Jak vypadá současná podoba fotovoltaických článků

aneb

o použití nanotechnologií na tisících km^2

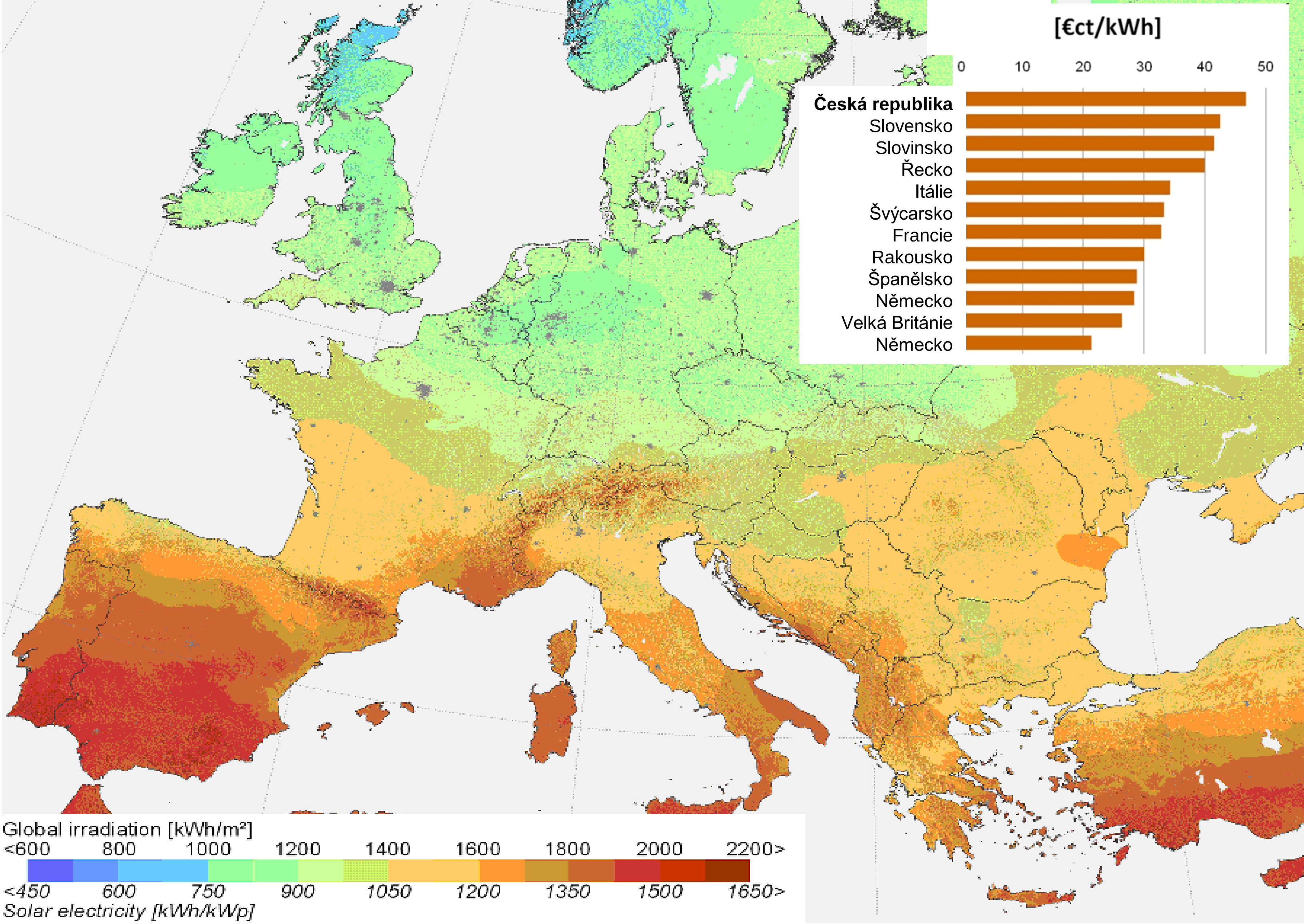
A. Fejfar

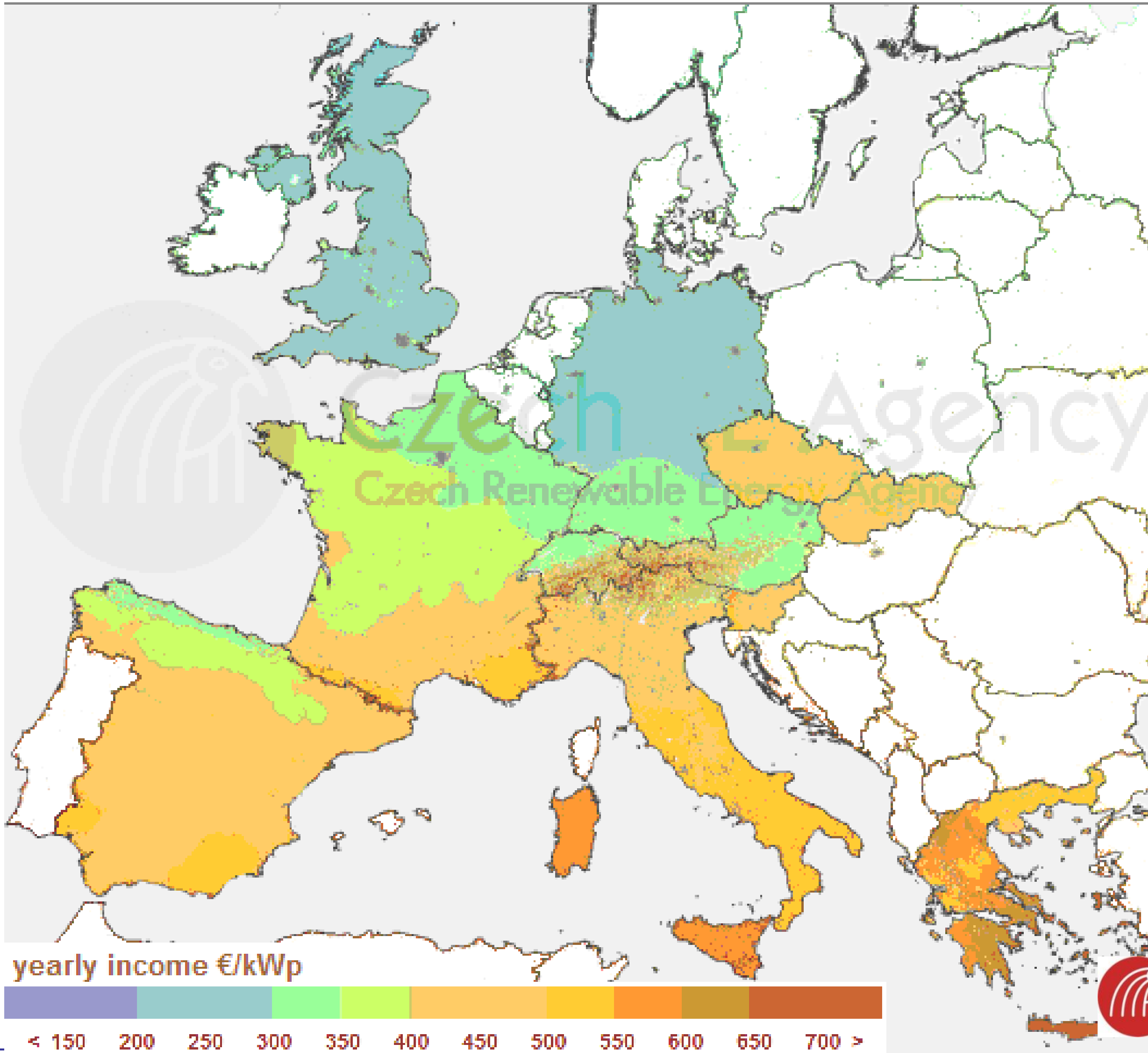
Fyzikální ústav Akademie věd České republiky, v. v. i.

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

The Czech Academy of Sciences

FZU Fyzikální ústav Akademie věd České republiky


[€ct/kWh]
0
10
20
30
40
50
Česká republika
Slovensko
Slovinsko
Řecko
Itálie
Švýcarsko
Francie
Rakousko
Španělsko
Německo
Velká Británie
Německo
Global irradiation [kWh/m²]
<600 800 1000 1200 1400 1600 1800 2000 2200>
<450 600 750 900 1050 1200 1350 1500 1650>
Solar electricity [kWh/kWp]



Source:
www.czrea.org

Czech RE Agency
Czech Renewable Energy Agency


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

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 18 TW (18000 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.

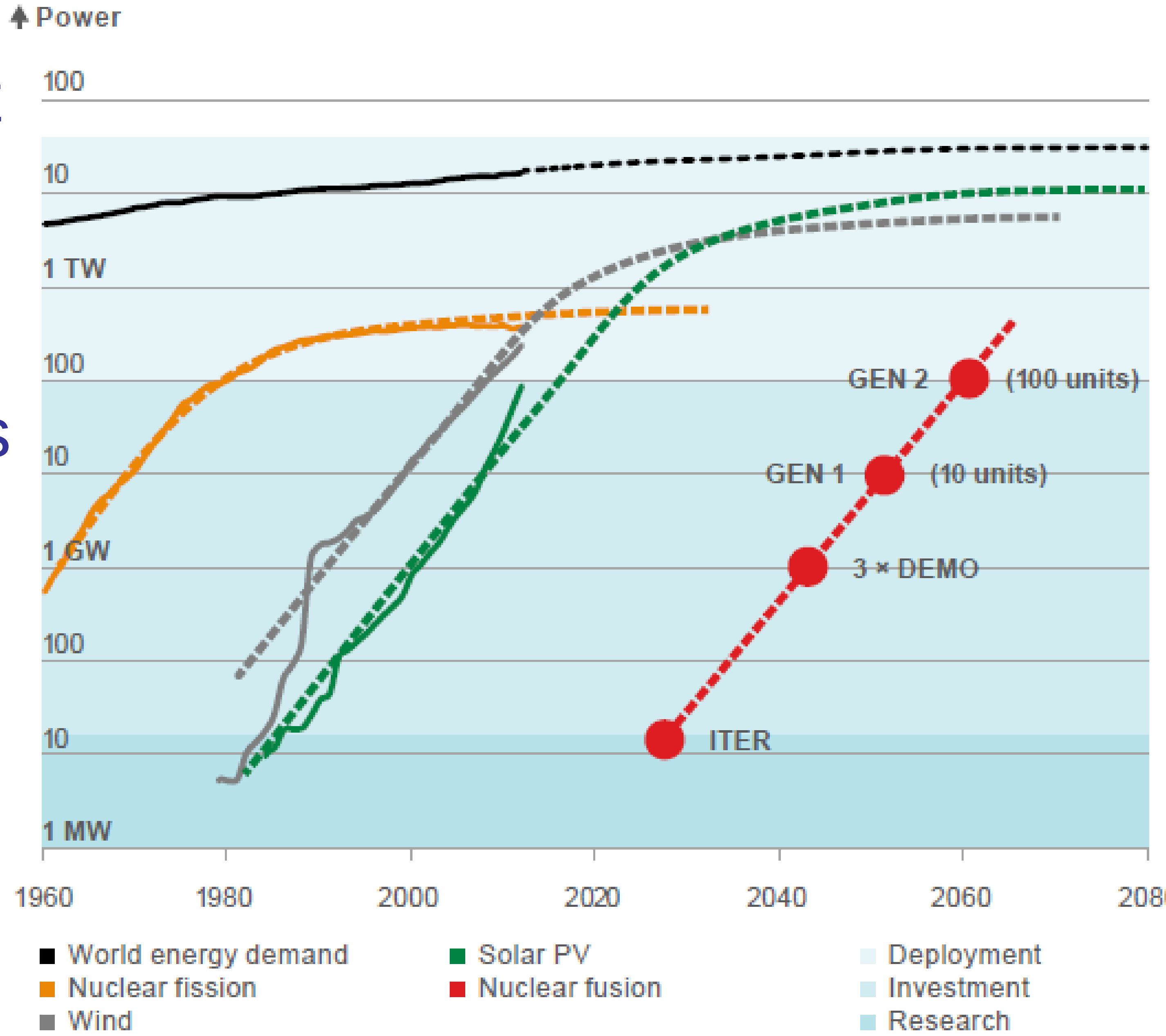
Přidání 10 TW znamená:

- Spuštění 1 GW elektrárny **každý den** po dobu 27.5 roků

- 2 MW FV elektrárna **každých10 minut** po dobu 81 roků

125 000 TW

Deployment rate for different energy technologies

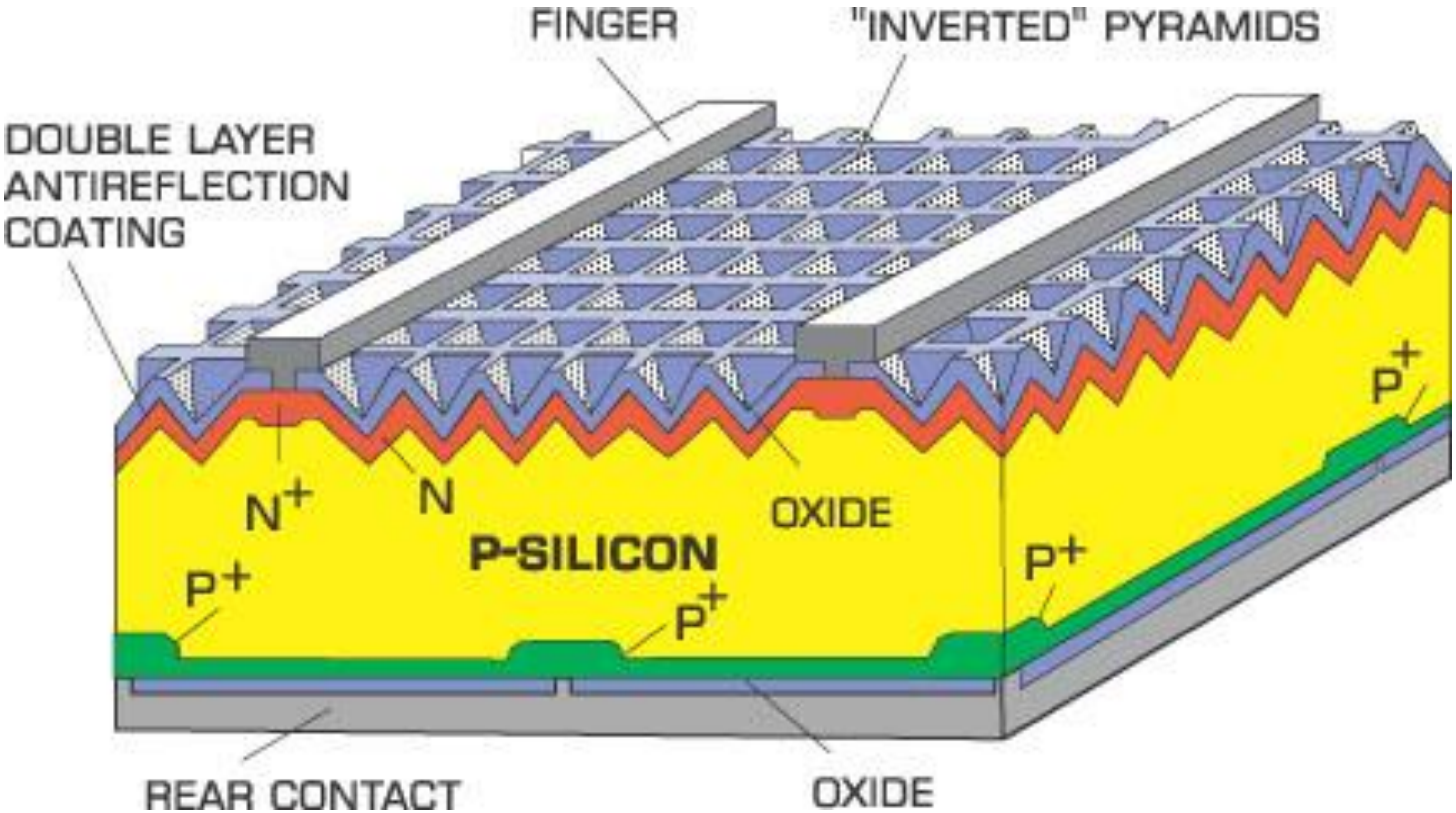


The dotted lines = model. Full lines = actual deployment rates based on OECD and IEA energy statistics. Note that 'Power' on the vertical axis denotes the average energy delivered to society per unit of time.

