Integration of PV in future electricity systems

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PVMD

Question?

Do we use
a desirable mix
of energy sources
in Netherlands?

European commission

March 2007: Climate and energy targets for 2020

The climate and energy package is a set of binding legislation which aims to ensure the European Union meets its ambitious climate and energy targets for 2020.

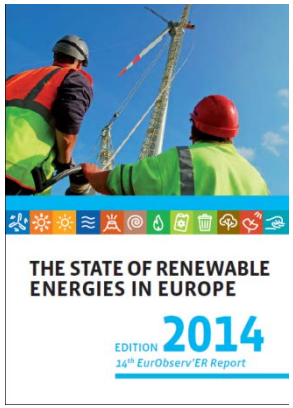
These targets, known as the **"20-20-20"** targets, set three key objectives for 2020:

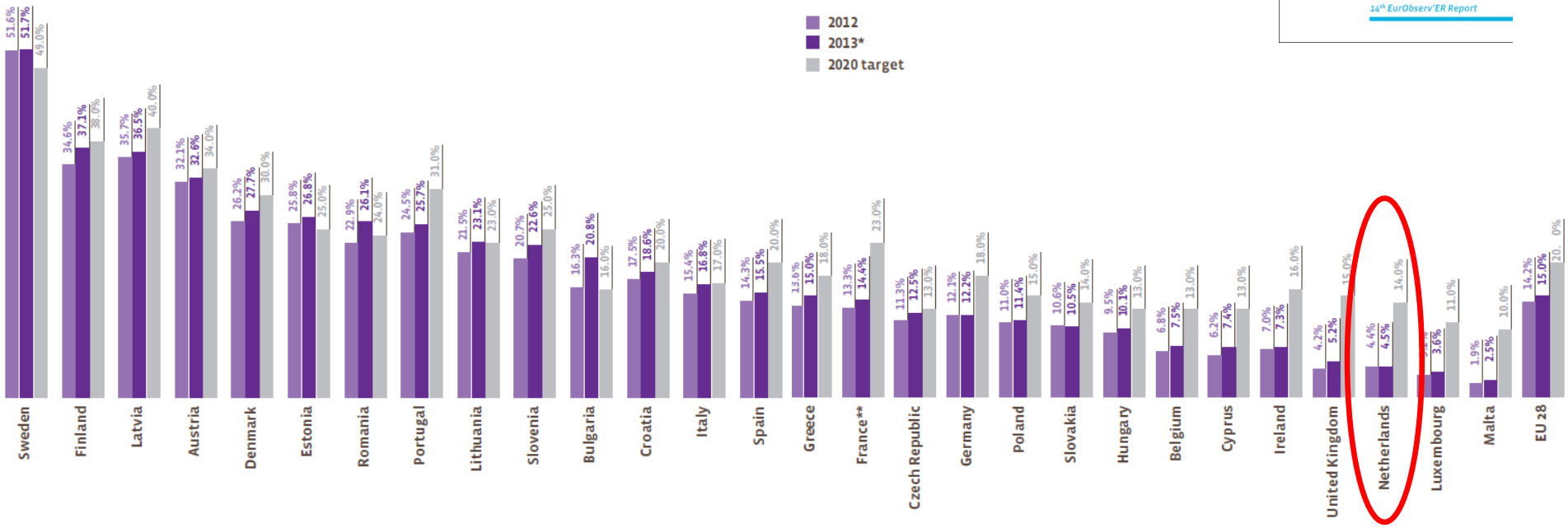
- 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU's energy efficiency.

http://ec.europa.eu/clima/policies/package/index_en.htm

Renewable energy use in Europe

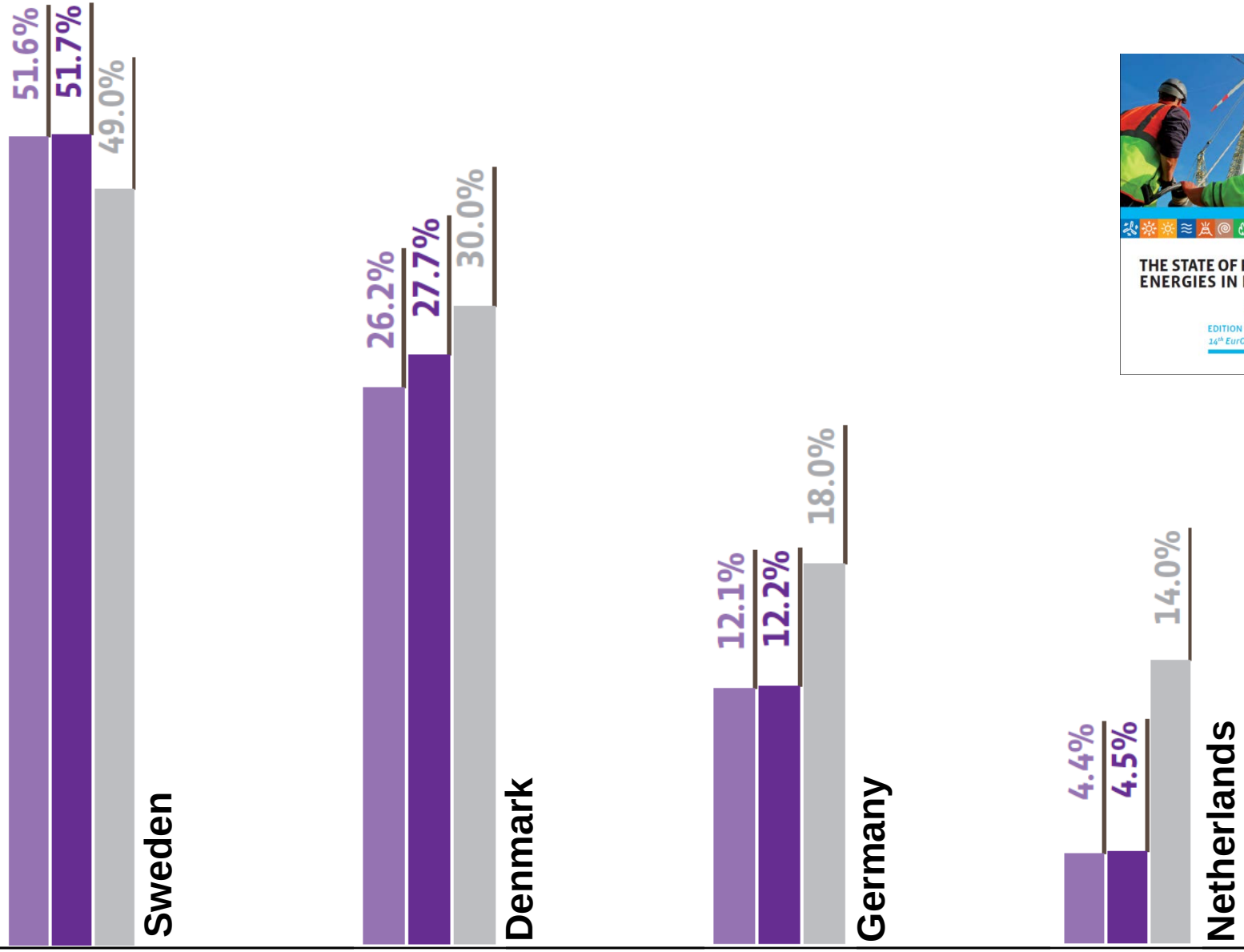
Share of energy from renewable energy sources in gross final energy consumption in 2012 and 2013 and national targets in 2020

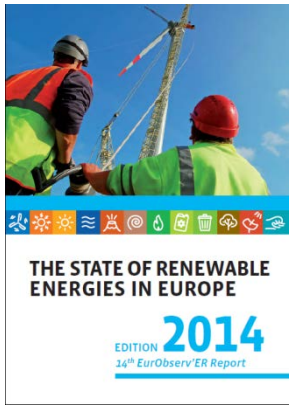




The state of renewable energies in Europe, Edition 2014, *14th EurObserv'ER Report*
http://www.energies-renouvelables.org/observ-er/stat_baro/barobilan/barobilan14_EN.pdf

Renewable energy use in Europe





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Question?

Do we use
a desirable mix
of energy sources
in Netherlands?

Answer

NO

Question

What can we do about it?

