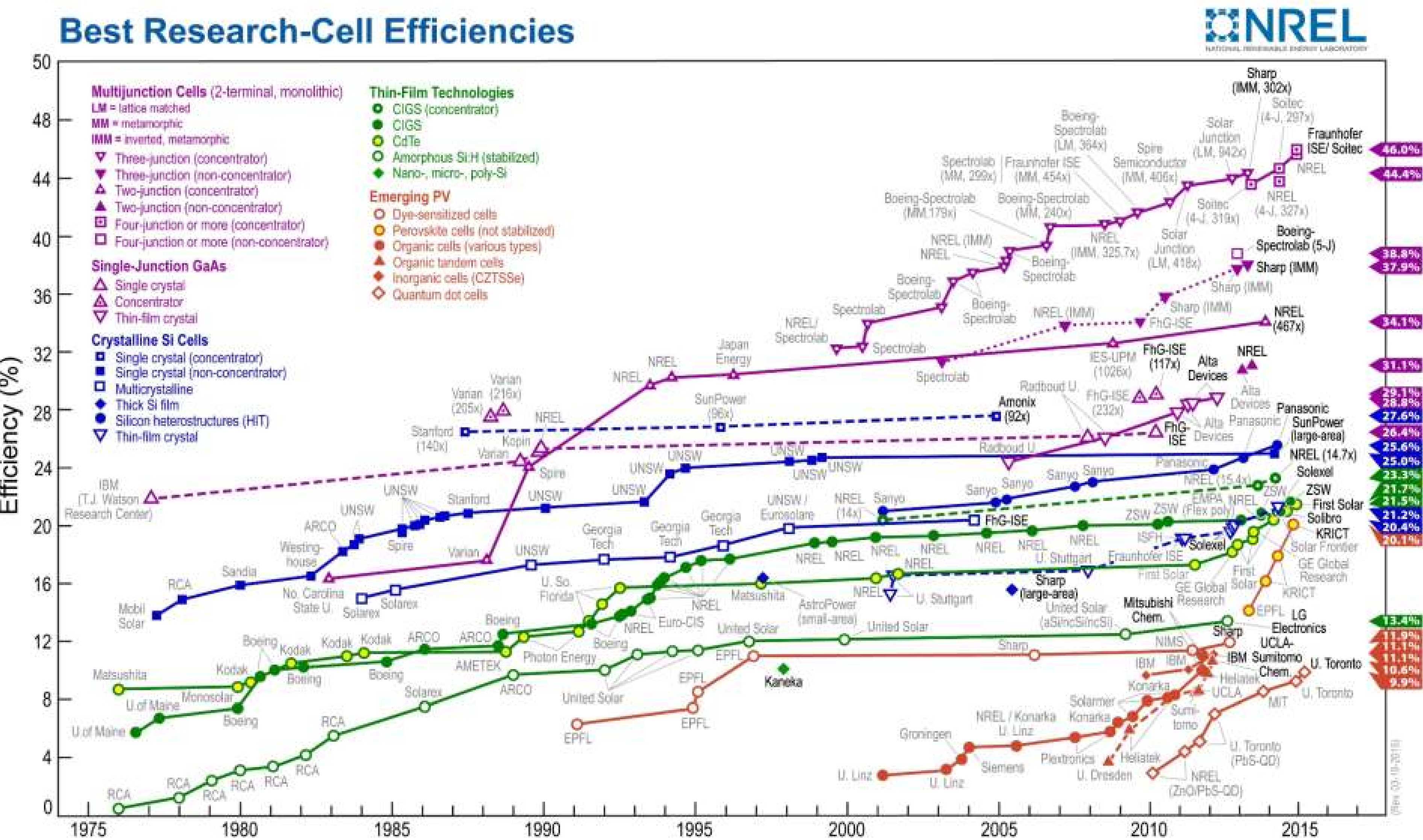


Notes: Orange dots indicate past module prices; purple dots are expectations. The oval dots correspond to the deployment starting in 2025, comparing the 2DS (left end of oval) and 2DS hi-Ren (right end).

KEY POINT: This roadmap expects the cost of modules to halve in the next 20 years.

Vývoj účinnosti:

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



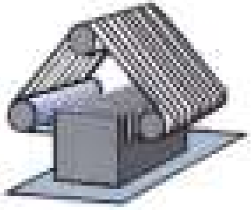
Výroba křemíkových článků:

PolySi

Crystal growth

Ingot squaring

Wafer cutting:



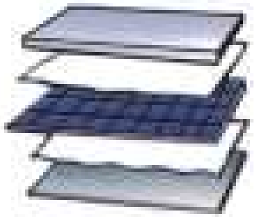
PN junction diffusion

Screen přinting of electrodes

Solar cell

Stringing

Lamination

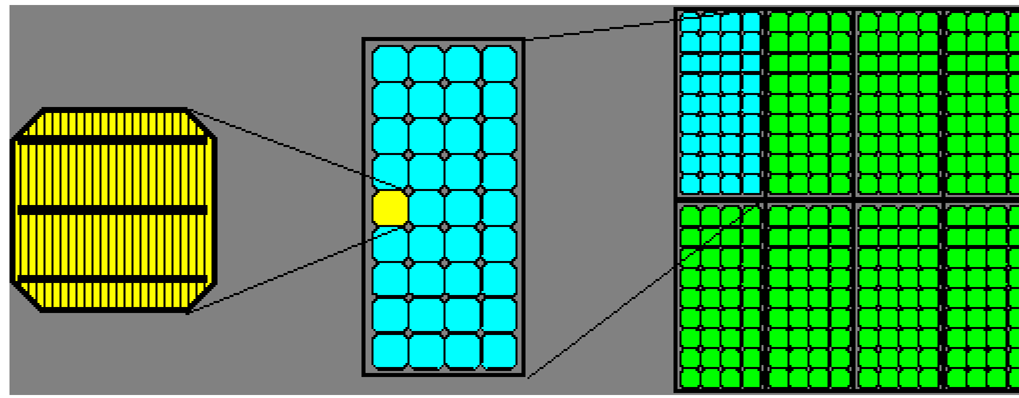


Framing

Module

1. Generace:

Články s PN přechodem v objemových polovodičích



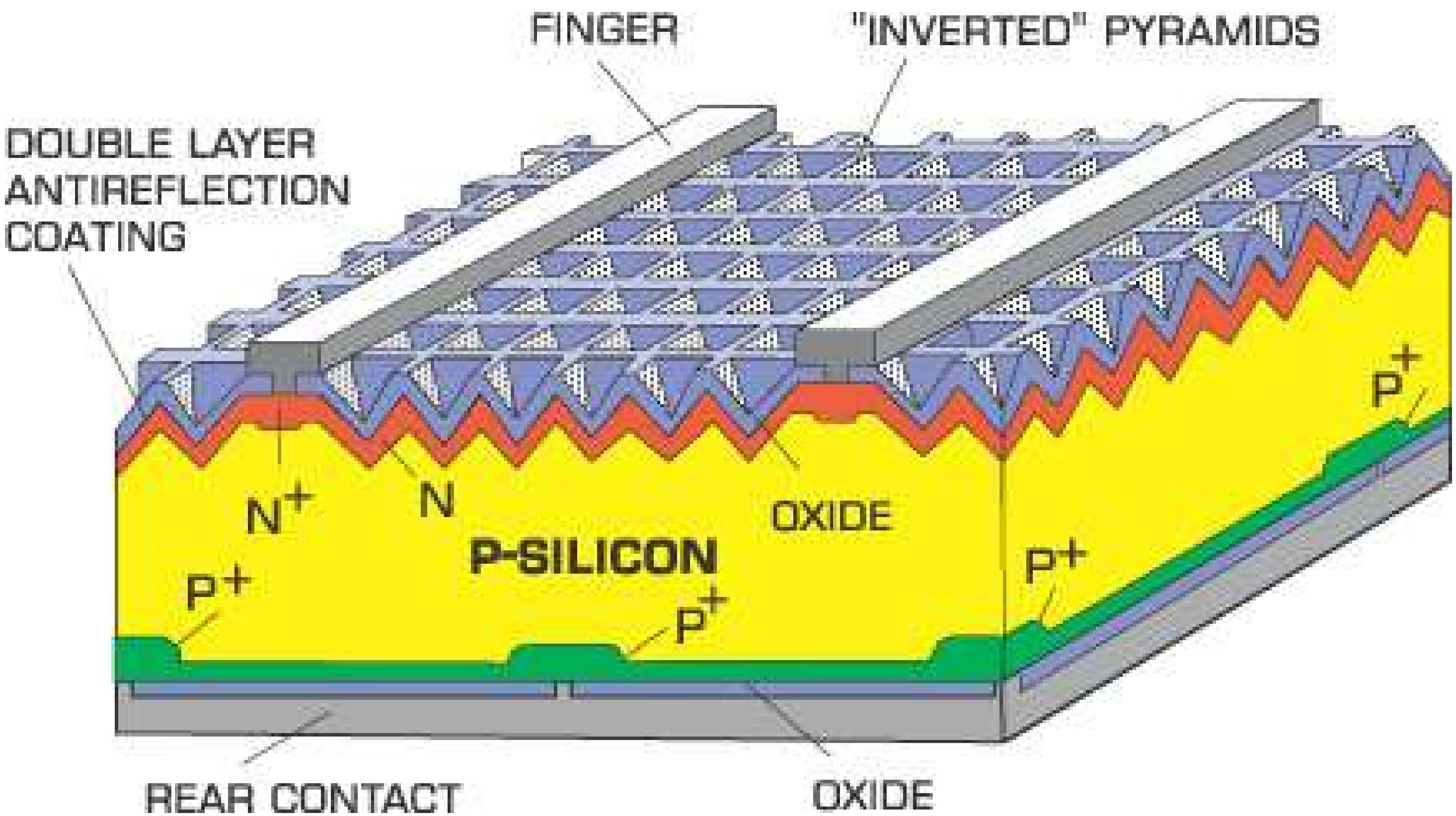
SOLARTEC®

Výroba solárních článků a fotovoltaické aplikace

účinnost článků: ~ 16 %

Moderní křemíkové sluneční články

M. Green, Centre for Photovoltaic Engineering, UNSW, Australia

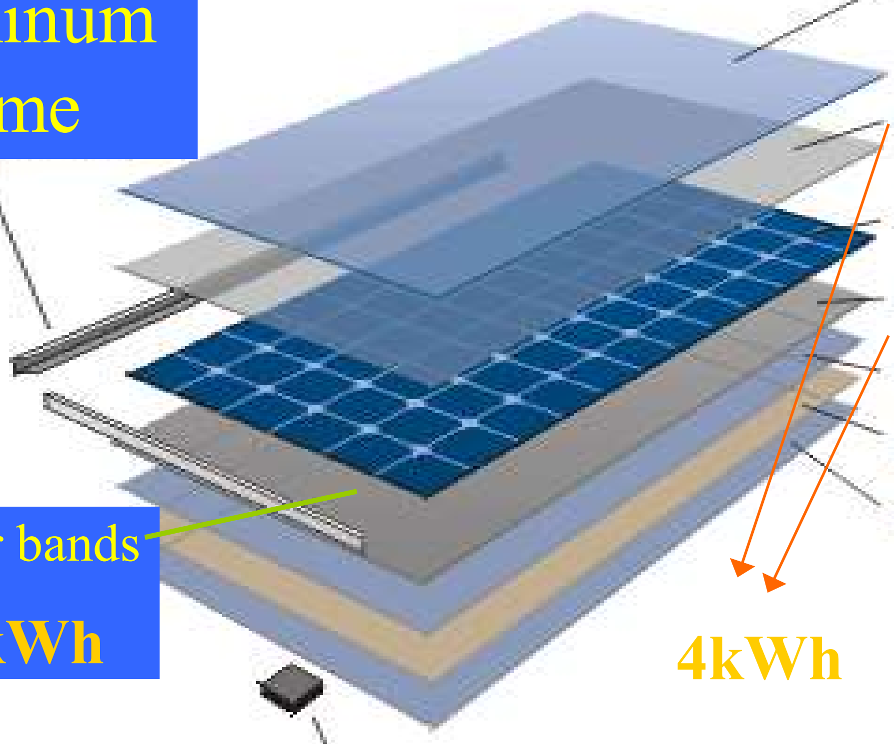


Účinnost 25 % (blížící se teoretické hranici 27 - 28%)