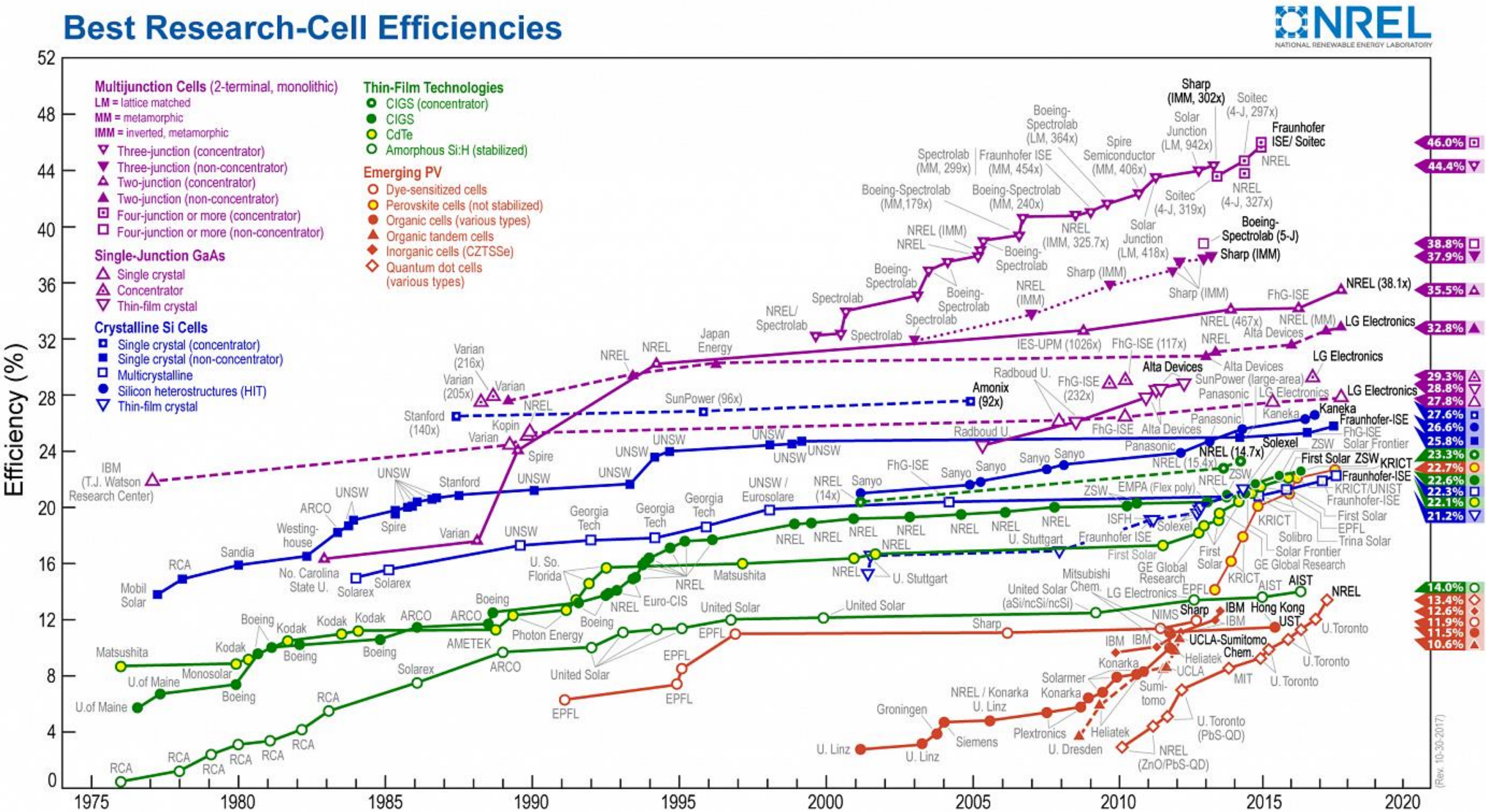
Why we have solar panels but no nuclear fusion power) by Niek Lopes Cardozo, Guido Lange and Gert Jan Kramer (NTvN 83, October 2017, page 350-354

Moderní křemíkové sluneční články

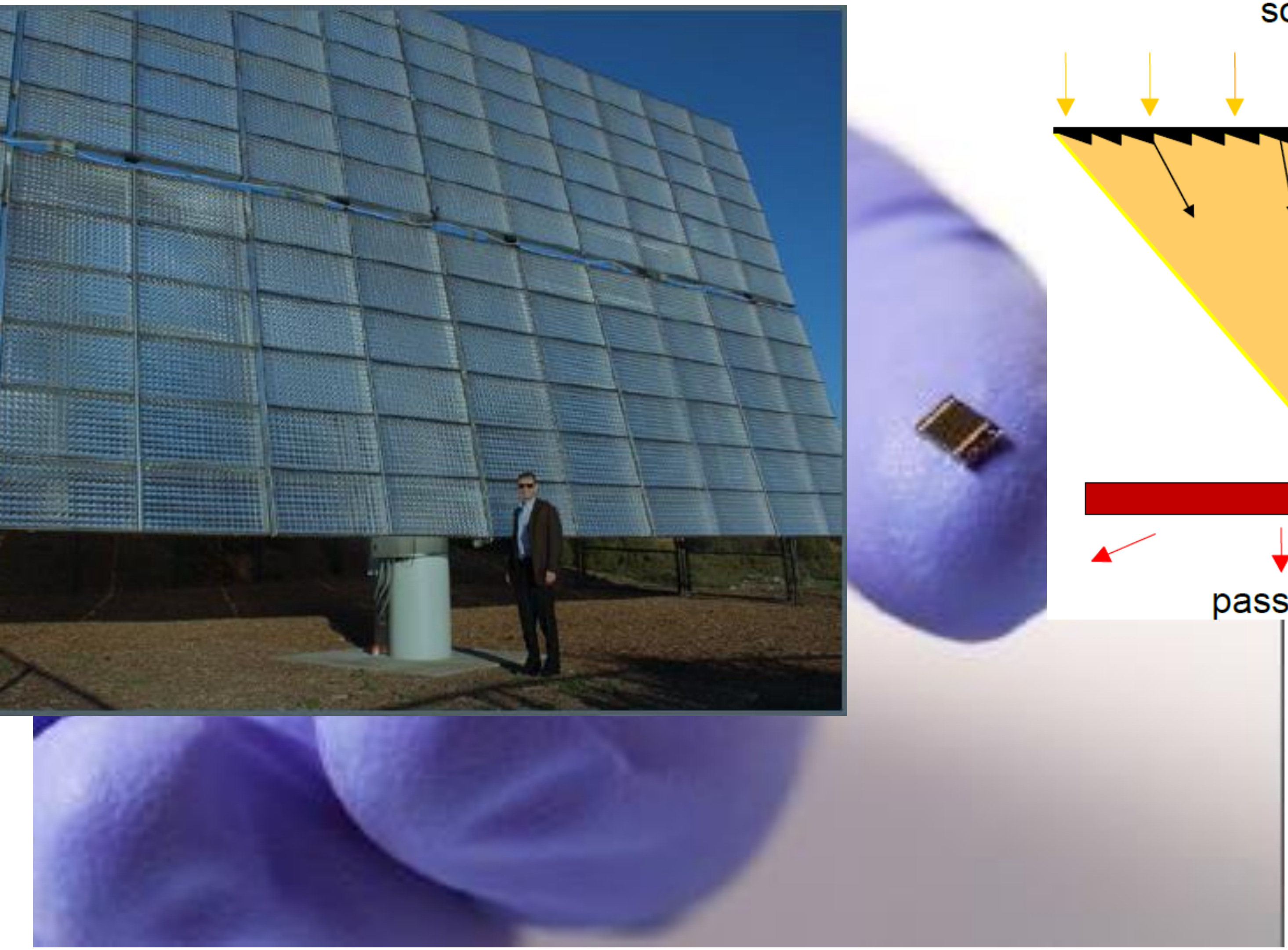
M. Green, Centre for Photovoltaic Engineering, UNSW, Australia

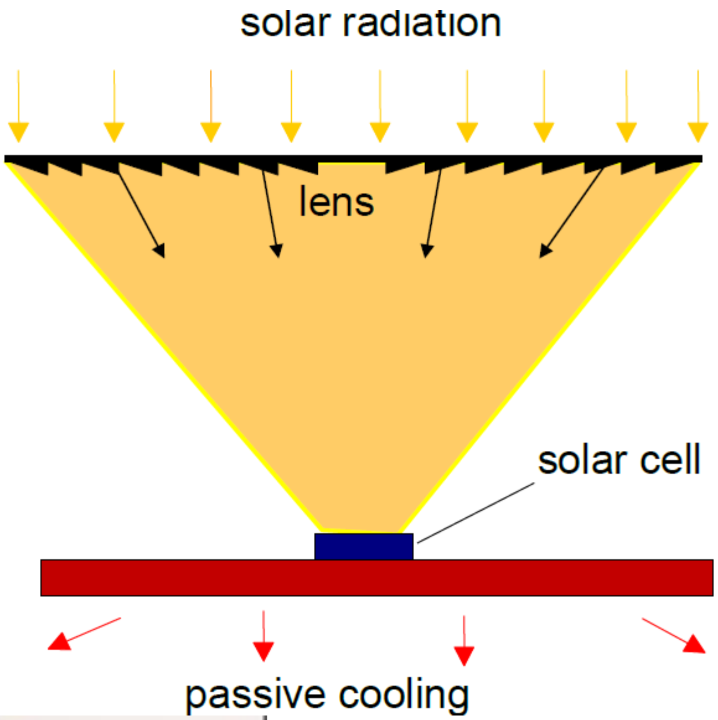


Účinnost 25 % (blížící se teoretické hranici ~29%)


Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells (various types)
46.0%
44.4%
38.8%
37.9%
35.5%
32.8%
29.3%
28.8%
27.8%
27.6%
26.6%
25.8%
23.3%
22.7%
22.6%
22.3%
22.1%
21.2%
14.0%
13.4%
12.6%
11.9%
11.5%
10.6%
(Rev. 10-30-2017)

Rekordní články: SOITEC

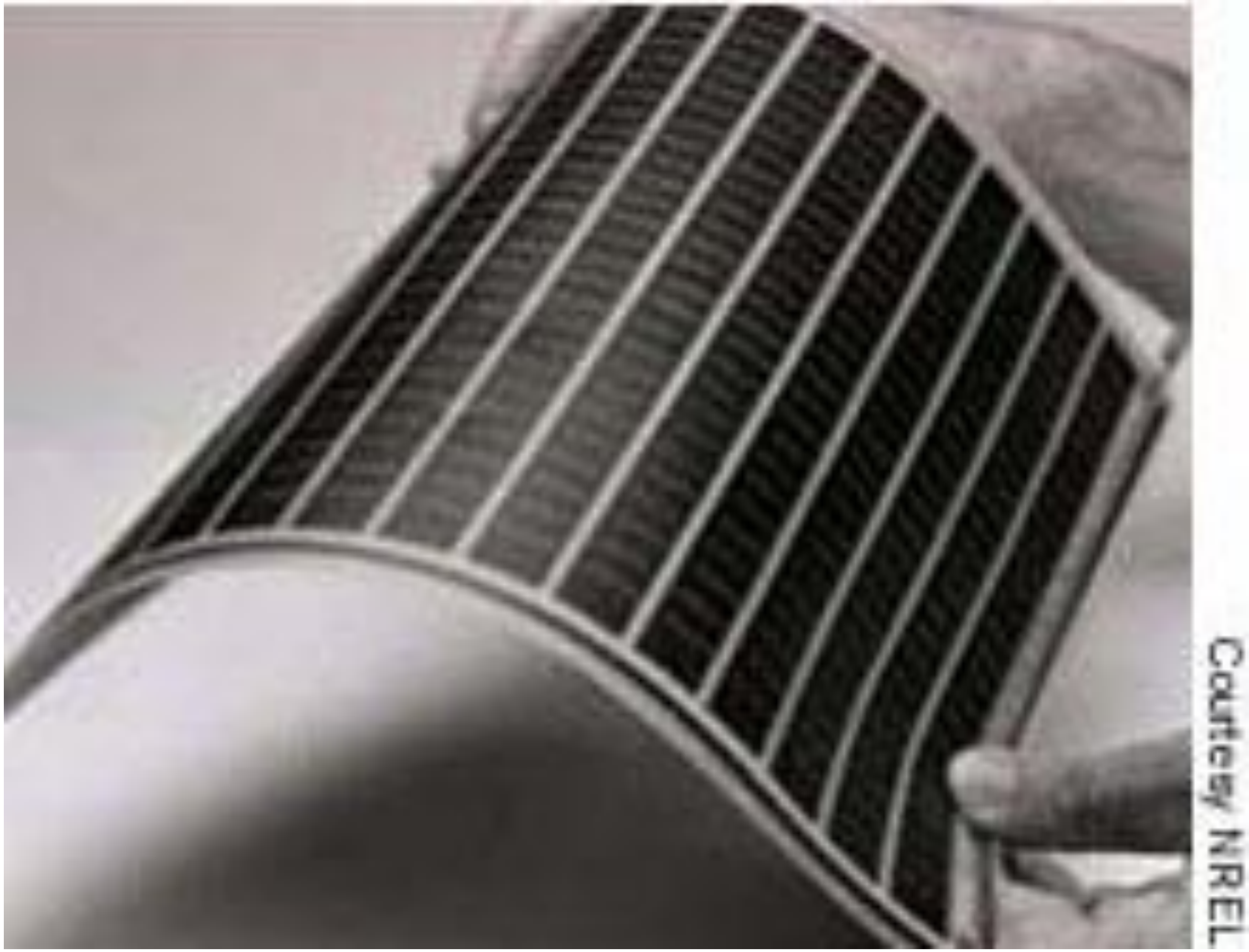




Snaha o omezení potřeby křemíku:

2. generace

Tenkovrstvé články



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:

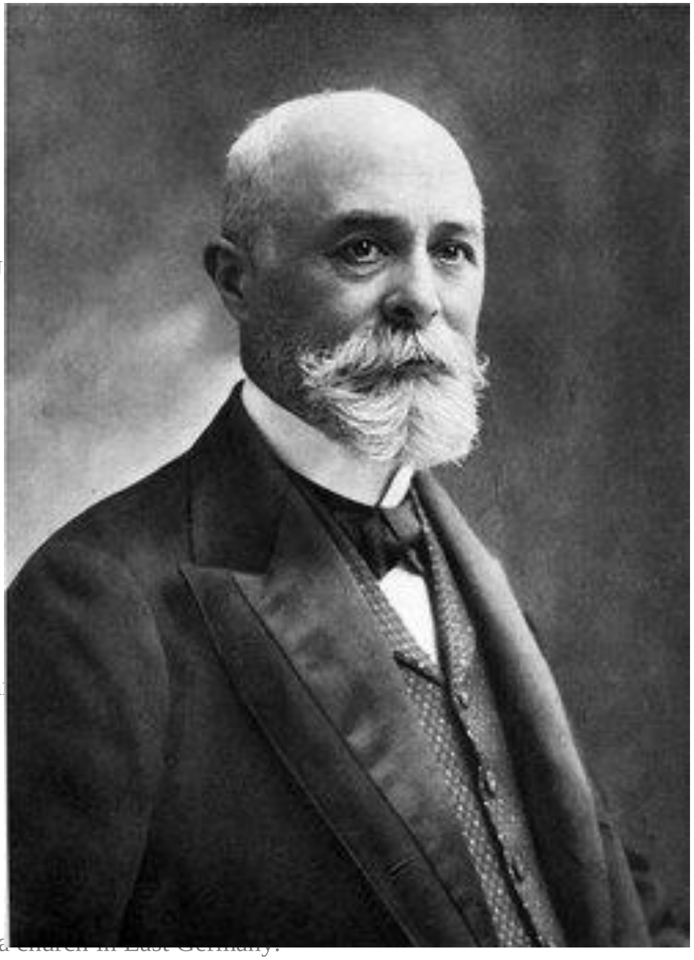
~ 4 km² per year

≅ area of Central Park

~ 50 km² per year

≅ area of Manhattan Island

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 church in East Germany.
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

1901 - Nikola Tesla the patent US685957, "Apparatus for the Utilization of Radiant Energy", and US685958, "
1902 - Philipp von Lenard - vnější fotoefekt v závislosti na barvě světla
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1918 - Jan Czochralski

1839 - Alexandre Edmond Becquerel - PV efekt
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1877 - Charles Fritts - první Se sluneční článek
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1901 - Nikola Tesla the patent US685957, "A
1902 - Philipp von Lenard - vnější fotoefekt
1904 - Wilhelm Hallwachs sluneční článek C
1905 - Albert Einstein
1913 - William Coblentz patent US1077219,
1914 - Sven Ason Berglund patents "method
1916 - Robert Millikan potvrdil Einsteinovo
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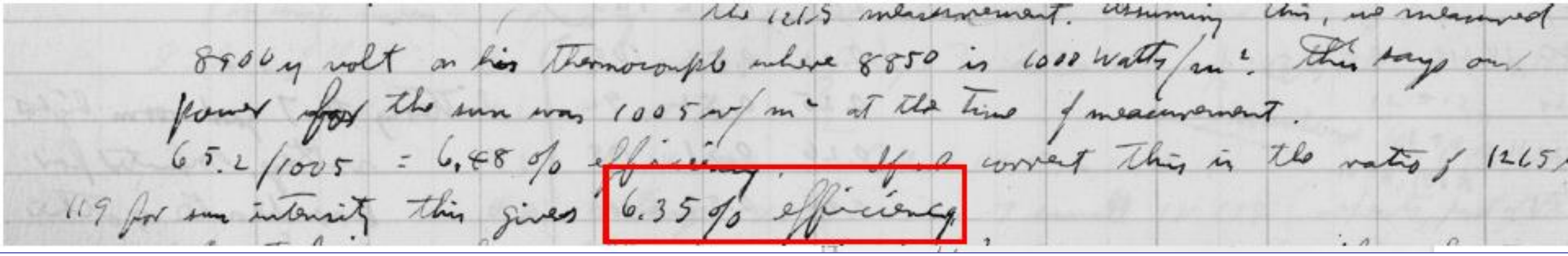
1980s - efficient silicon cells are in productio
1989 - efficient concentrator solar cell are in
1990 - The Cathedral of Magdeburg installs s
1991 - President George H. W. Bush directs
1993 - National Renewable Energy Laboratory
2001 - Helios

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



The Bell labs 1954

Cross section of the first cell:

- Arsenic-doped n-type base
- Boron-diffused emitter
- Back contact structure

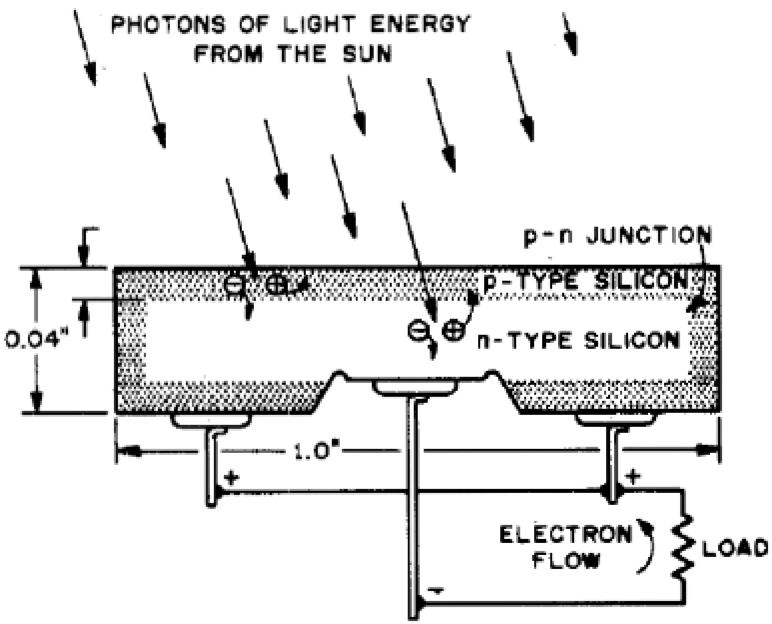


Fig. 2. Schematic of early silicon solar cell [8].

The first publication in Journal of Applied Physics:

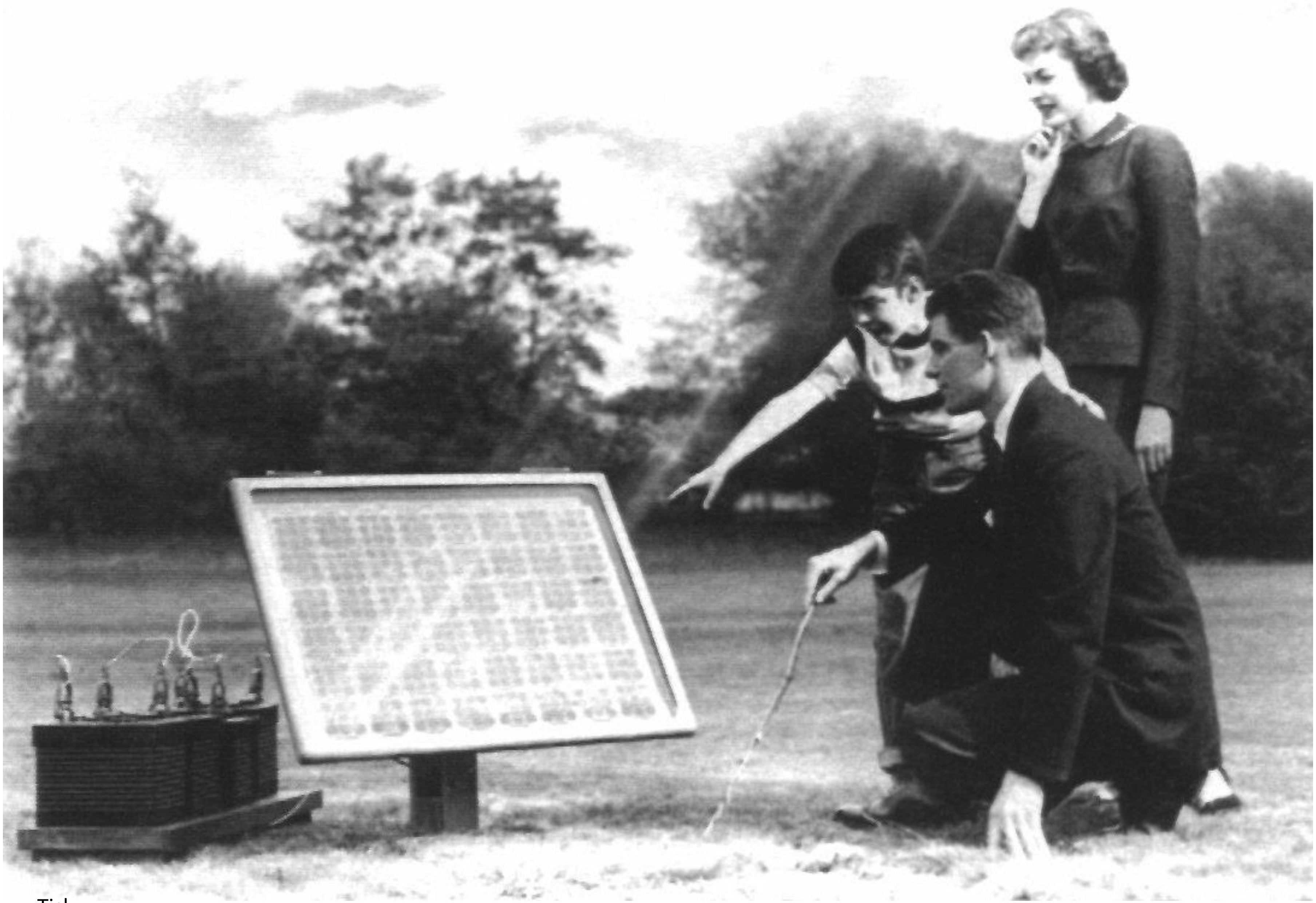
A New Silicon *p-n* Junction Photocell for Converting Solar Radiation into Electrical Power

D. M. Chapin, C. S. Fuller, and G. L. Pearson
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey
(Received January 11, 1954)

THE direct conversion of solar radiation into electrical power by means of a photocell appears more promising as a result of recent work on silicon *p-n* junctions. Because the radiant energy is used without first being converted to heat, the theoretical efficiency is high.

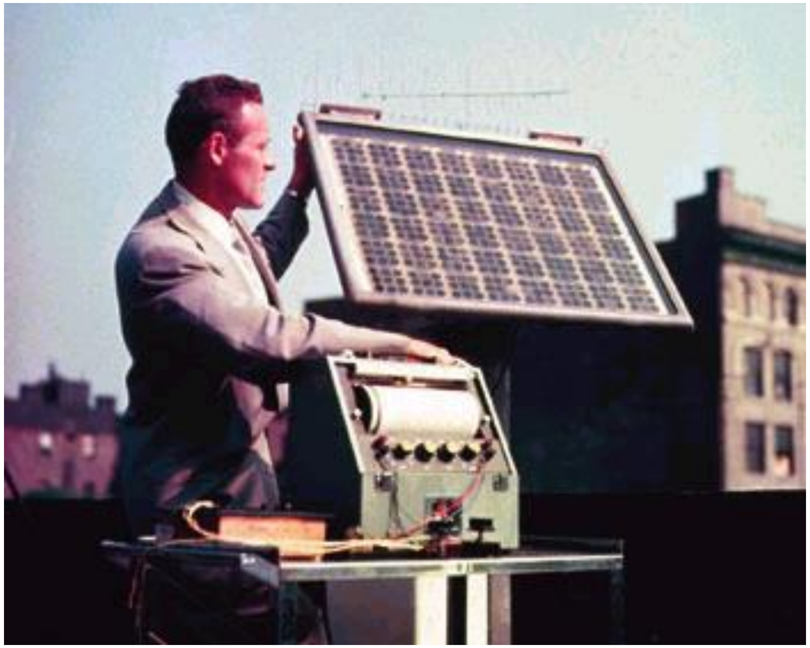
G.L- Pearson, American J. Phys. 25, p.591 (1957)

F.M Smits, IEEE TED 23, p.640 (1976)

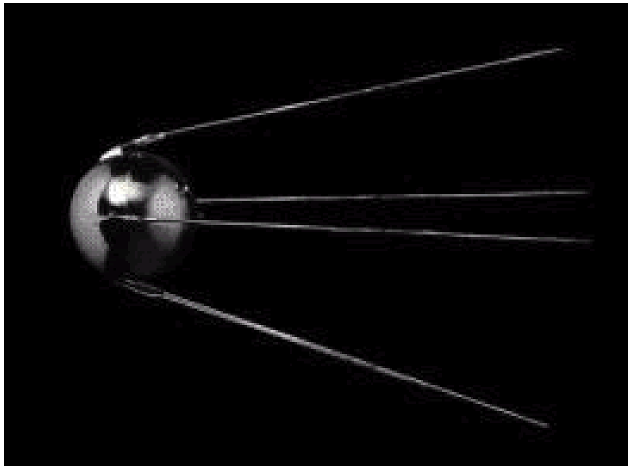


Tisk:
„počátek nové éry využití neomezené energie Slunce” (Times)
„jednoho dne mohou sluneční články vyrobit více energie než zdroje založené na uhlí, ropě či jádru” (New York Times).