Answer

Accelerate
energy transition towards **sustainable energy**

Sustainable energy

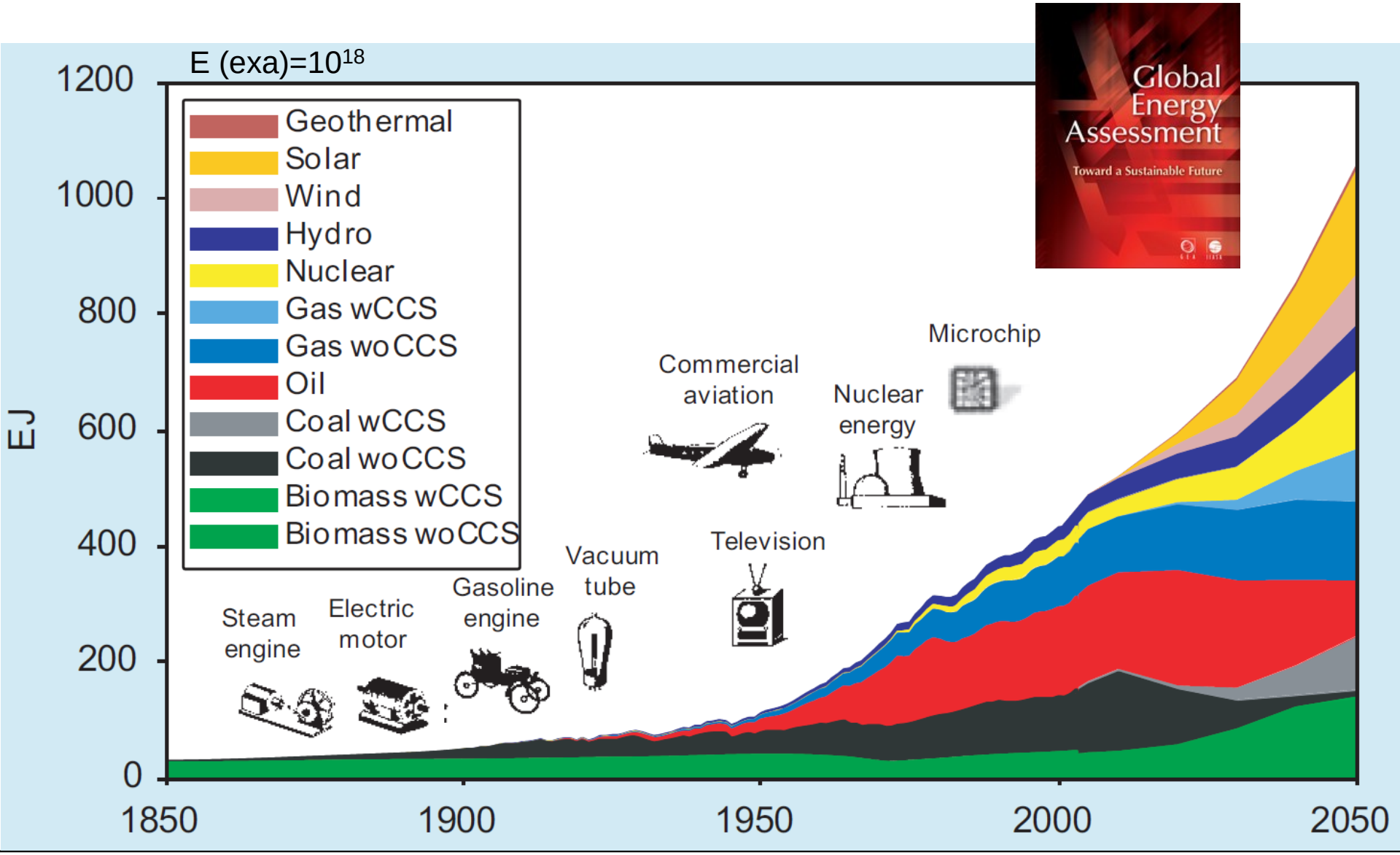
Sustainable energy: energy obtained from non-exhaustible resources

Sustainable energy technologies:

1. **Technologies utilizing renewable energy sources**
   (hydroelectricity, solar energy, wind energy, wave power, geothermal energy, bioenergy, tidal power)

2. **Technologies designed to improve energy efficiency**

Energy transition scenario



Source: Global Energy Assessment, 2012, http://webarchive.iiasa.ac.at/Research/ENE/GEA/index.html

Growing demand for energy

2010: ~550 EJ (17 TW installed power)

2050: 1000 EJ (32 TW installed power)

In 40 years additional 15 TW power has to be installed

15 000 GW/14600 days = **~ 1 GW / day**

Borssele Nuclear Power Plant

Installed capacity: 485 MW

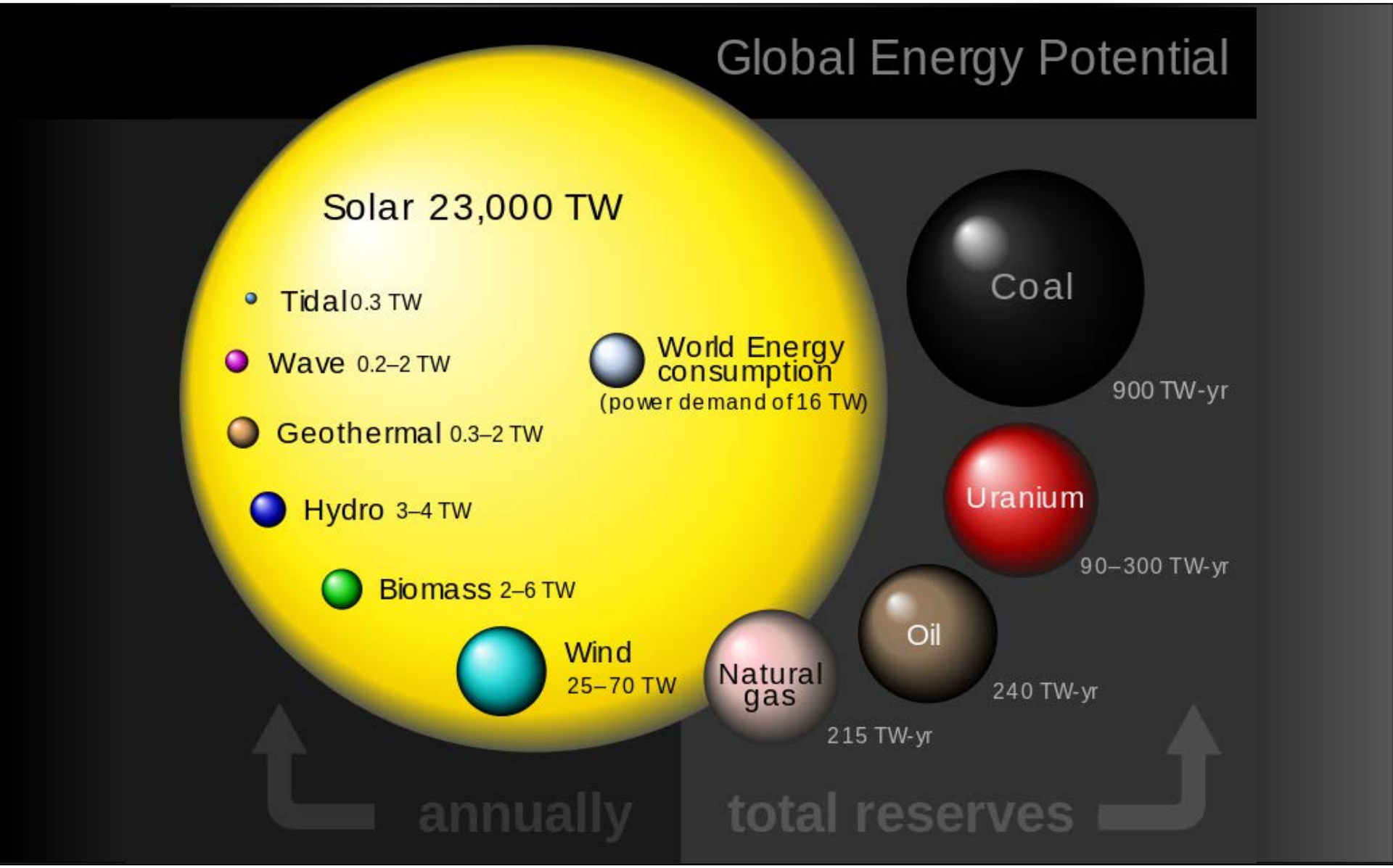
Electricity generation: ~4000 GWh/y

1 300 000 households in NL

Assumption: 3000 kWh/y per household

From now on everyday for coming 40 years one nuclear power plant of 1 GW capacity has to be build to fulfil the future energy requirements