Energetické náklady panelu

Radix 72-112

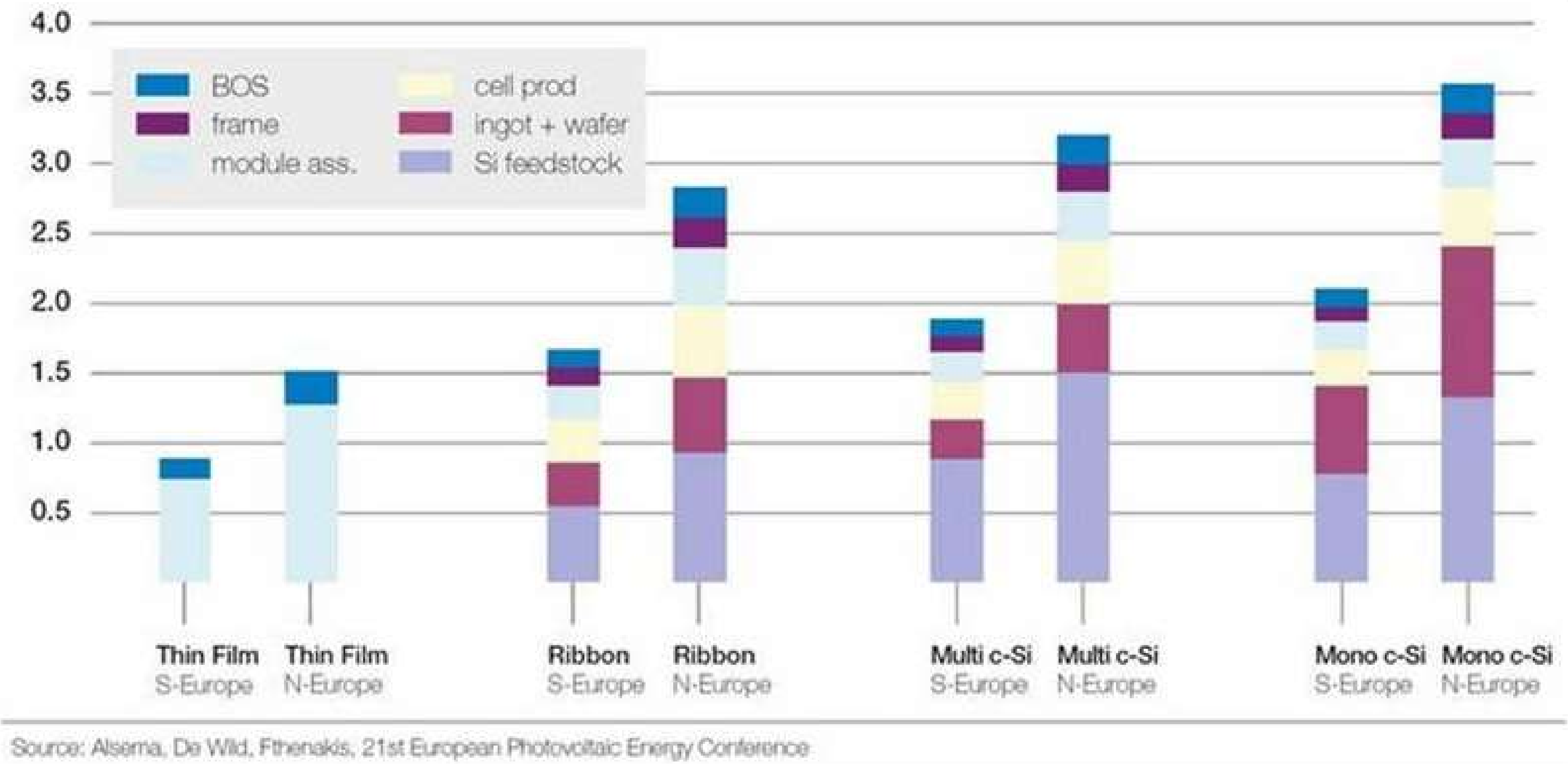
553,5kWh



Frameless panel - 4%

BIPV - facade - 3%

Doba energetické návratnosti



ERoEI = Energy Return on Energy Invested = energetický zisk

Příklady EROEI :

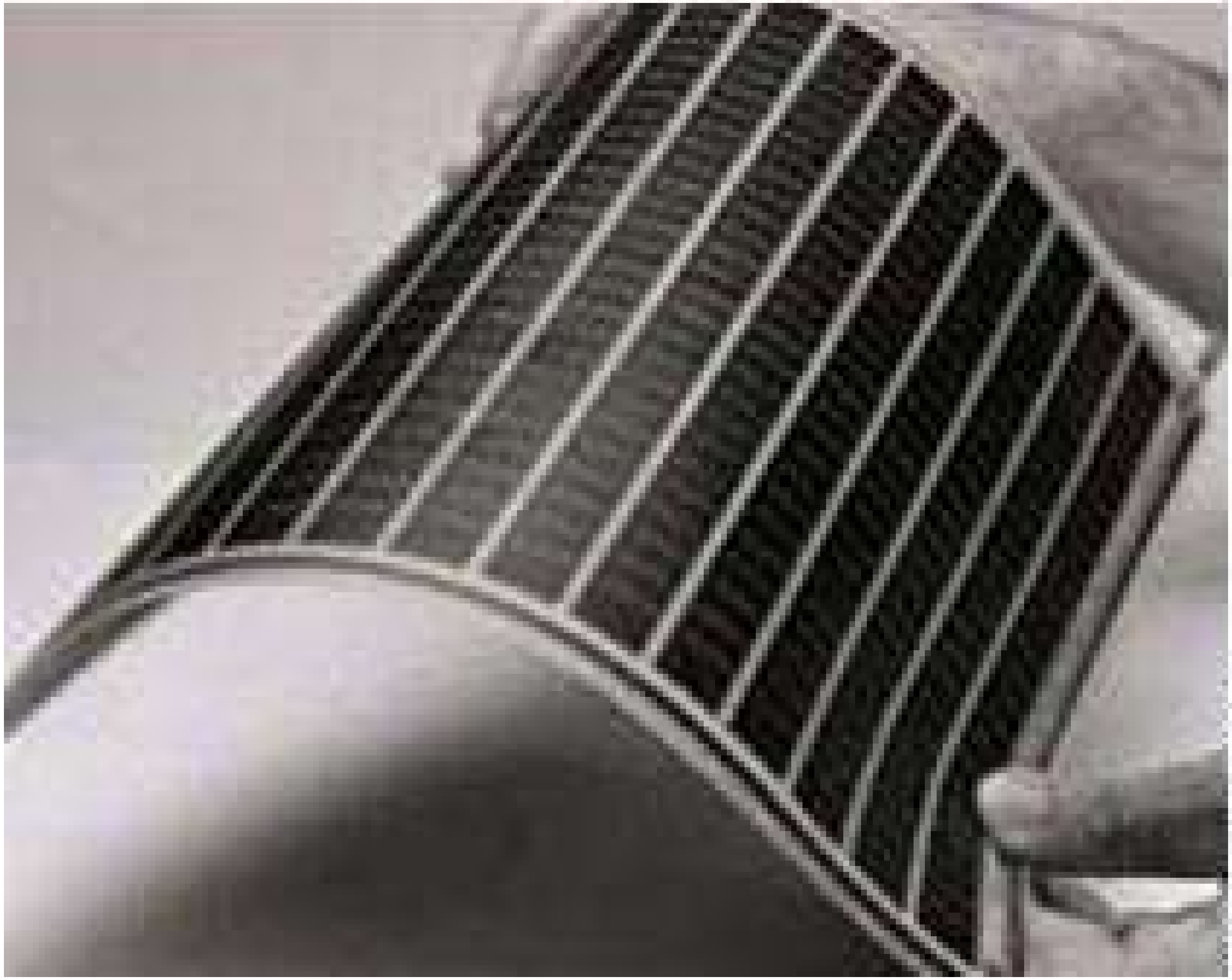
Ropa v počátcích těžby	**100**
Texaská ropa okolo roku 1930	**60**
Ropa z Blízkého Východu.	**30**
Jiná ropná pole	**10–35**
Přírodní plyn	**20**
Kvalitní uhlí (Austrálie)	**10–20**
Nekvalitní uhlí (ČR)	**4–10**
Vodní elektrárny.	**10–40**
Větrné elektrárny	**5–10**
Jaderná energie	**4–5**
Ropné písky	**Max. 3**
Bitumen	**Max. 1,5**
biopaliva (v Evropě).	**0,9–4**