Americus, Georgia, USA: První testy Bellovských slunečních baterií



Bell Labs, 1955



4. října 1957: Sputnik
83 kg na oběžné dráze 250 km

Vanguard I.

17.3.1958

1.47 kg

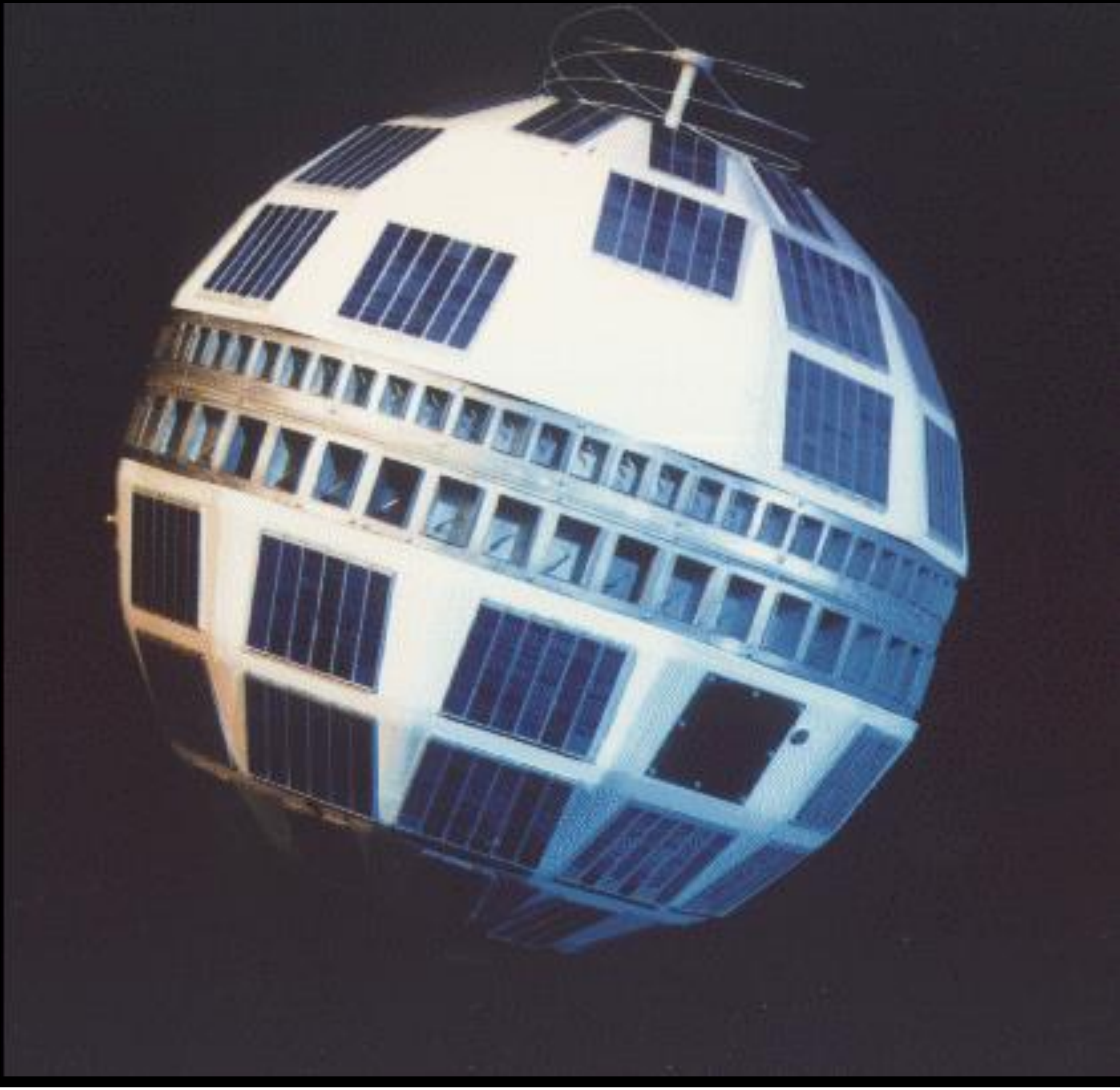
Grapefruit na oběžné dráze
(Nikita Chruščov)

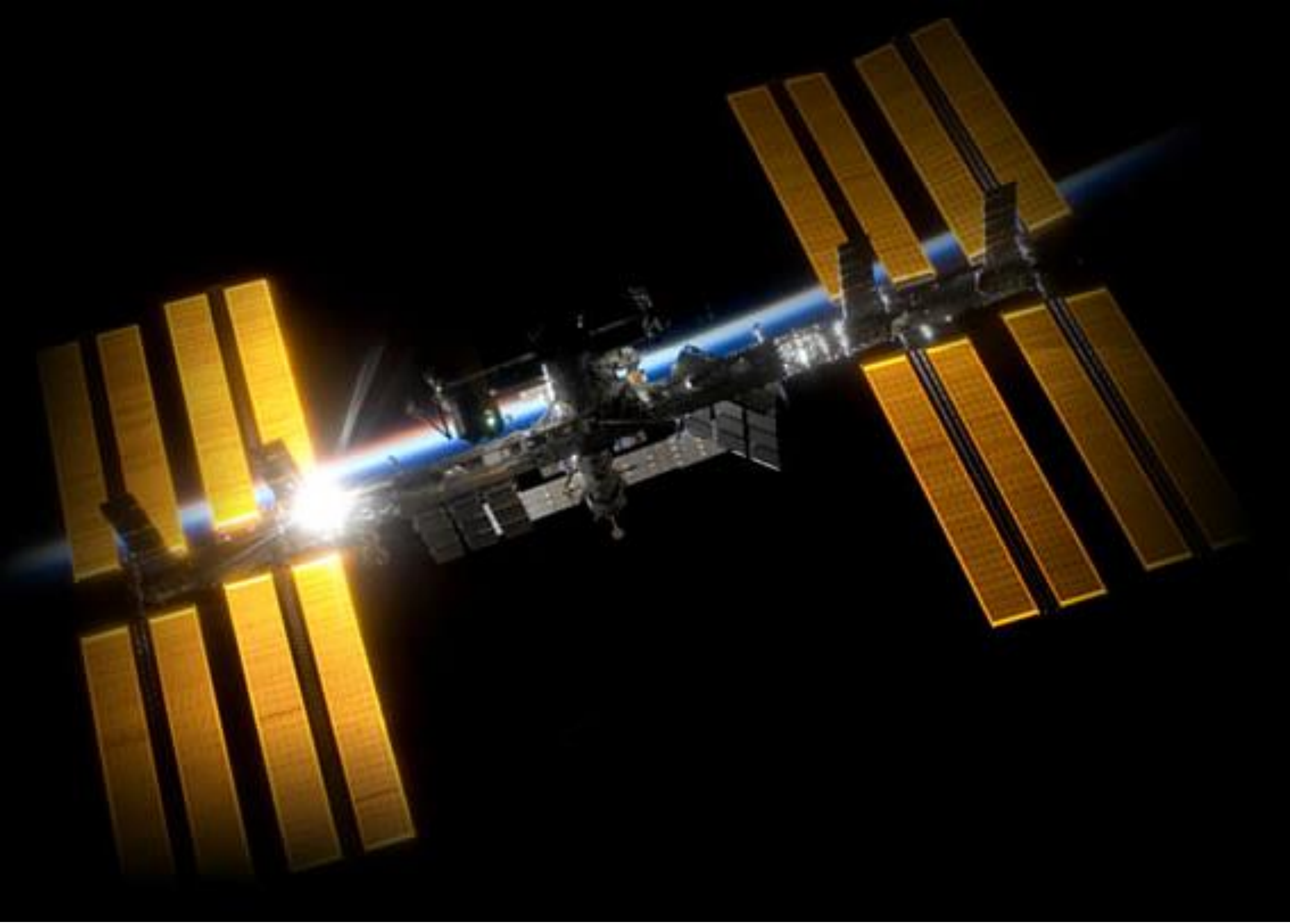
"kaputnik" (*Daily Express)*, "flopnik" (*Daily Herald)*, "puffnik" (*Daily Mail),* "stayputnik" *News Chronicle*.[