Available energy sources

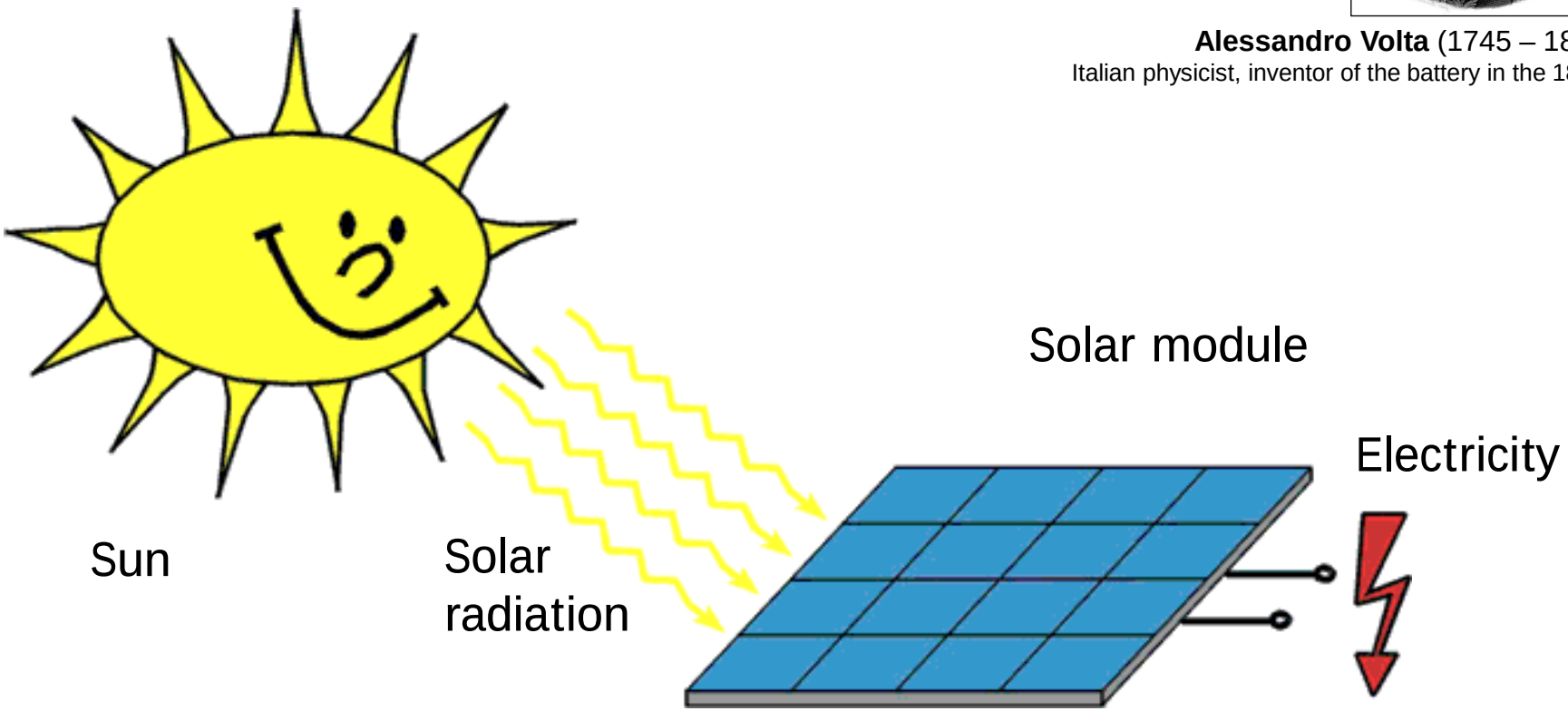


https://commons.wikimedia.org/wiki/File:Global_energy_potential_perez_2009_en.svg

Solar energy

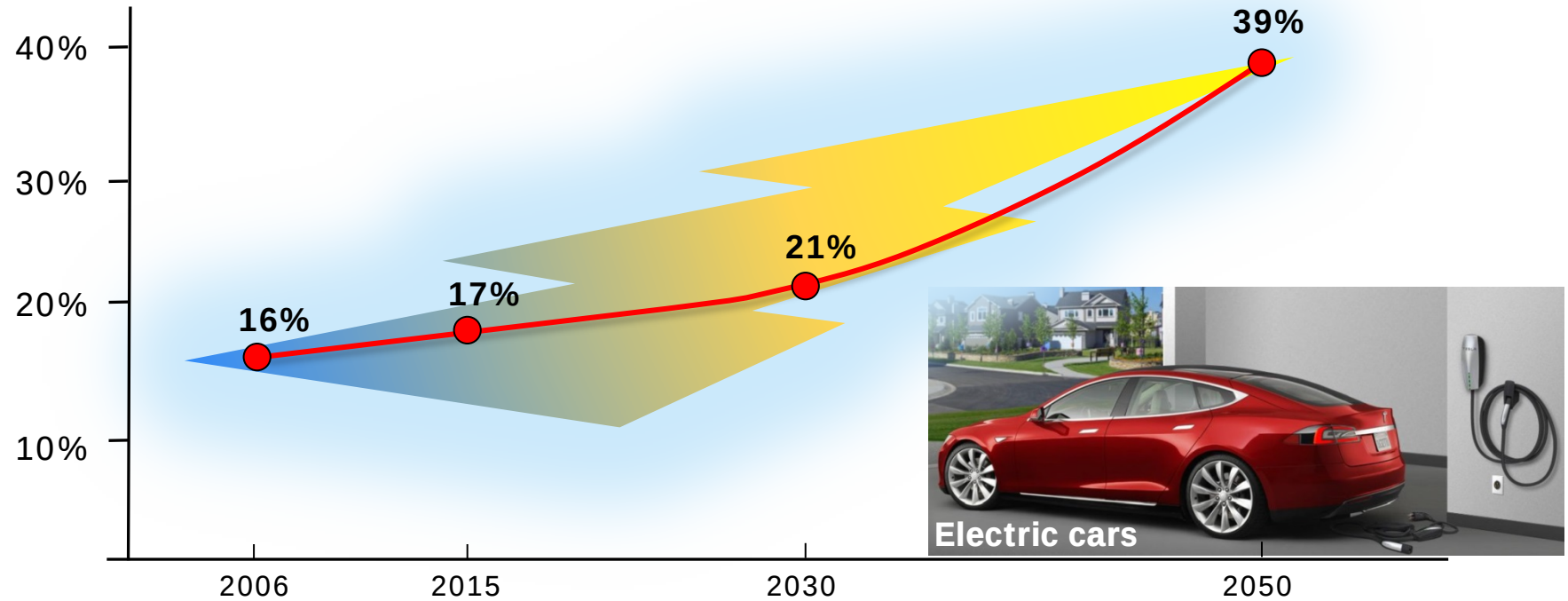
Technologies utilizing solar energy: Photo-Volta-ics

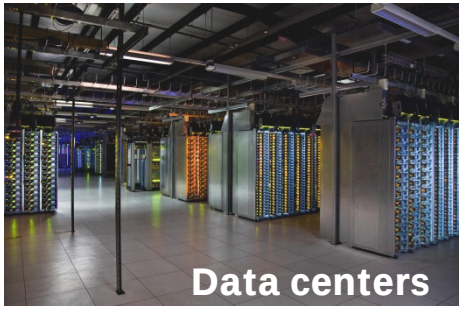
Alessandro Volta (1745 – 1827)
Italian physicist, inventor of the battery in the 1800s



Global electricity development

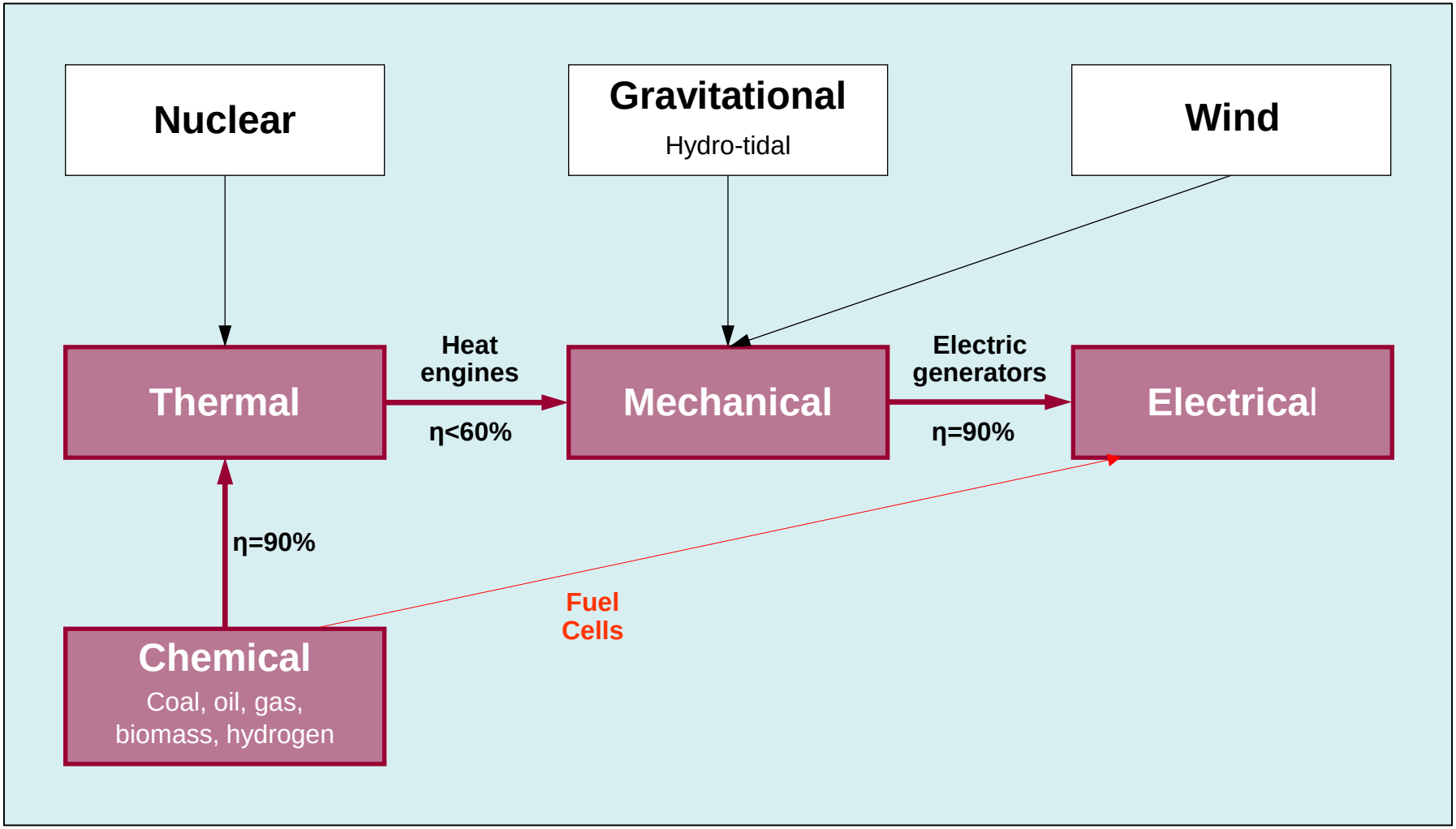
Share of electricity in total energy consumption