(Martin Kašík, Václav Cílek: Vesmír 87, únor 2008 | http://www.vesmir.cz)

Snaha o omezení potřeby křemíku:

2. generace

Tenkovrstvé články



Courtesy NREL

Křemíkové tenké vrstvy – počátky v 60. letech:

Solid-State Electronics Pergamon Press 1965. Vol. 8, pp. 653–654. Printed in Great Britain

CHEMICAL VAPOUR DEPOSITION PROMOTED BY r.f. DISCHARGE

H. F. STERLING and R. C. G. SWANN

Standard Telecommunication Laboratories, London Road, Harlow, Essex

(*Received* 20 *January*, 1965; *in revised form* 1 *March* 1965)

Solid-State Electronics Pergamon Press 1968. Vol. 11, pp. 683–684. Printed in Great Britain

THE PREPARATION OF THIN LAYERS OF Ge AND Si BY CHEMICAL HYDROGEN PLASMA TRANSPORT

S. VEPŘEK and V. MAREČEK

Institute of Physics, Czechoslovakia Academy of Sciences, Prague, Czechoslovakia

(*Received* 31 *July* 1967; *in revised form* 26 *December* 1967)

Praha: instalace tenkovrstvých článků na střeše Národního divadla

Roční výroba Si tenkých vrstev:

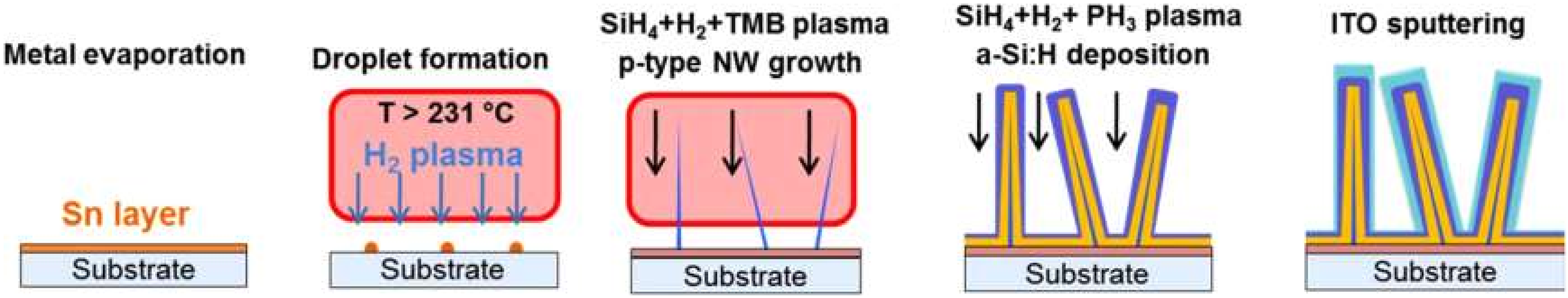
~ 4 km^2 per year

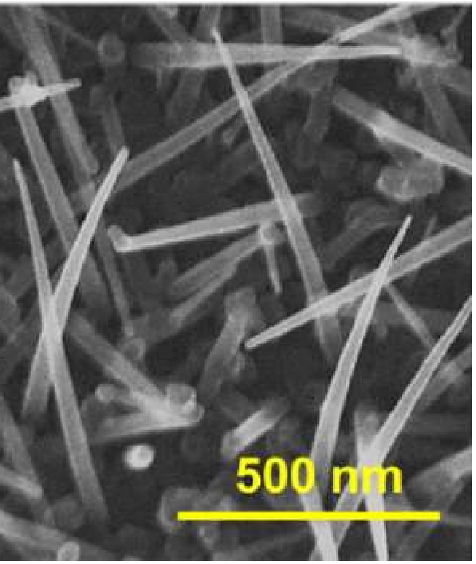
≅ area of Central Park

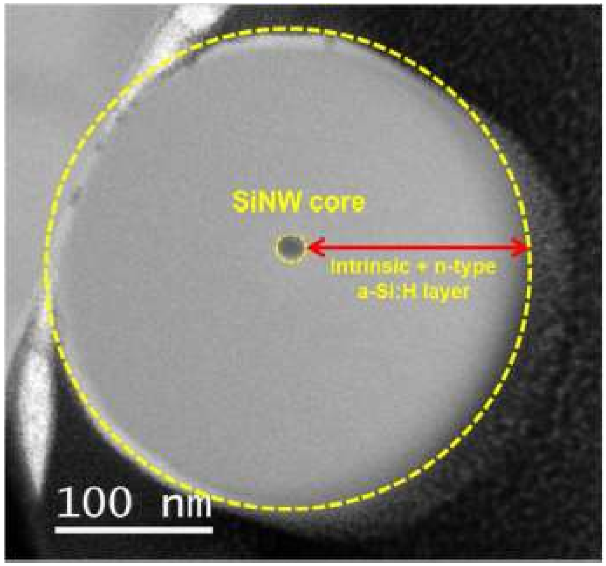
~ 50 km^2 per year

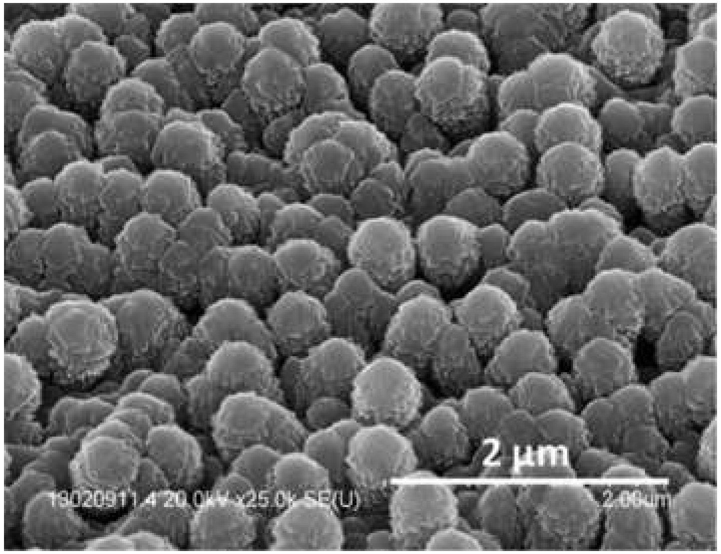
≅ area of Manhattan Island

Nano články









Jsc 15.2 mA/cm^2, V_{oc} of 0.82 V and FF 73.7%, ~9.2% for 0.126 cm^2 area [Misra et al, *IEEE Journal of Photovoltaics* 2015]