1962
Bellovské články napájely

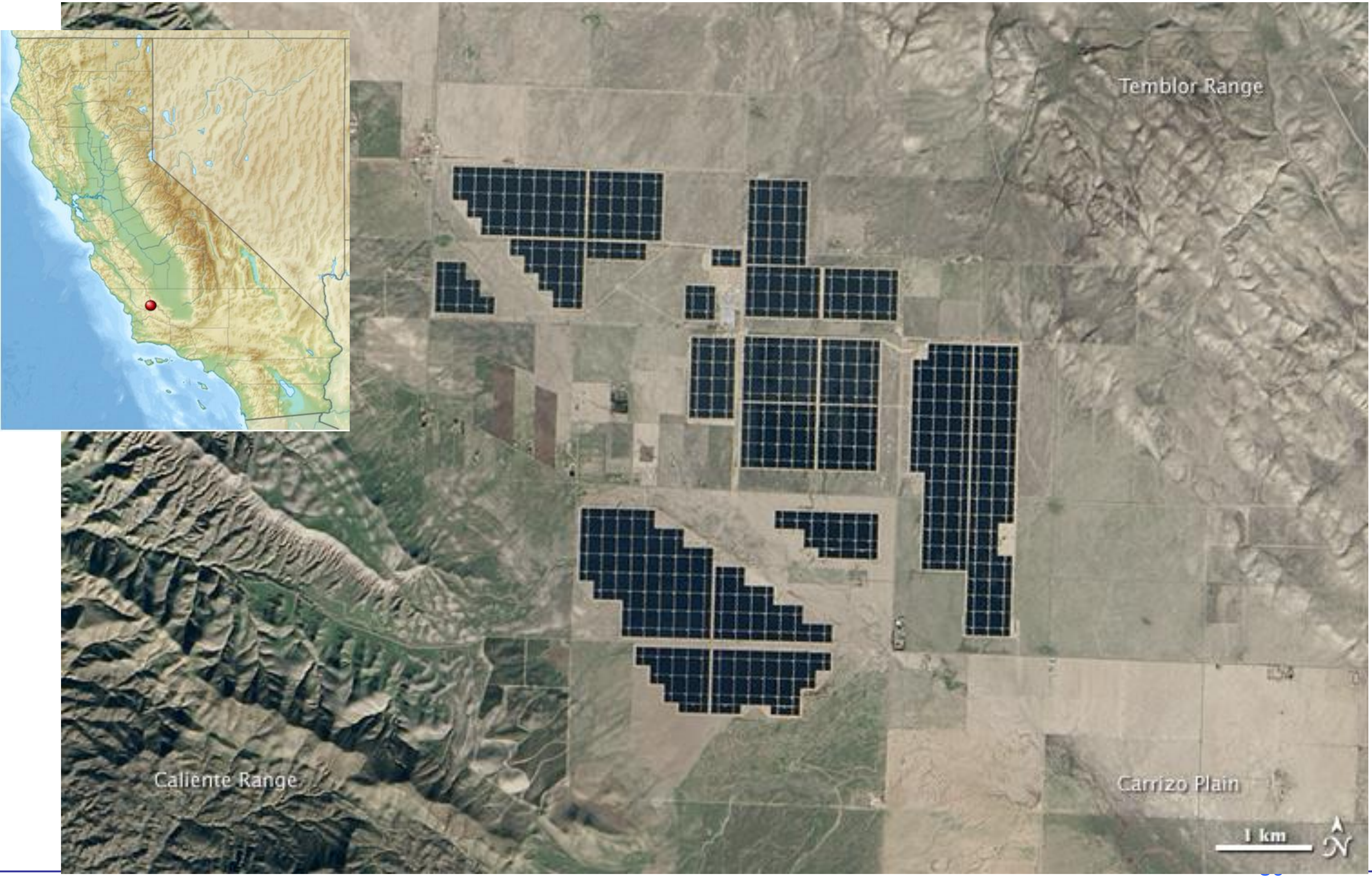
Telstar

10.července 1962

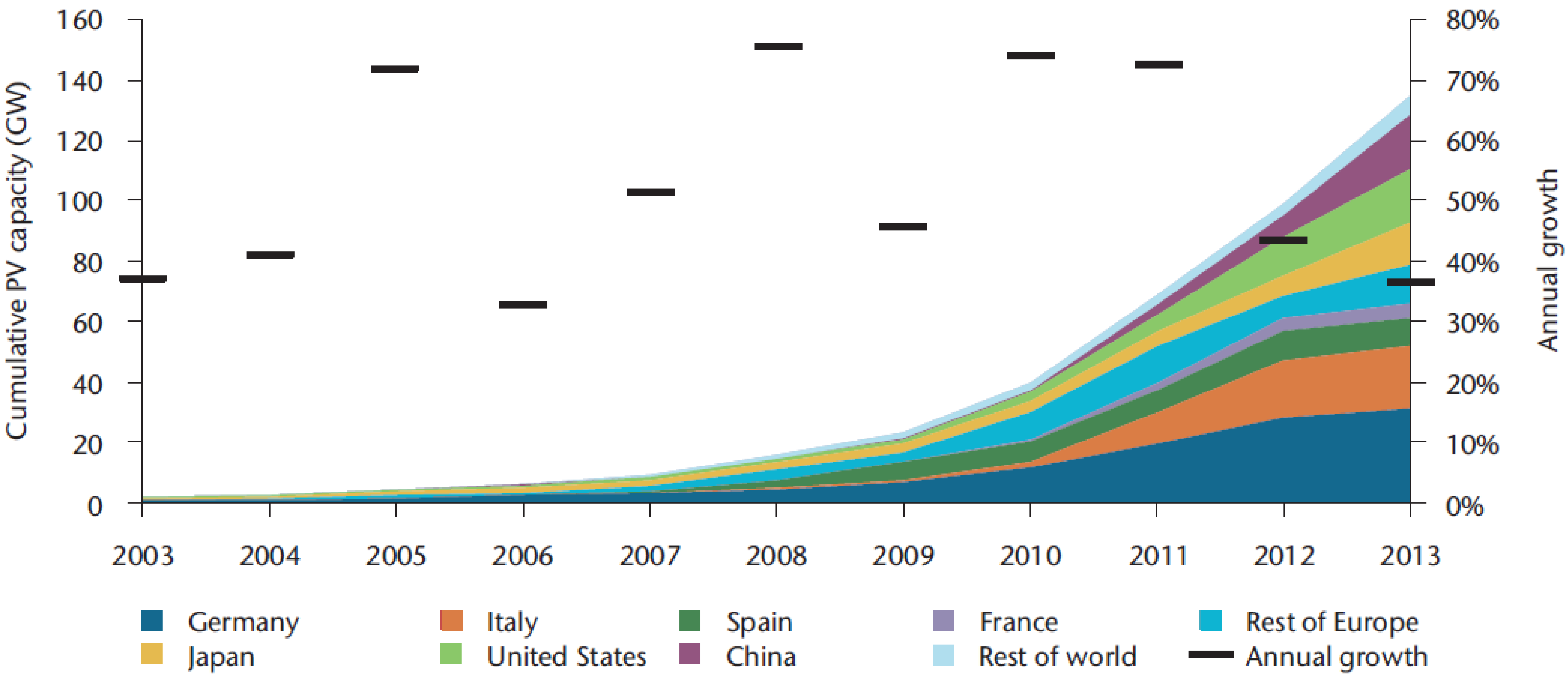




Fotovoltaika dnes: **je velká !**



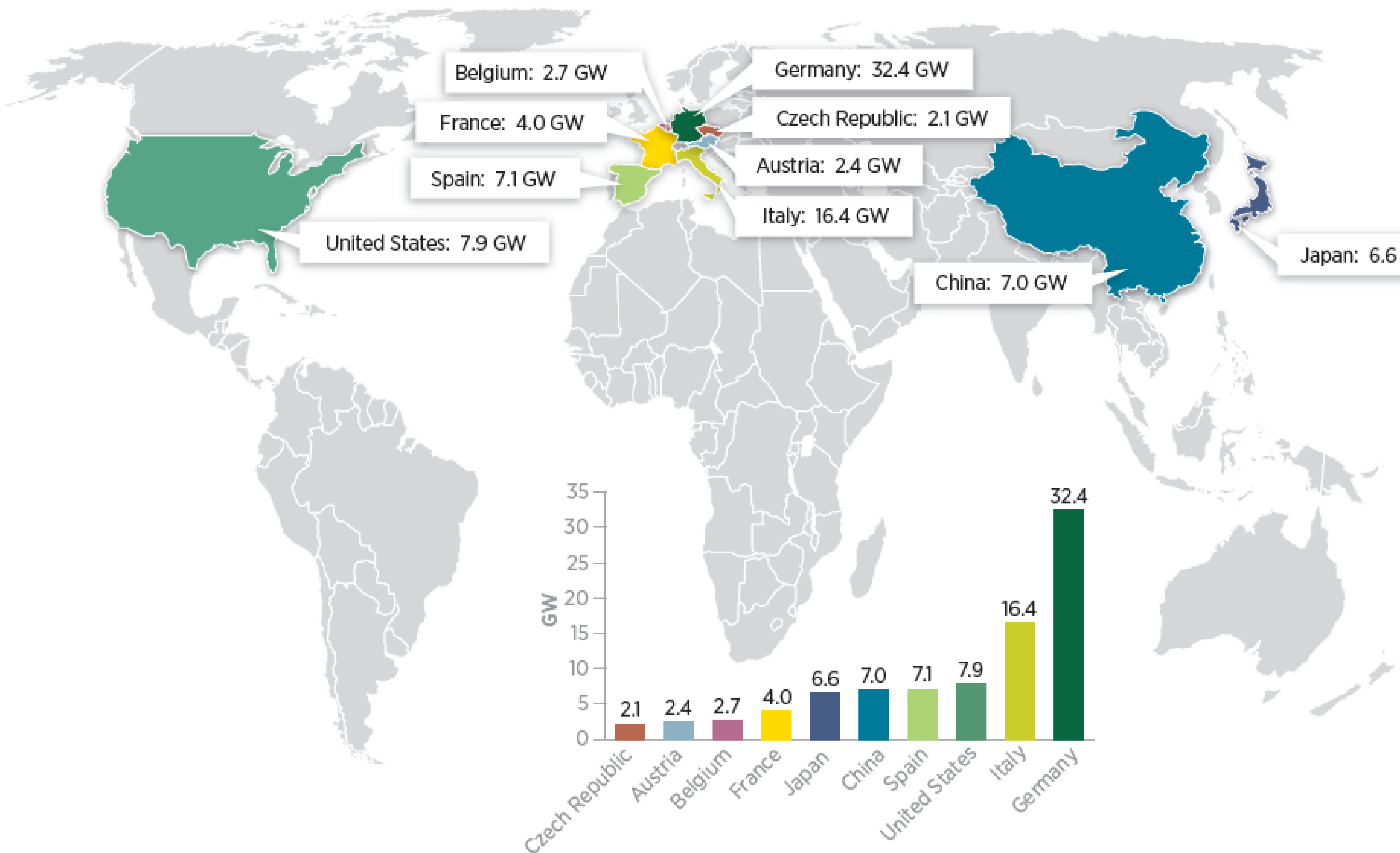
IEA Technology Roadmap: Solar Photovoltaic Energy - 2014 edition



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



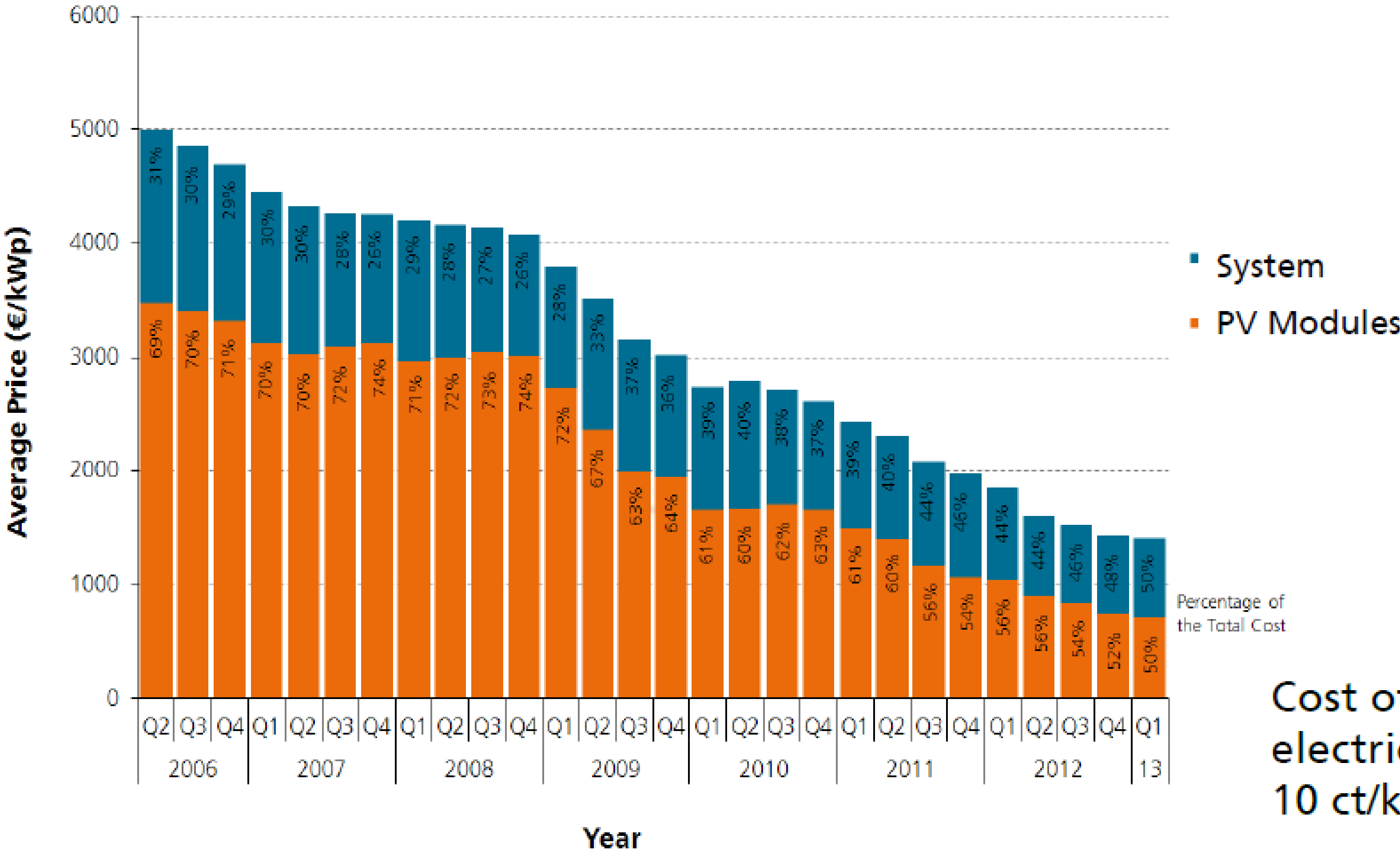
V

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

* Includes PV and CSP

Průměrná cena

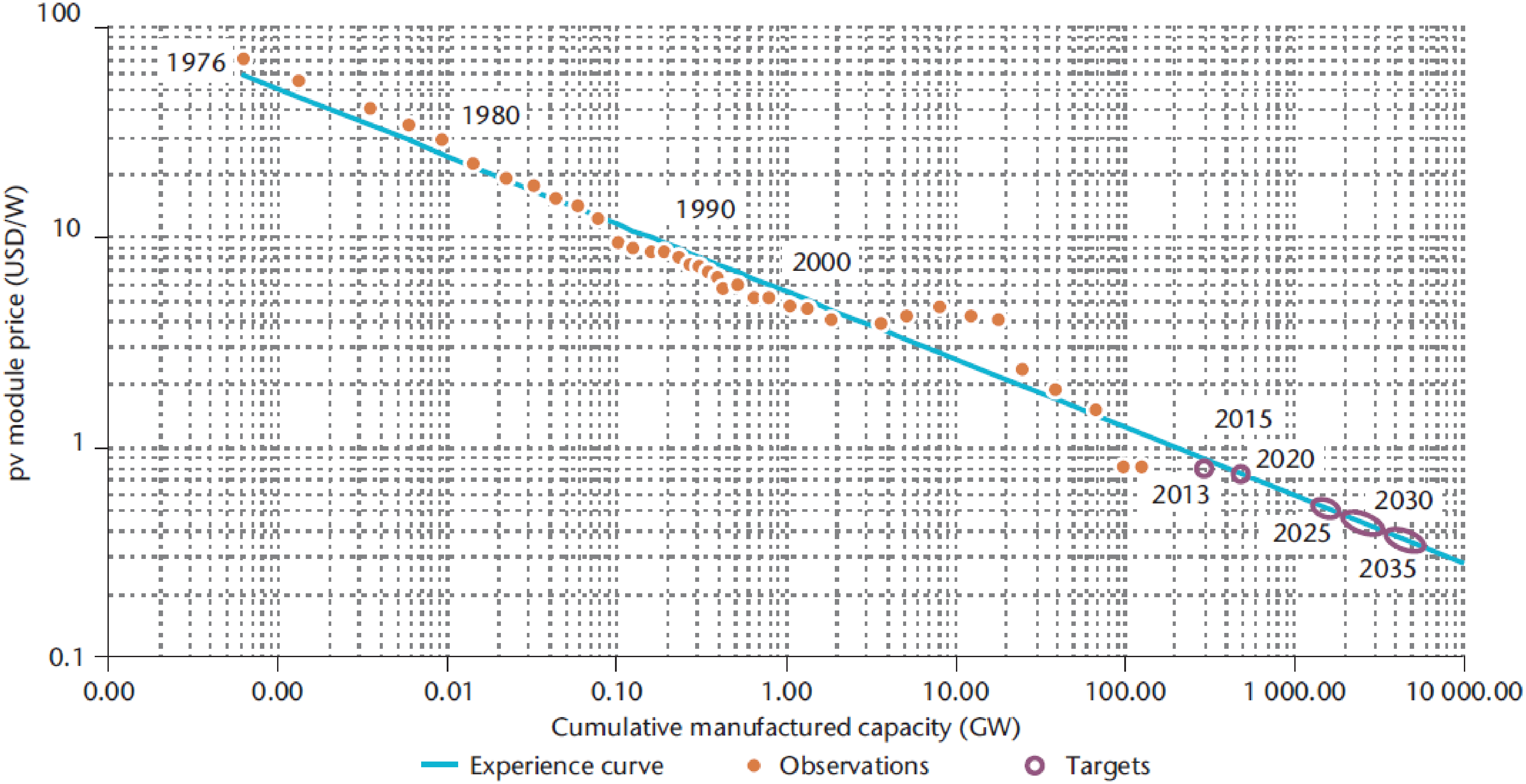
Average price for PV rooftop systems in Germany



Cost of PV electricity: 10 ct/kWh

IEA Technology Roadmap: Solar Photovoltaic Energy - 2014 edition

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

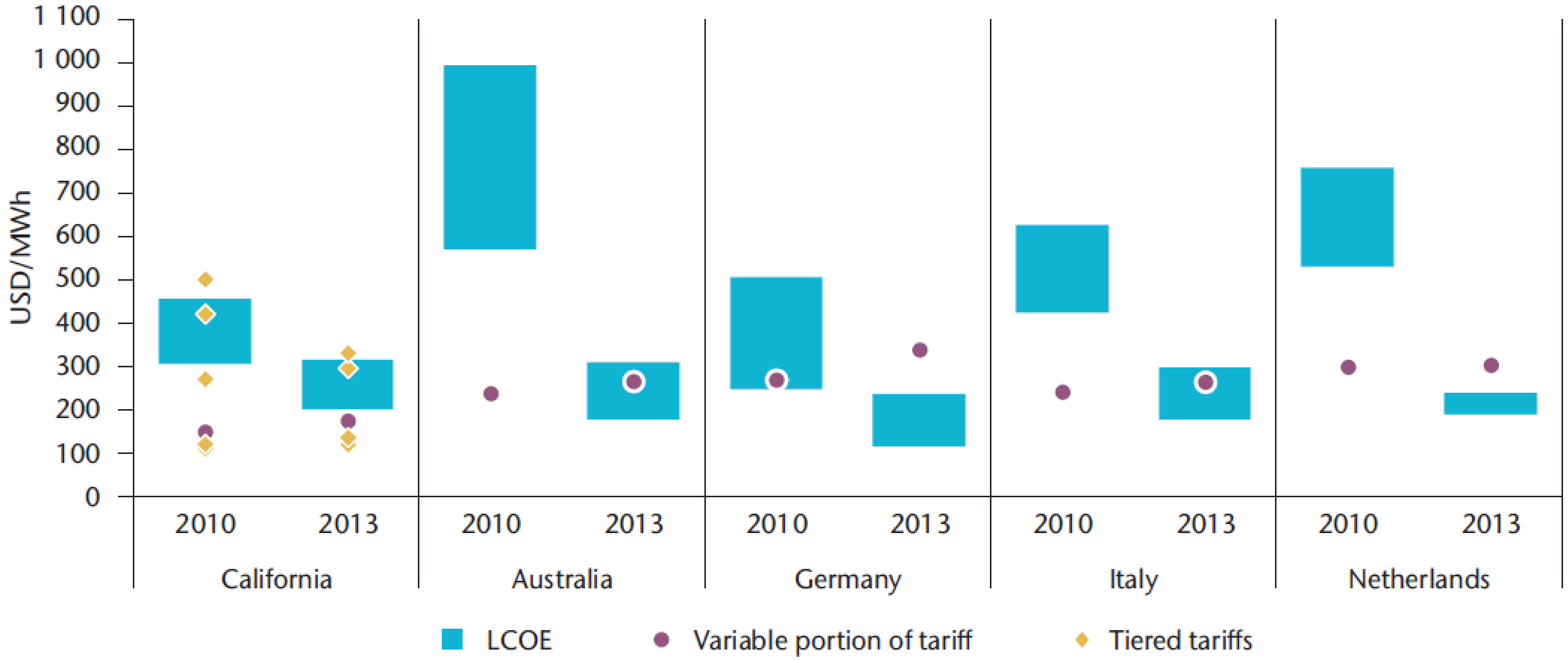


Notes: Orange dots indicate past module prices; purple dots are expectations. The oval dots correspond to the deployment starting in 2025, comparing the 2DS (left end of oval) and 2DS hi-Ren (right end).