Source: IEA 2008, EC 2011 data.html

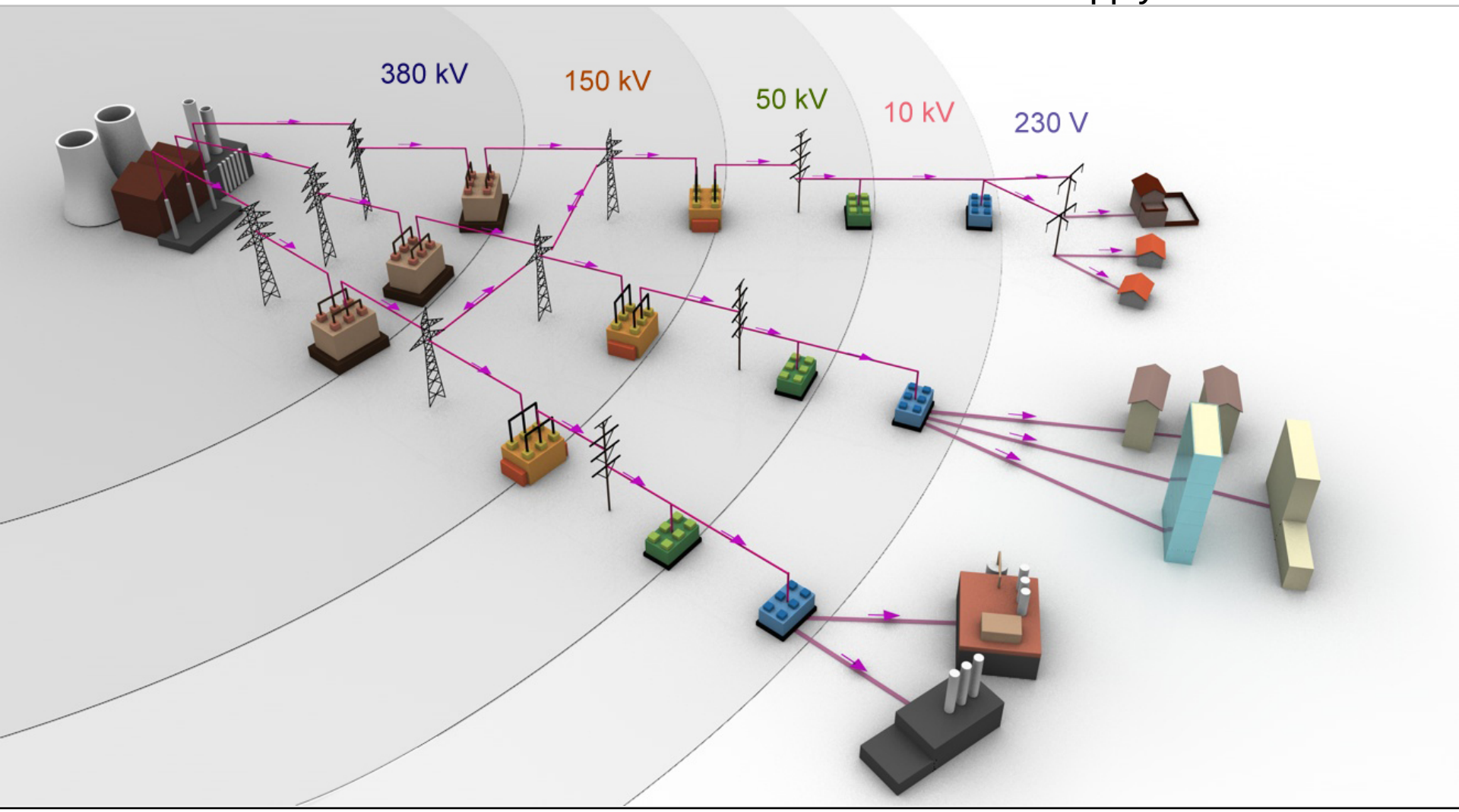
Electricity generation



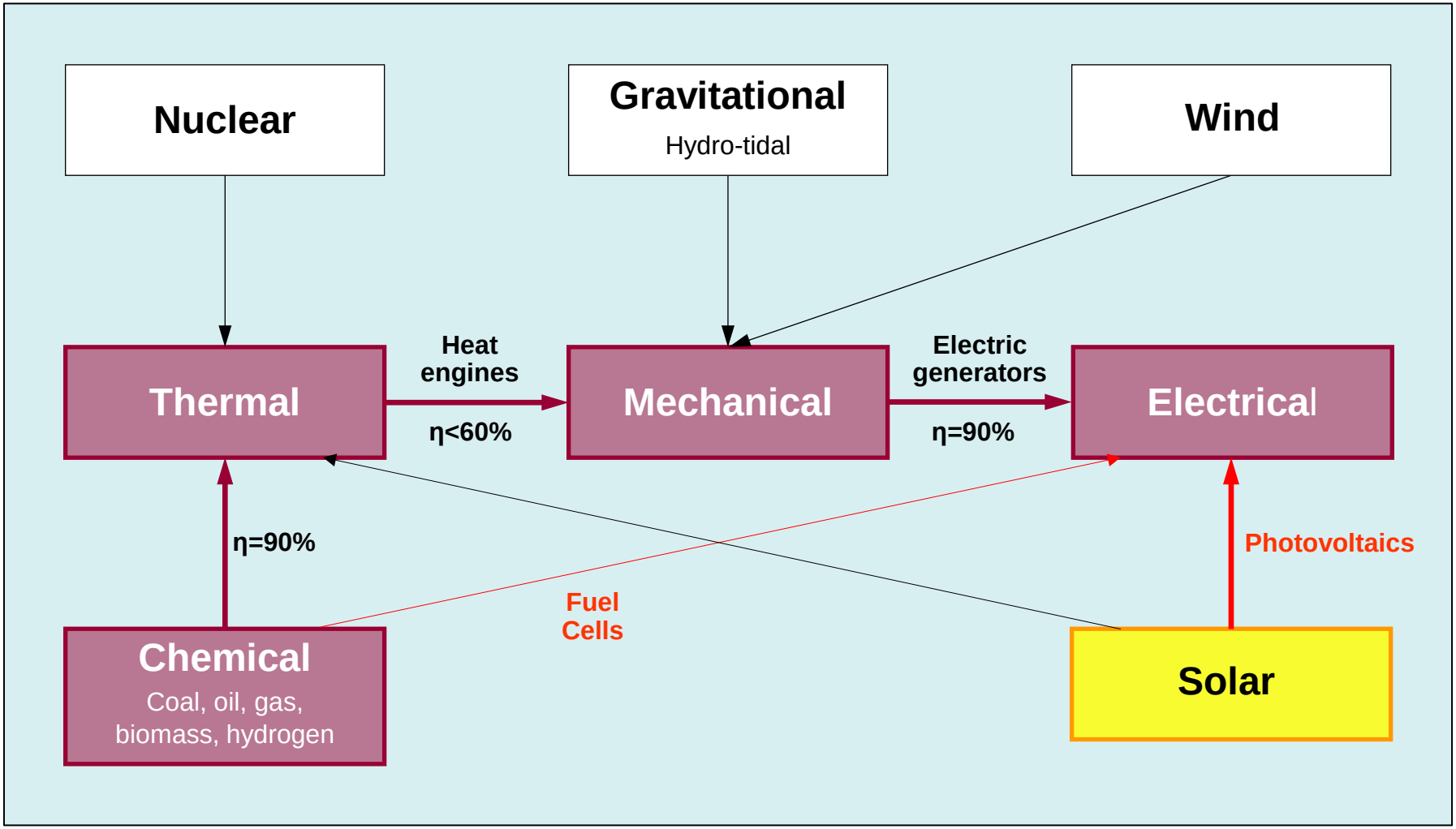
Source: L. Freris, D. Infield, Renewable Energy in Power Systems, Wiley 2008