Absorbce světla versus sběr nábojů

Planární články **Nanodrátové články**

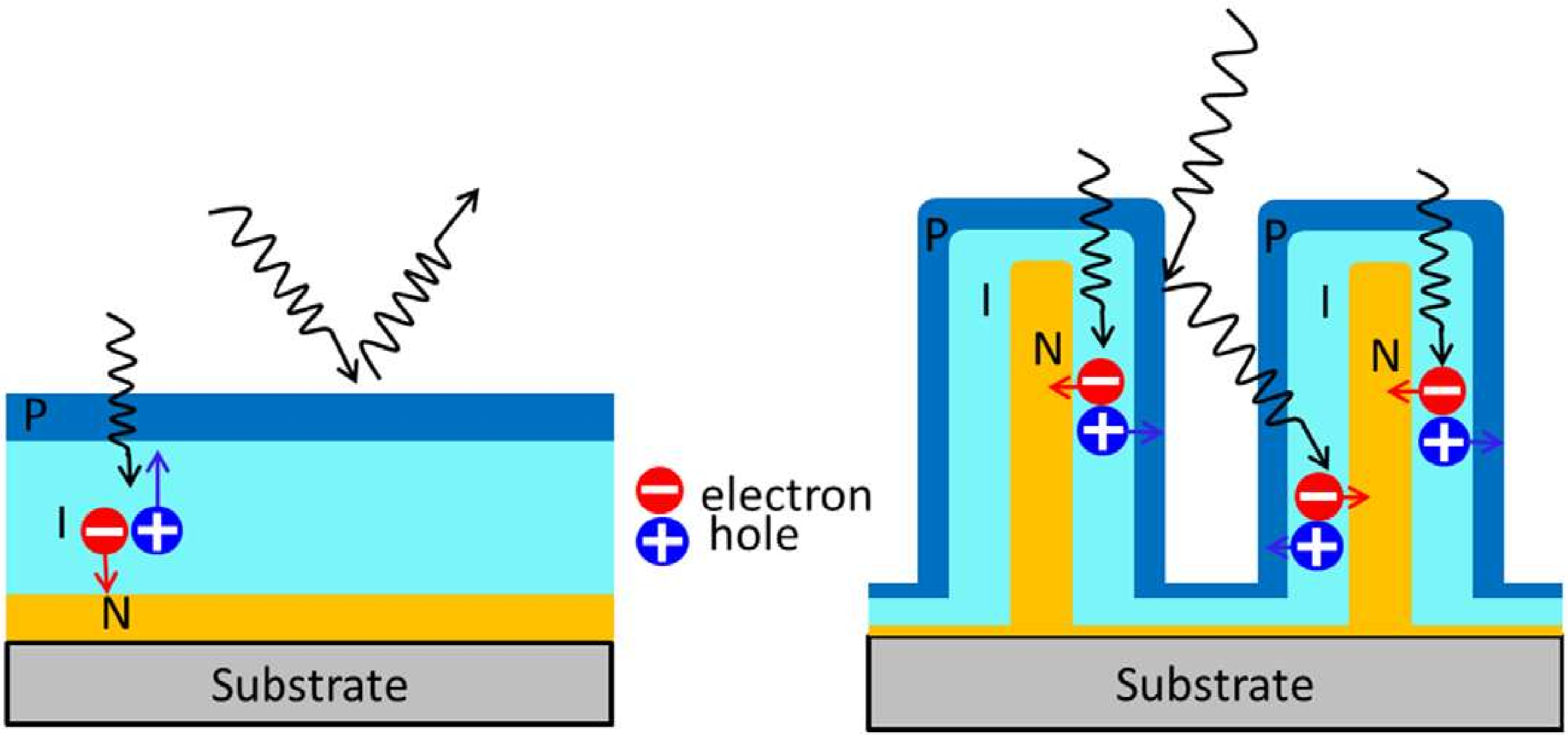


Illustration from:
Soumyadeep Misra, Linwei Yu, Wanghua Chen, Martin Foldyna, and Pere Roca i Cabarrocas.
'A Review on Plasma-Assisted VLS Synthesis of Silicon Nanowires and Radial Junction Solar Cells'.
Journal of Physics D: Applied Physics 47 (2014): 393001.

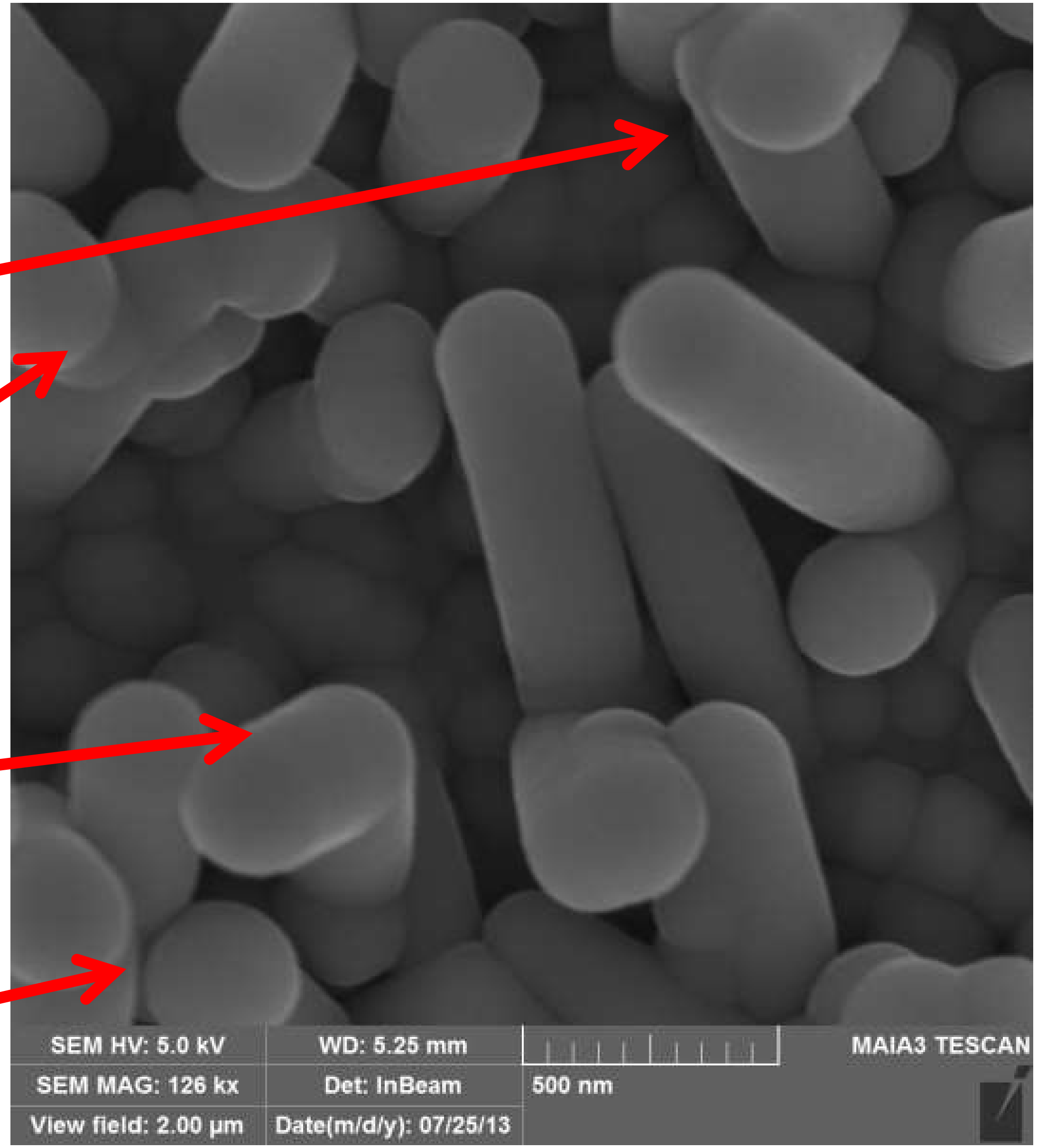
Disorder ZOO:

Shading

Crossing

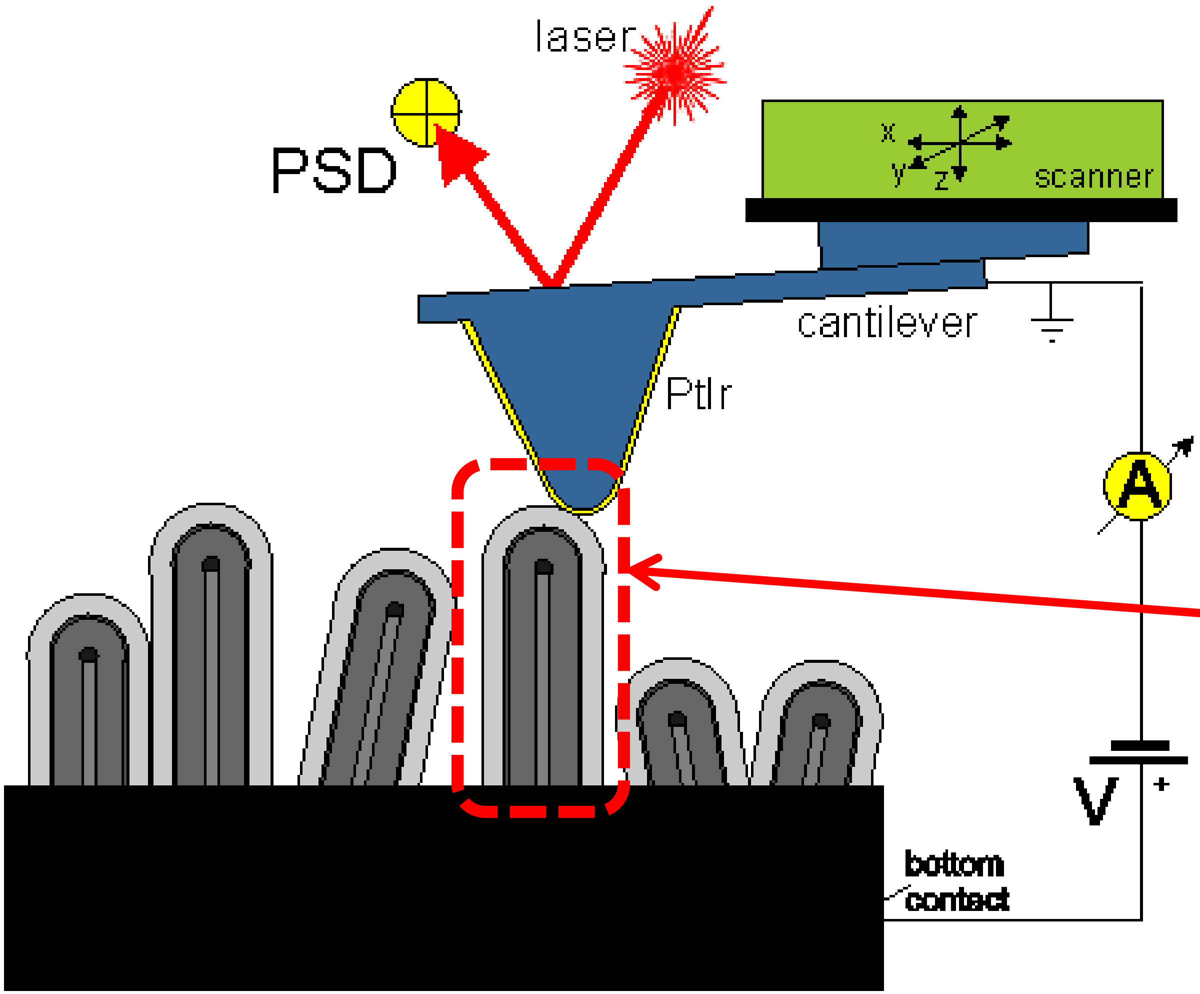
Kinks

Crowding



Microscopy of PV conversion

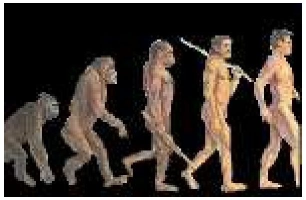
We use conductive AFM tip
to contact and measure individual radial junctions:



RJ cells on Si NWs have additional benefit: well defined unit cells.

Závěry:
Fotovoltaická revoluce?

Historická období



Doba kamenná

Doba bronzová

The sky disk of Nebra

Doba železná

Hallstatt C Iron Sword

Doba sluneční