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

IEA Technology Roadmap: Solar Photovoltaic Energy - 2014 edition

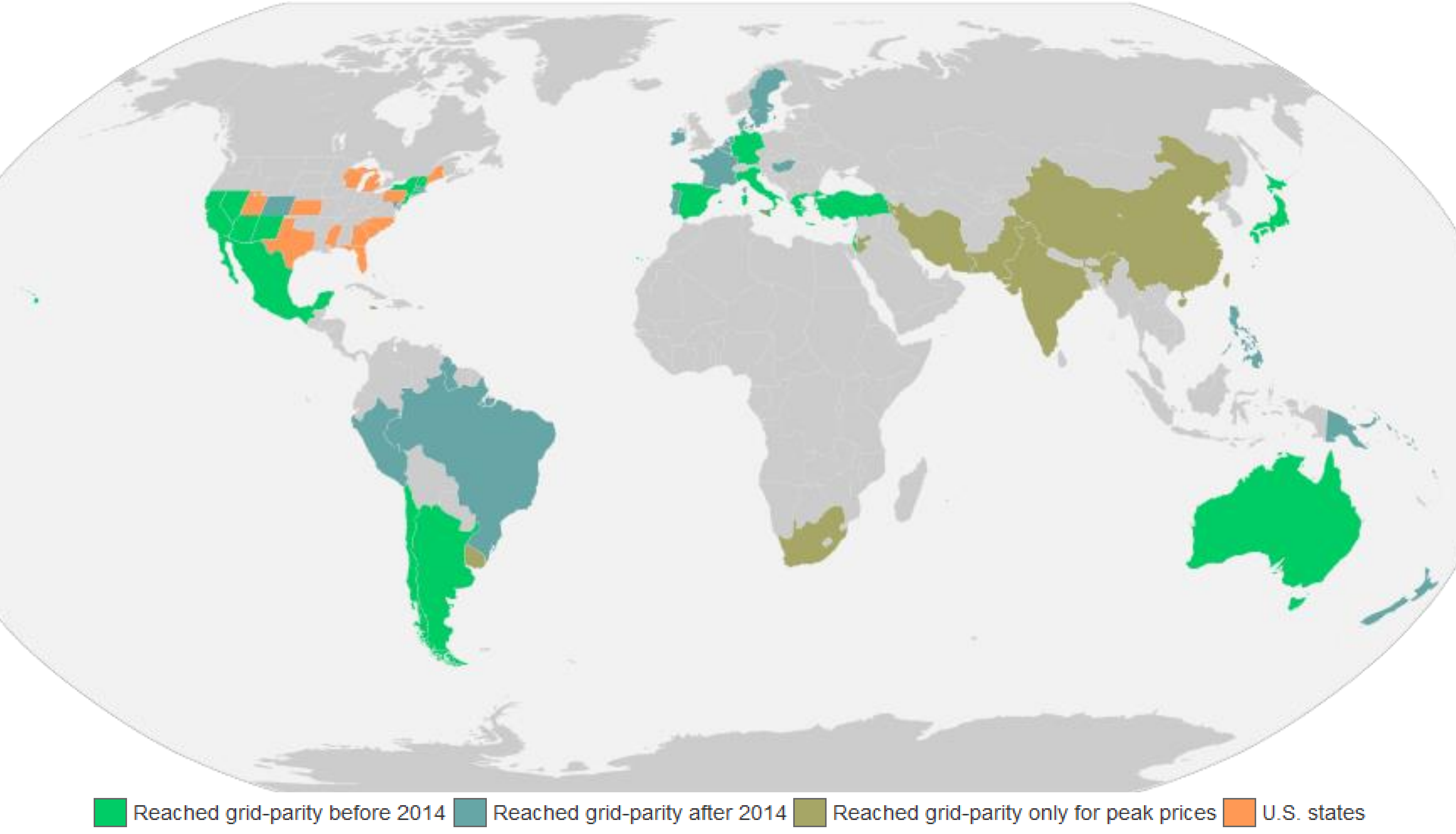
Figure 4: Grid parity was reached in 2013 in various countries



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.

Země, kde bylo dosaženo parity se sítí



https://commons.wikimedia.org/wiki/File:Grid_parity_map.svg

2.99$c/kWh

The Dubai Electricity & Water Authority (DEWA) received a world record-low bid of 2.99$c/kWh for the 800 MW third phase of its 5 GW Mohammed bin Rashid al-Maktoum solar project

http://www.pv-magazine.com/news/details/beitrag/third-phase-of-dubais-dewa-solar-project-attracts-record-low-bid-of-us-299-cents-kwh_100025683/#ixzz4RLX0j0X1

5.38 euro cents/kWh

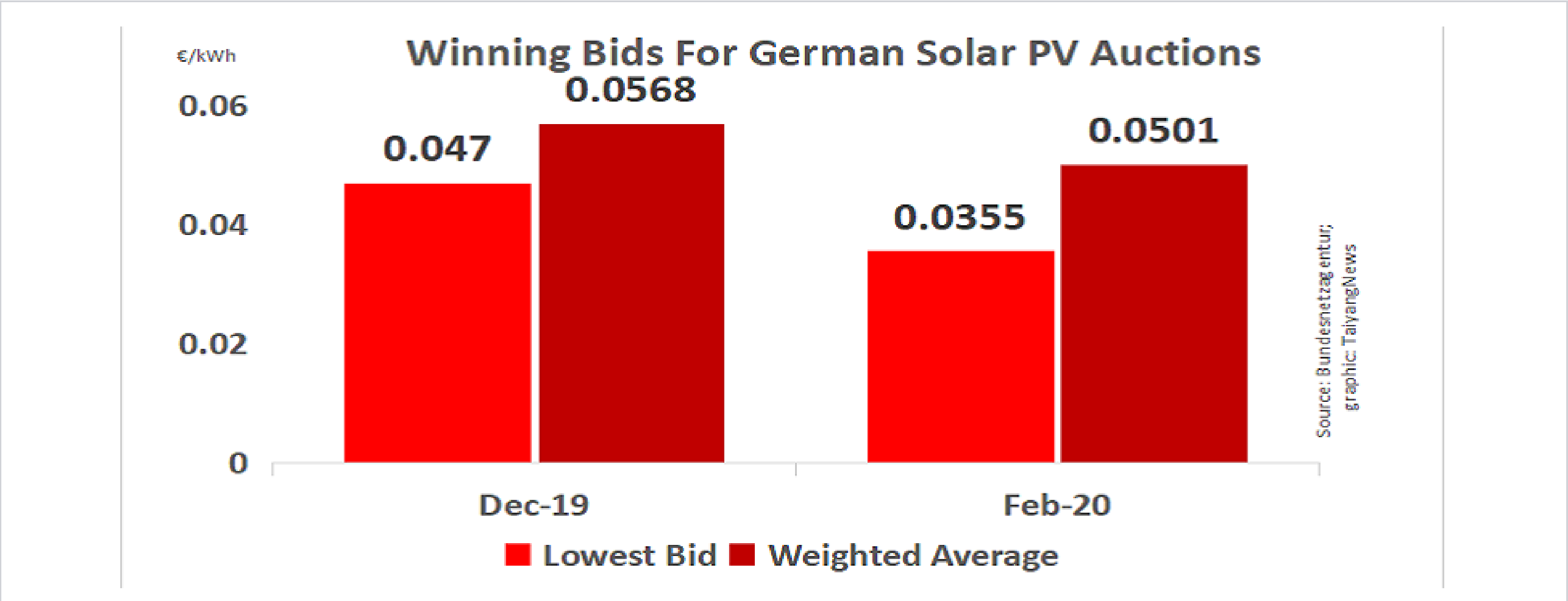
- The first cross-border solar tender in Europe sees five Danish solar developers with 50 MW of PV capacity in German auction. Winning bids of EUR 5.38 cents/kWh almost two cents lower than previous German solar tender.

http://www.pv-magazine.com/news/details/beitrag/cross-border-solar--denmark-gets-50-mw-of-german-tender-with-bids-of-538-euro-cents-kwh_100027030/#axzz4RTlpA2sd

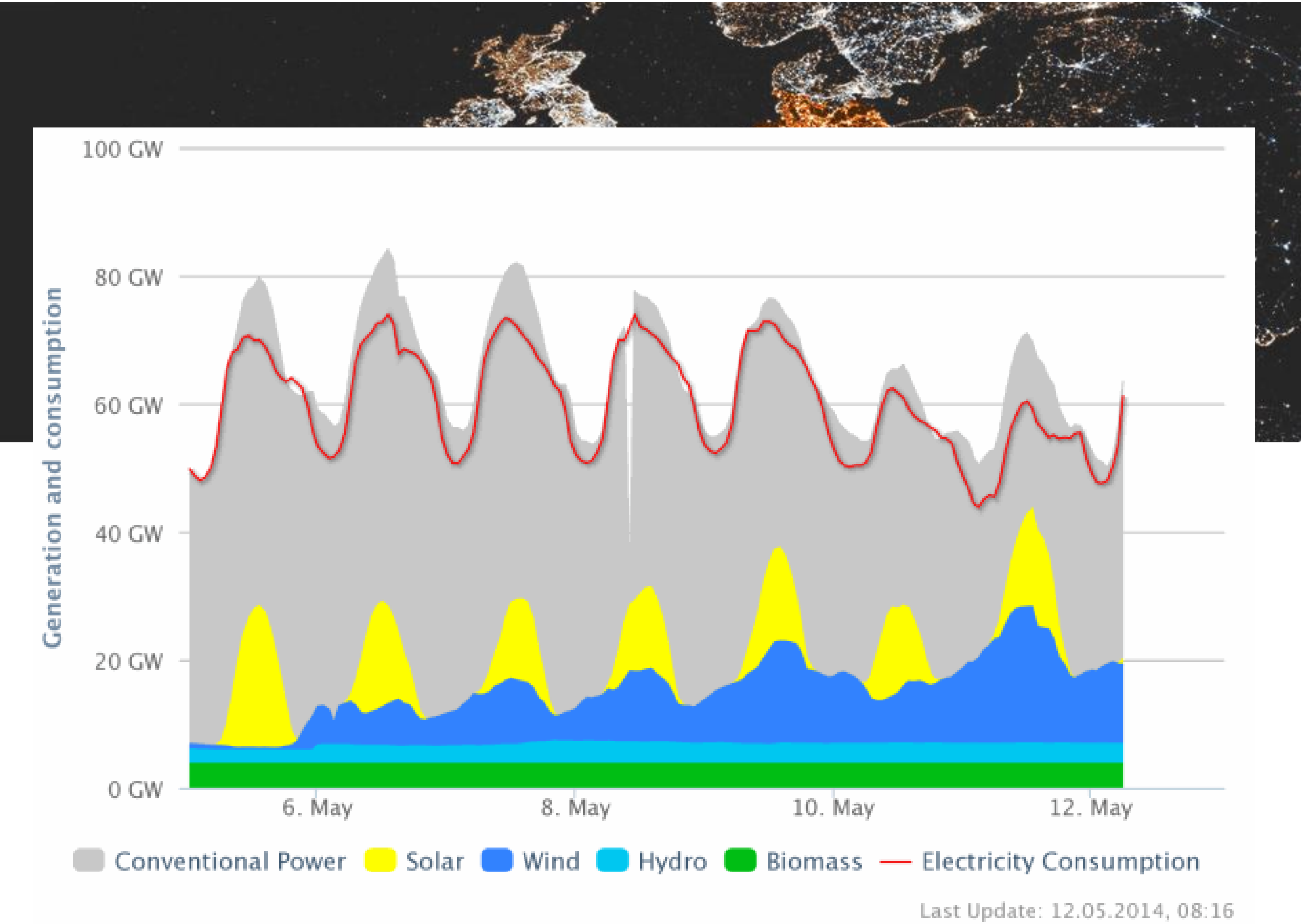
Record Low €0.0355 Winning Bid in German Auction

Bundesnetzagentur Awards 100.55 MW Under First Solar PV Auction Of 2020 In Germany With Average Winning Bid Coming In At €0.0501/kWh