Electricity power network: Today

Supply follows demand



Electricity generation



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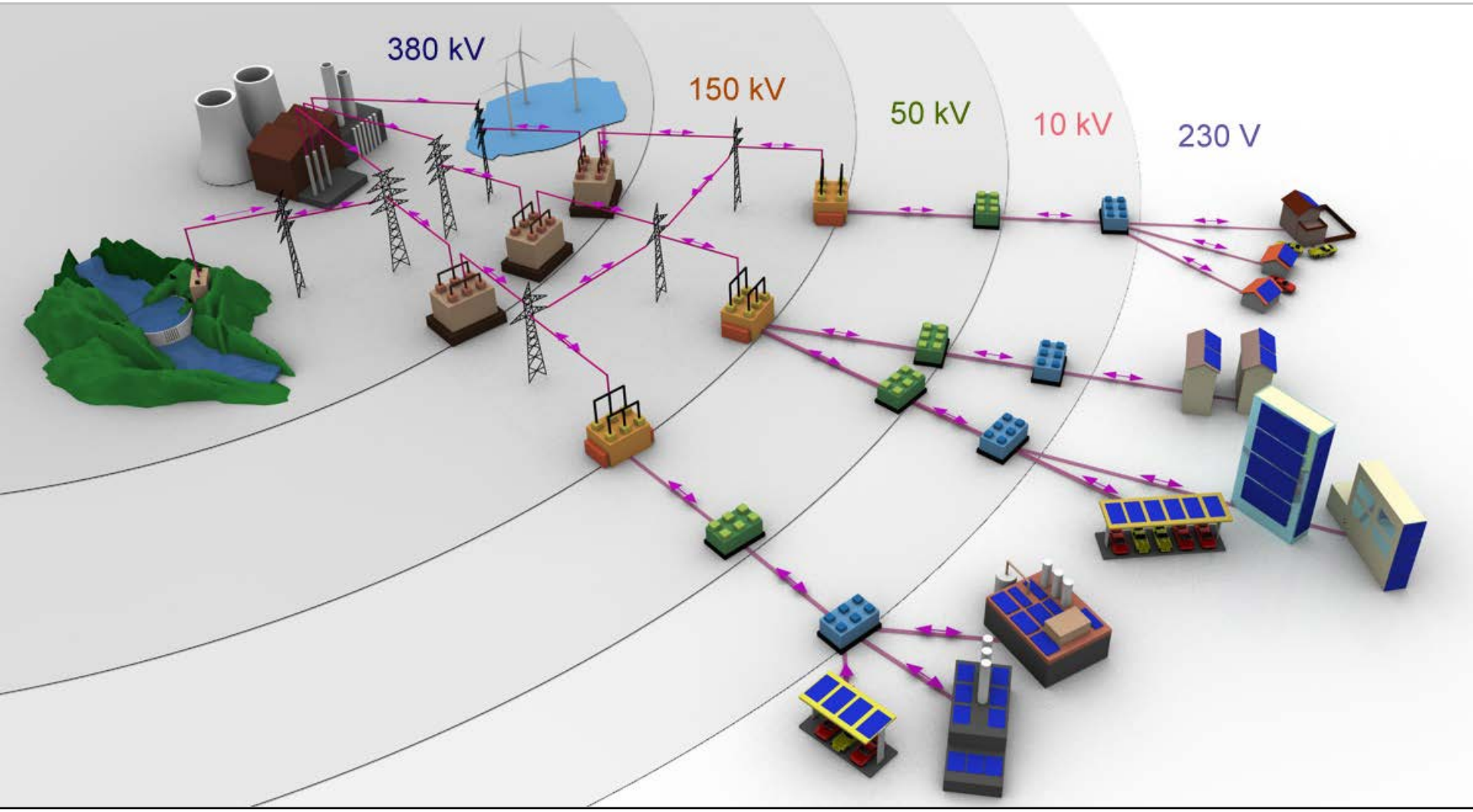
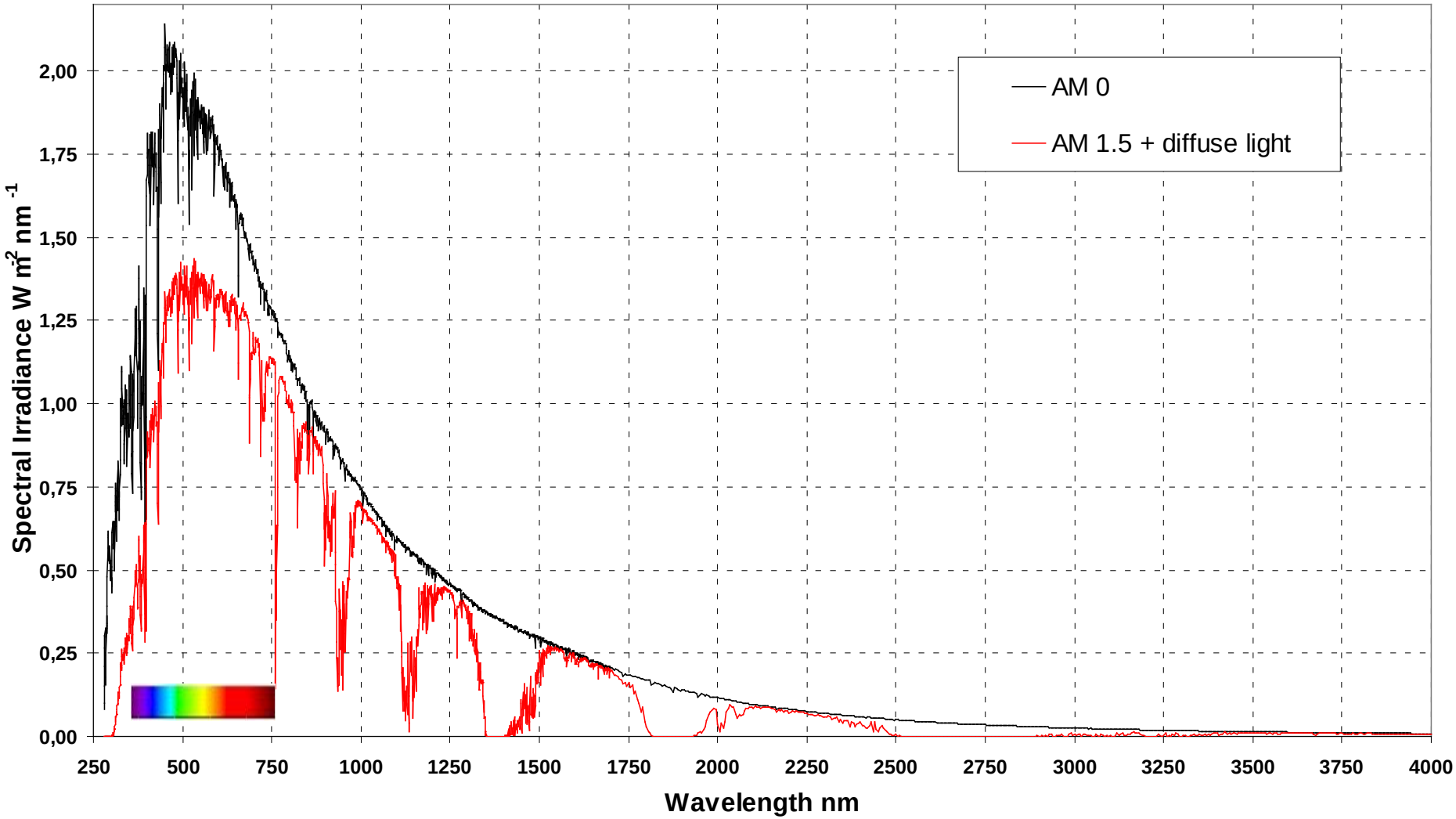
Electricity power network: Today

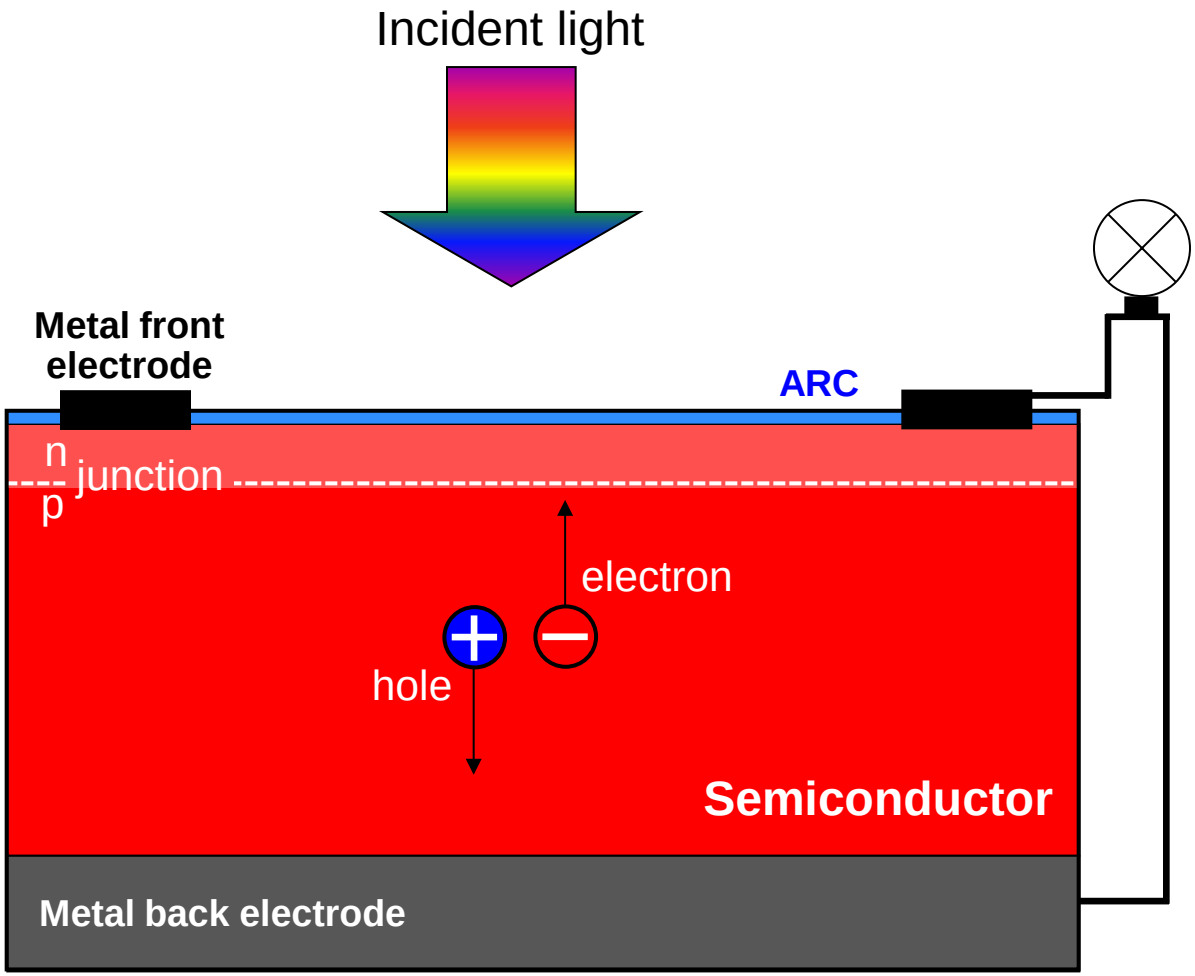
Demand follows supply



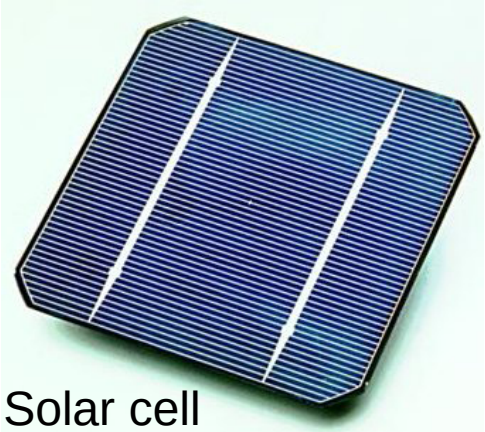
Solar spectrum



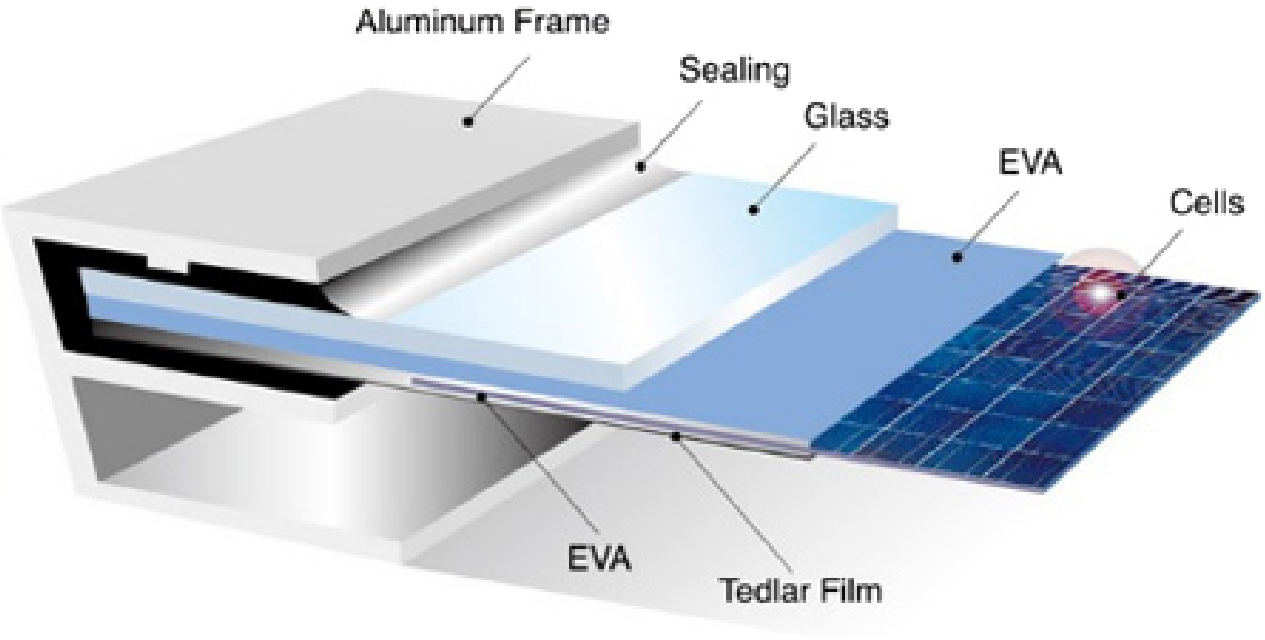
Typical solar cell

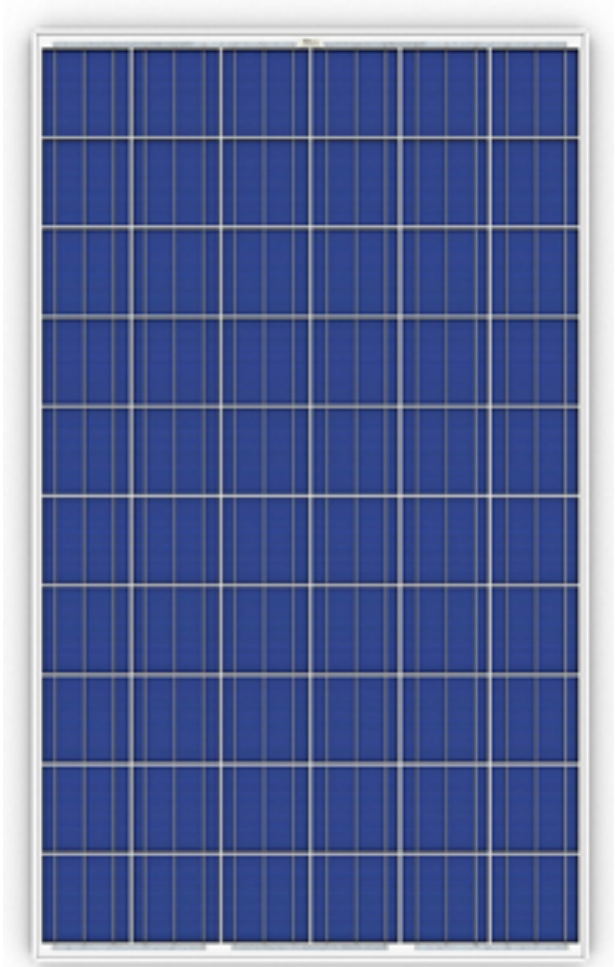


Solar modules