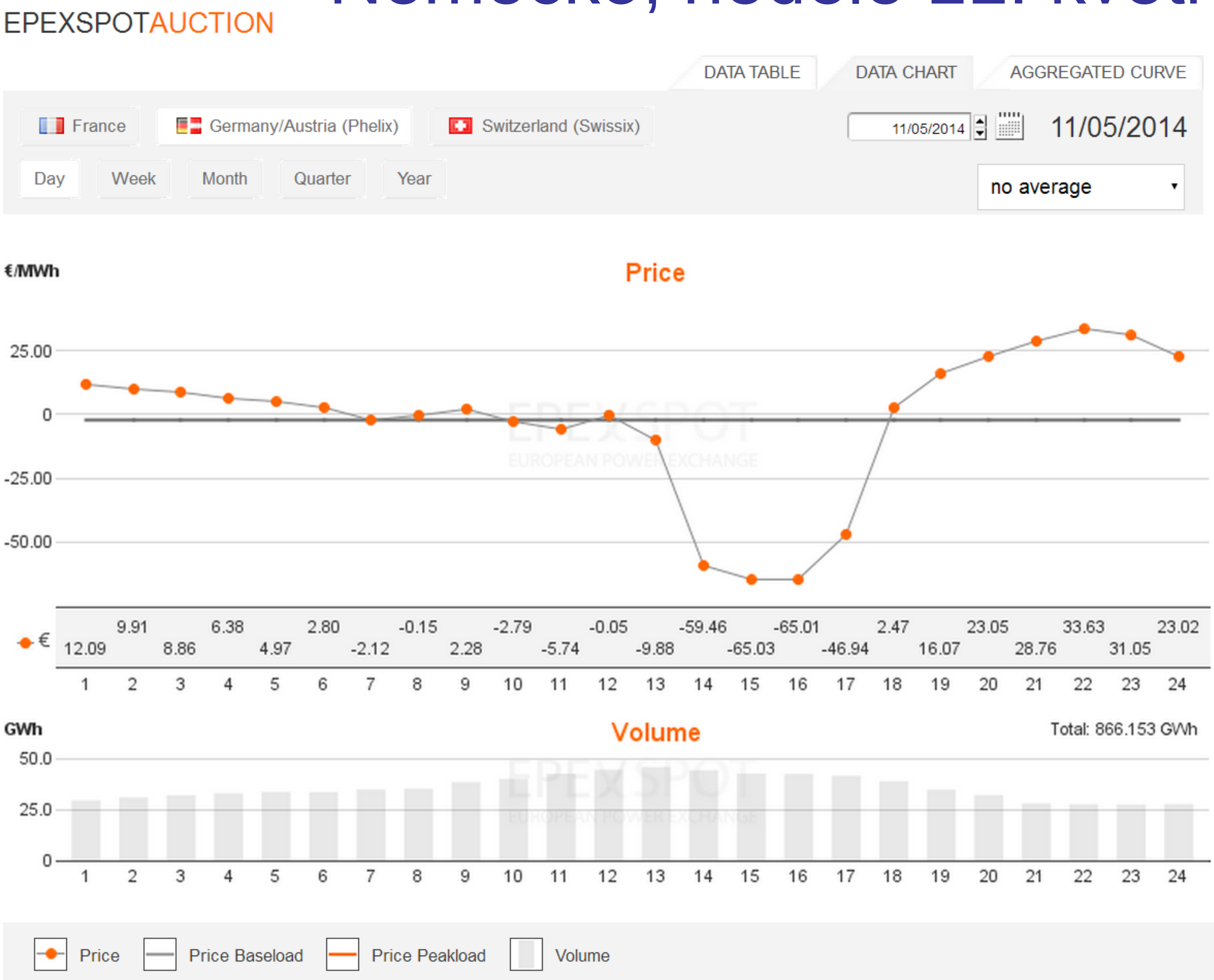
09:27 AM (Beijing Time) - 21. February 2020



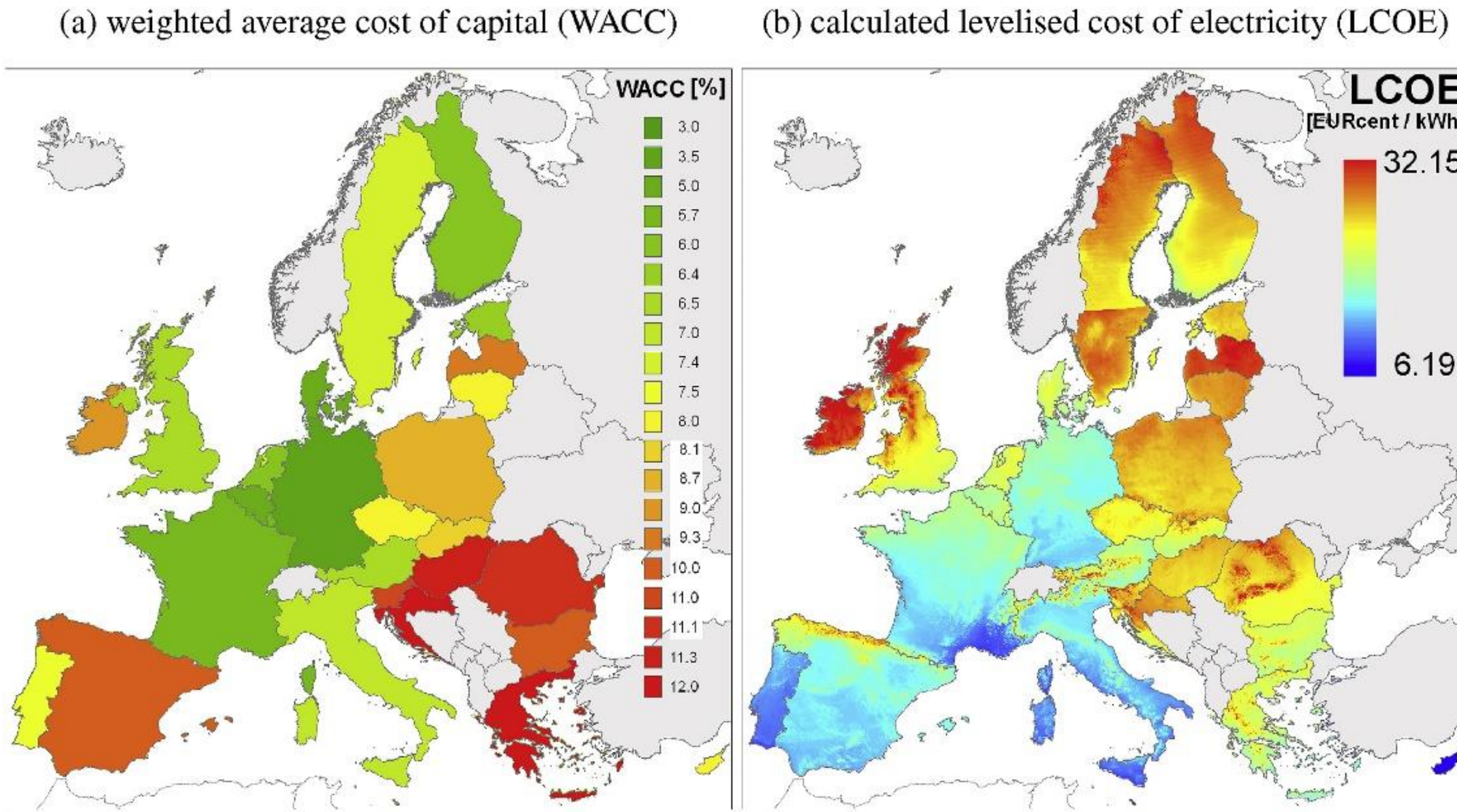
http://taiyangnews.info/markets/record-low-e0-0355-winning-bid-in-german-auction/


100 GW
80 GW
60 GW
40 GW
20 GW
0 GW
Generation and consumption
6. May
8. May
10. May
12. May
Conventional Power
Solar
Wind
Hydro
Biomass
Electricity Consumption
Last Update: 12.05.2014, 08:16

Německo, neděle 11. května 2014

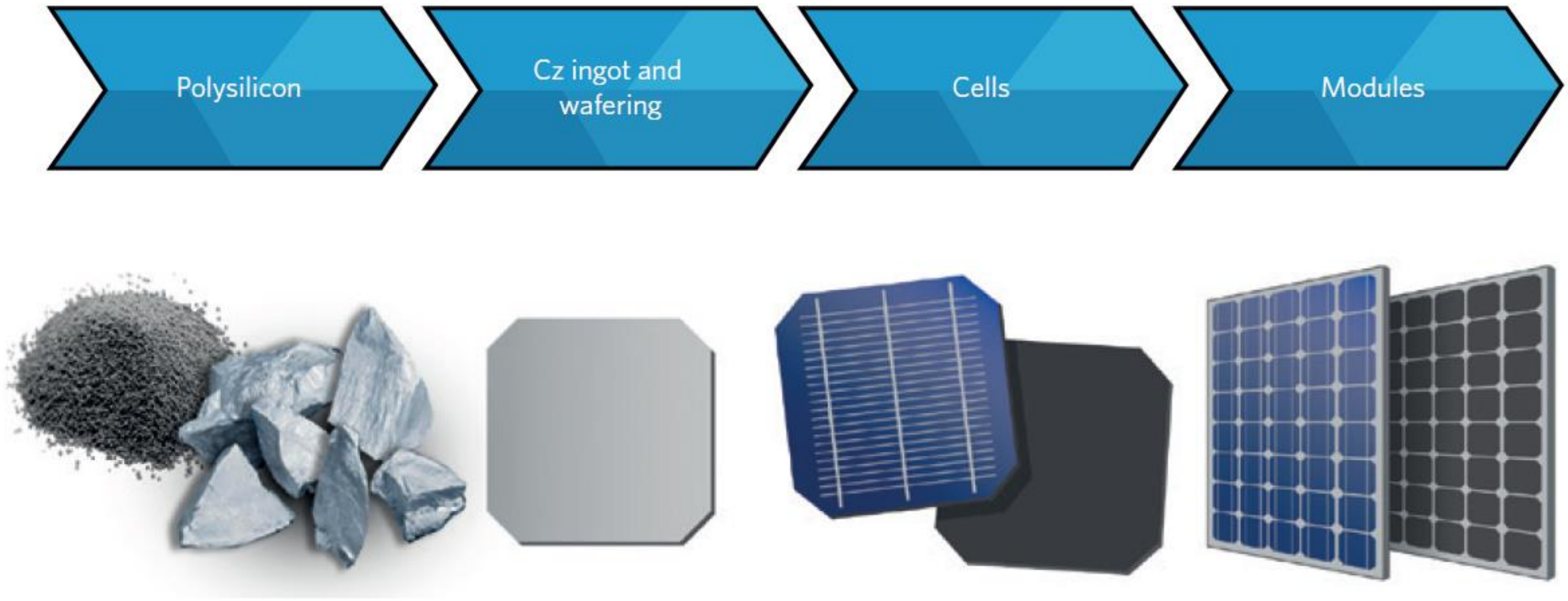


Grid parity map – EU 2019



Map of the WACC values and spatial distribution of the LCOE
of rooftop solar PV systems in the EU

The dominant technology: Si wafers



M.A. Green, Commercial progress and challenges for photovoltaics, Nature Energy. 1 (2016) 15015. doi:10.1038/nenergy.2015.15.

Výroba křemíkových článků:

PolySi

Crystal growth

Ingot squaring

Wafer cutting:

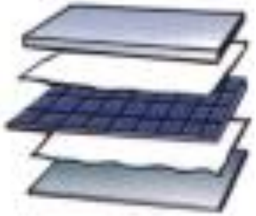
PN junction diffusion

Screen printing of electrodes

Solar cell

Stringing

Lamination

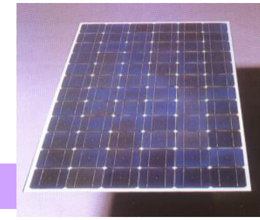


Framing

Module

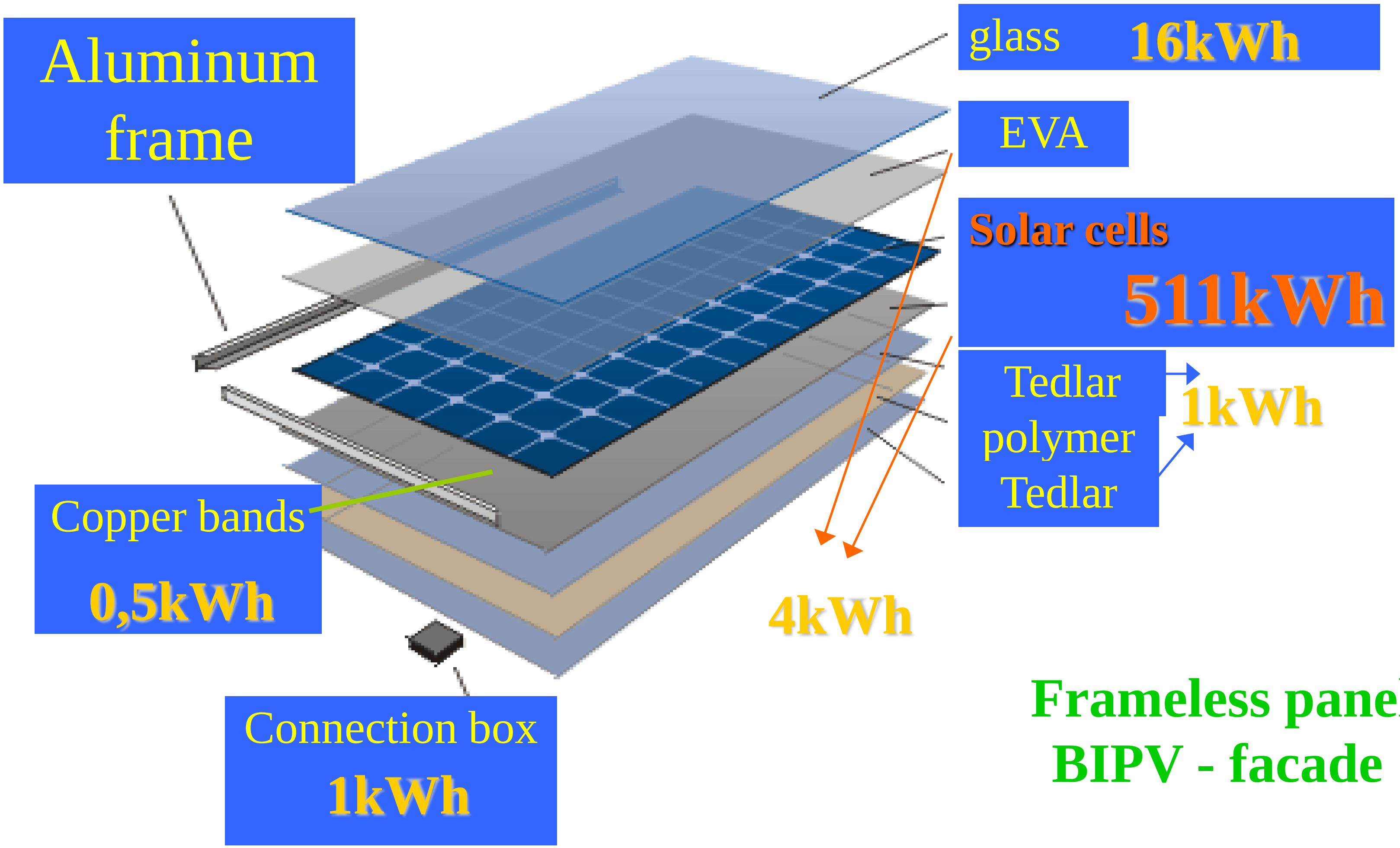
Energetické náklady panelu

Schematischer Aufbau von Status



Radix 72-112

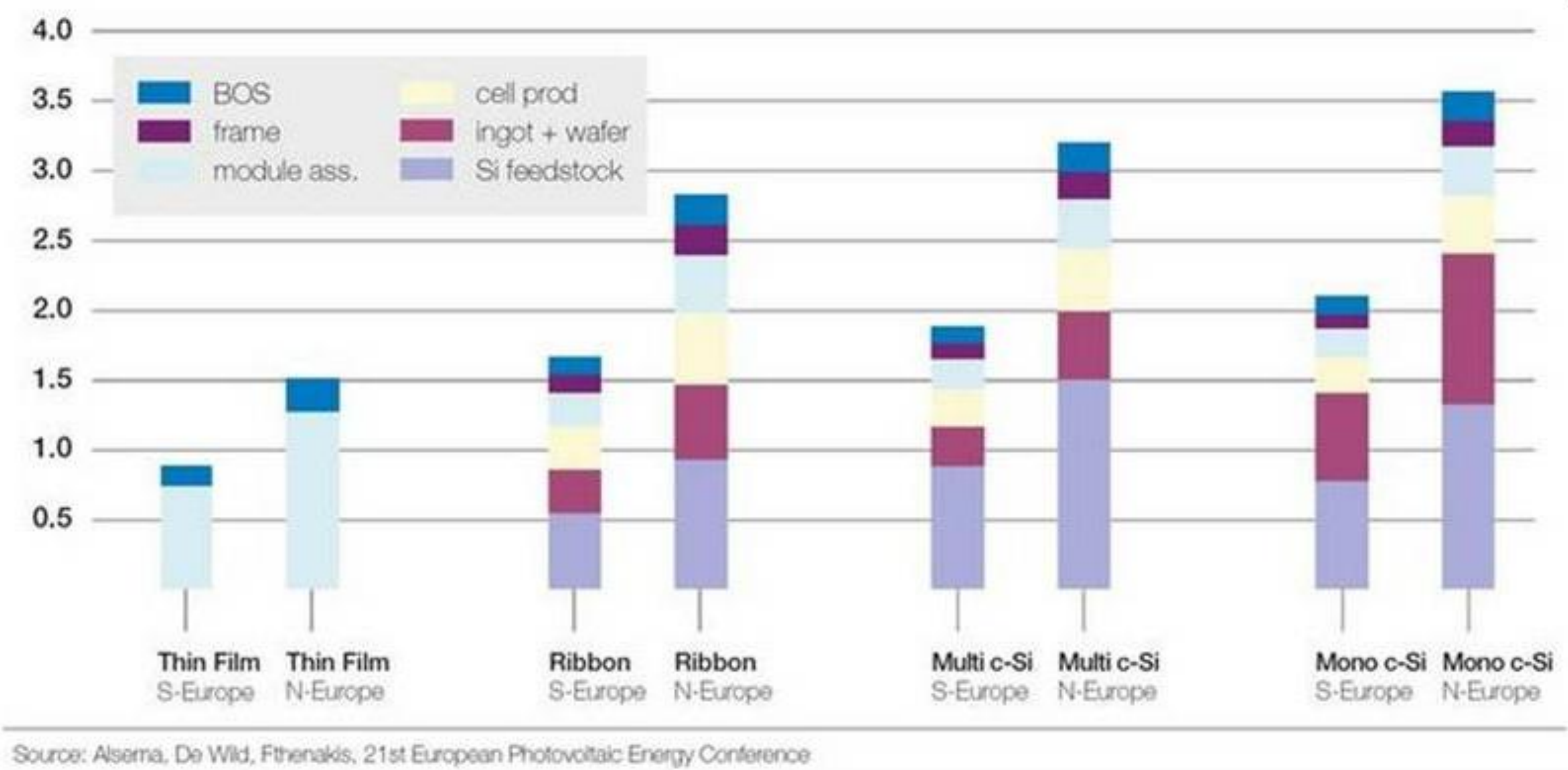
553,5kWh



Frameless panel - 4%

BIPV - facade - 3%

Doba energetické návratnosti

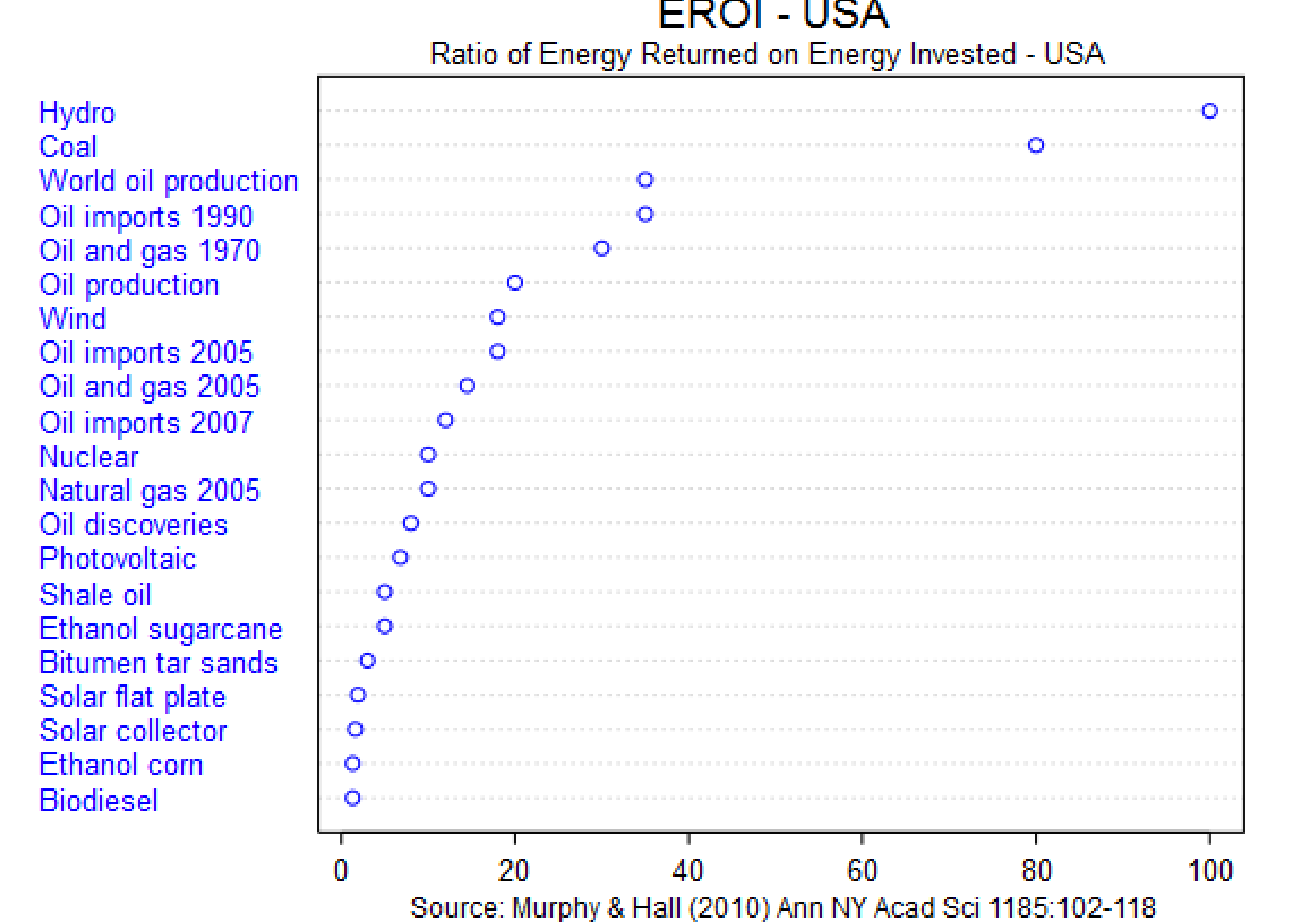


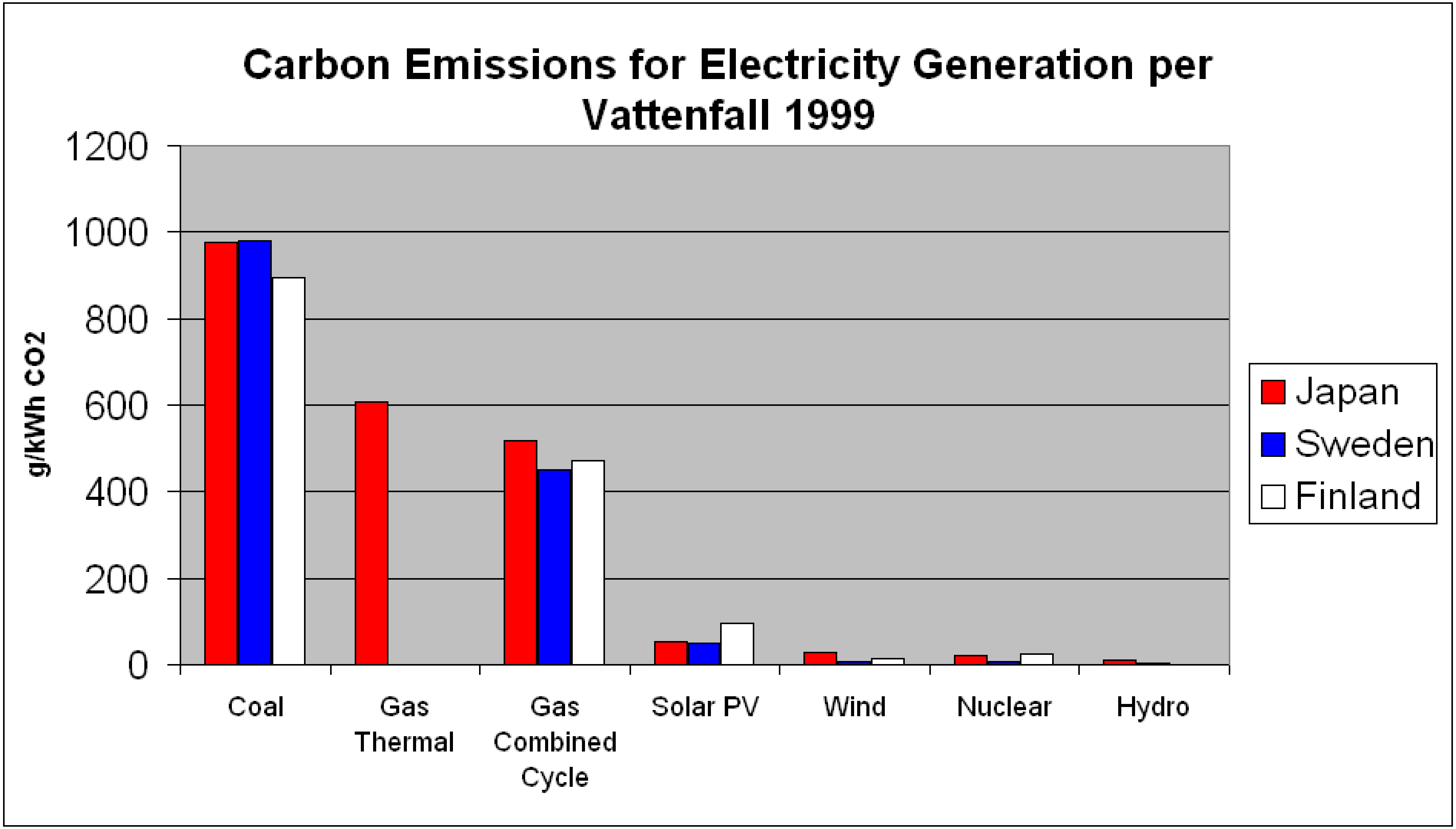
EROEI = Energy Return on Energy Invested (energetický zisk) pro FV je 10 - 20

Příklady EROEI pro jiné energetické zdroje

Zdroj	EROEI
Ropa v počátcích těžby	100
Texaská ropa okolo r. 1930	60
Blízkovýchodní ropa	30
Jiná ropná pole	10-35
Přírodní plyn	20
Kvalitní uhlí (Austrálie)	10 – 20
Nekvalitní uhlí (např. ČR)	4 – 10
Vodní elektrárny	10 – 40
Jaderné elektrárny	4 – 5
Ropné písky	Max. 3
Bitumenové břidlice	Max. 1,5
Biopaliva (v Evropě)	0,9 – 4

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


EROI - USA
Ratio of Energy Returned on Energy Invested - USA
Hydro
Coal
World oil production
Oil imports 1990
Oil and gas 1970
Oil production
Wind
Oil imports 2005
Oil and gas 2005
Oil imports 2007
Nuclear
Natural gas 2005
Oil discoveries
Photovoltaic
Shale oil
Ethanol sugarcane
Bitumen tar sands
Solar flat plate
Solar collector
Ethanol corn
Biodiesel
0
20
40
60
80
100
Source: Murphy & Hall (2010) Ann NY Acad Sci 1185:102-118



https://commons.wikimedia.org/wiki/File:Greenhouse_emissions_by_electricity_source.PNGReference: the UIC effectively [http://www.uic.com.au/nip57.htm], which gets data from Vattenfall 1999, which is built upon Japan's Central Research Institute of the Electric Power Industry's work

Death Rate per 1000 TWh

Energy Source	Mortality Rate (deaths/trill. kWh)	
Coal – global average	170,000	(50% global electricity)
Coal – China	280,000	(75% China's electricity)
Coal – U.S.	15,000	(44% U.S. electricity)
Oil	36,000	(36% of energy, 8% of electricity)
Natural Gas	4,000	(20% global electricity)
Biofuel/Biomass	24,000	(21% global energy)
Solar (rooftop)	440	(< 1% global electricity)
Wind	150	(~ 1% global electricity)
Hydro – global average	1,400	(15% global electricity)
Nuclear – global average	90	(17% global electricity w/Chern&Fukush)

Another way to describe this human health energy fee is that it costs about 2,000 lives per year to keep the lights on in Beijing but only about 200 lives to keep them on in New York.

http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/#64f7a5ae49d2


Private Area
PV CYCLE
PV RECYCLING
PV CYCLE
LEGISLATION

GREEN ENERGY

SOLAR CITY: HIDDEN-IN-PLAIN-SIGHT SOLAR PANELS

125 000 TW