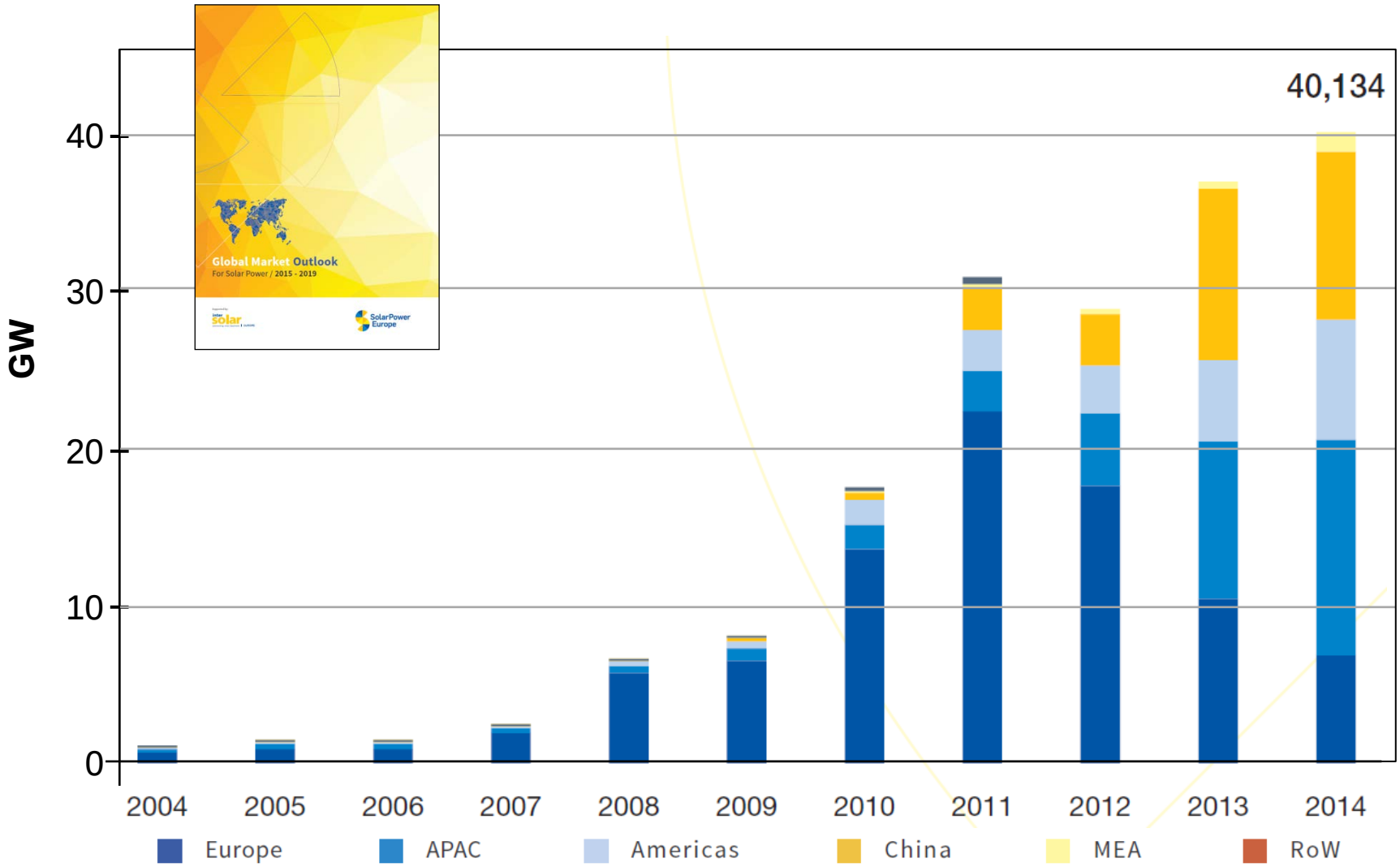
Solar cell





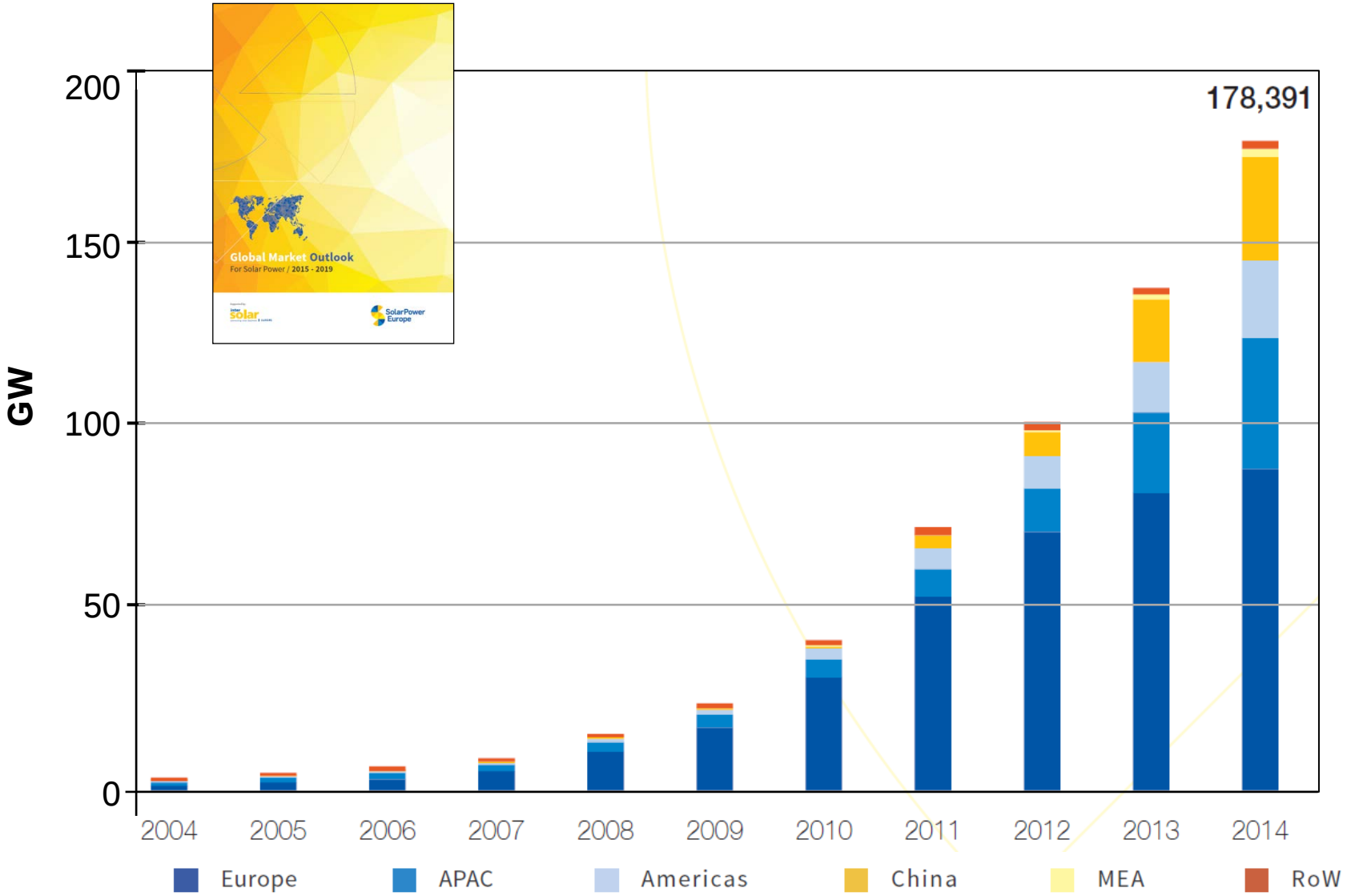
Solar module

Global annual PV installations



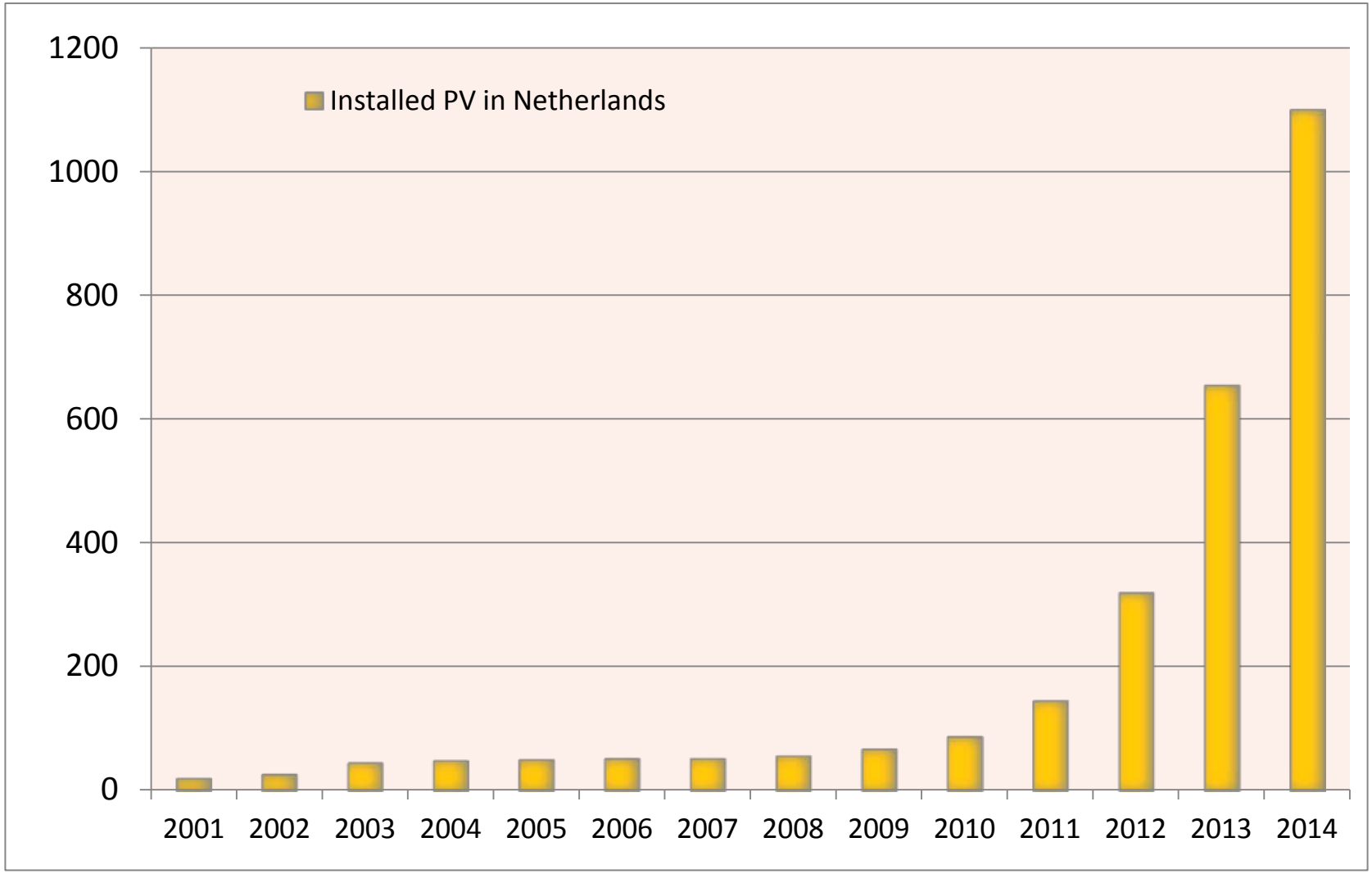
Source: Solar Power Europe, Global Market Outlook For Solar Power / 2015 – 2019

Global cumulative installed PV power



Source: Solar Power Europe, Global Market Outlook For Solar Power / 2015 – 2019

Annual installed PV capacity in Netherlands



https://en.wikipedia.org/wiki/Solar_energy_in_the_European_Union

Global cumulative installed PV power

World in 2014:
PV power installed: **179 GW**

nuclear-power capacity equivalent

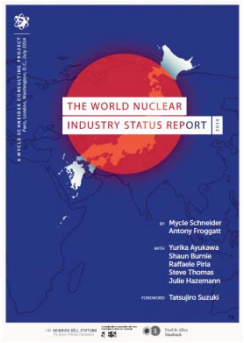
56×0.5 GW

Netherlands in 2014:
PV power installed: **1.1 GW**

nuclear-power capacity equivalent

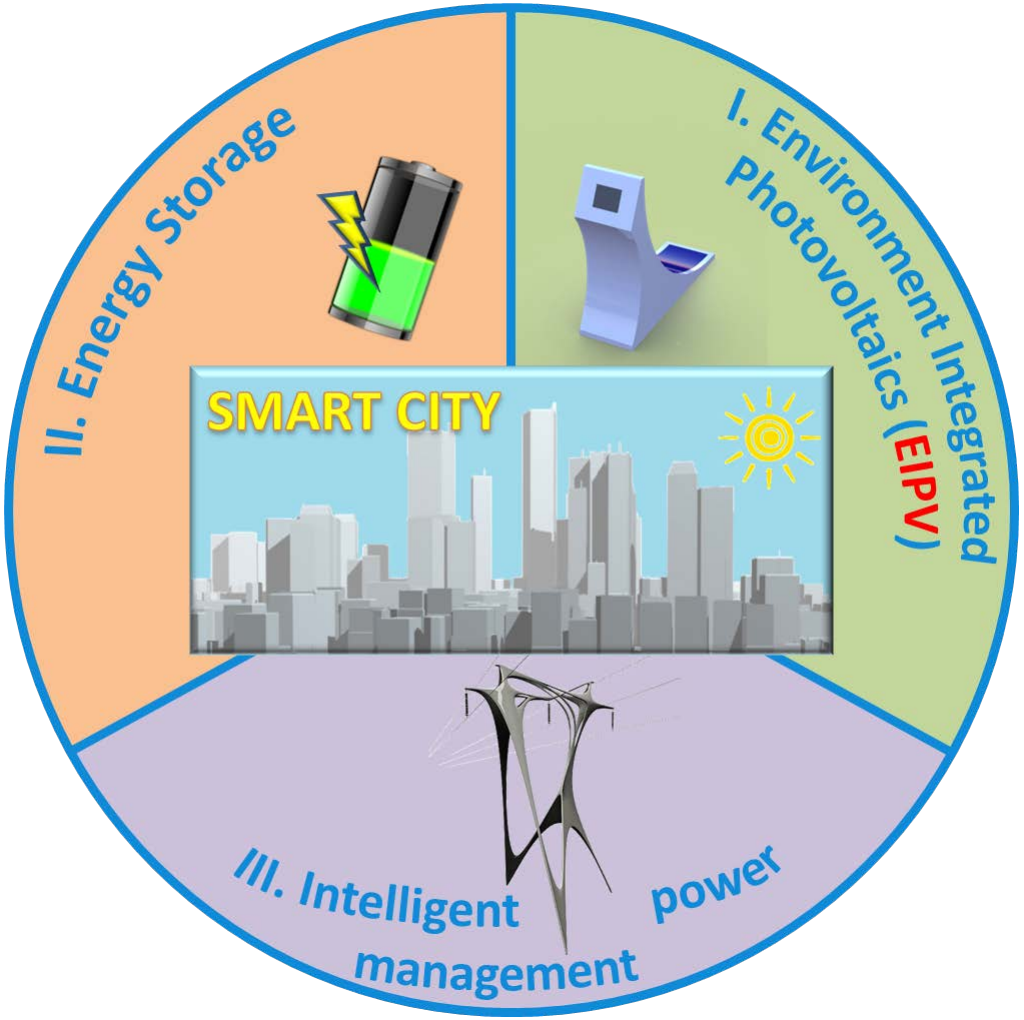
0.3×0.5 GW

Total number of nuclear power plants in operation is 388 with a combined installed capacity of 333 GW



Applications: Smart Cities

The main pillars of future electricity infrastructure:



(i) grid-connected environment integrated PV (EIPV)
deals with PV systems integrated in a given location

(ii) energy storage
provides energy buffer during those periods of time in which there is energy need but not PV generation

(iii) intelligent power management
takes care of system's most efficient energy use

Solar electricity

Houses running on solar electricity

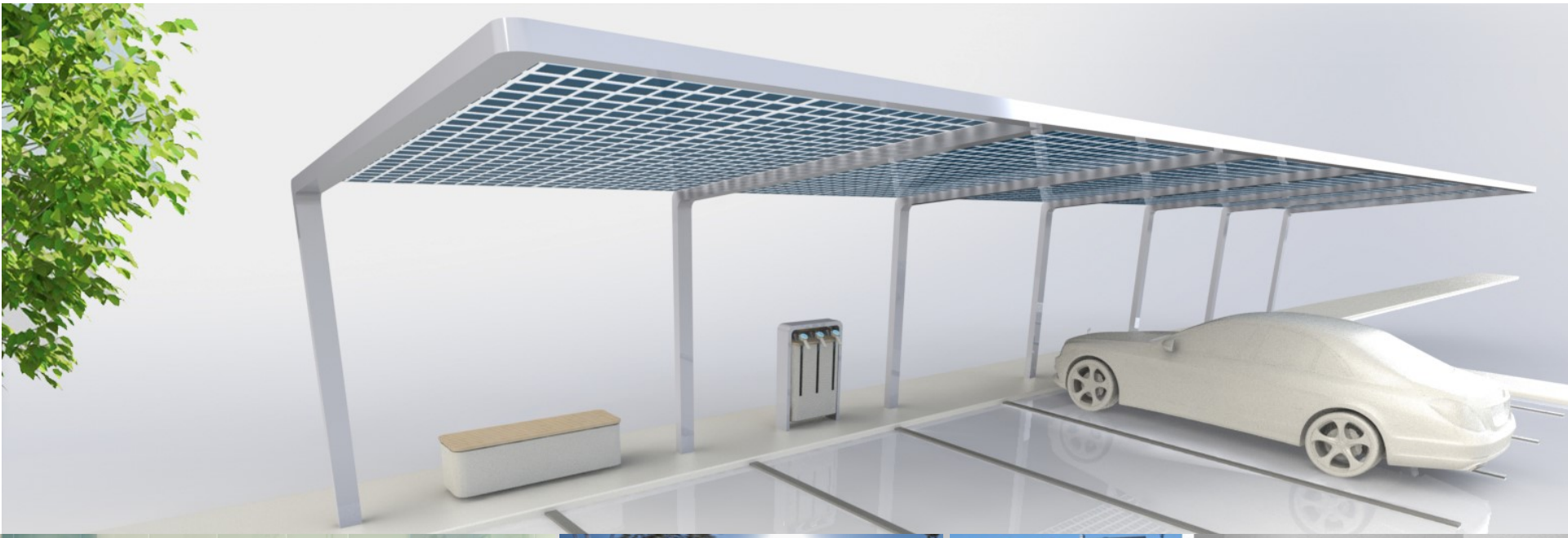
Typical Dutch family houses

Prêt-à-Loger house:
Energy neutral and more space

Solar electricity

Cars running on solar electricity

PhD project: Solar Charging station



Electricity power network: Future

Features

- Sustainable (“green”) energy
- New devices and technology
- Massive amounts of (small) generators and devices
  - Generators: Solar cells, Wind turbines, Biomass, µCHP
  - Consumers: Electric cars, Heat pumps, Data centers



µCHP: Micro combined heat and power

Electricity power network: Future

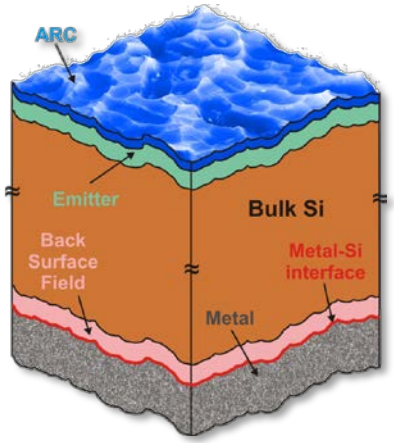
How to approach this?

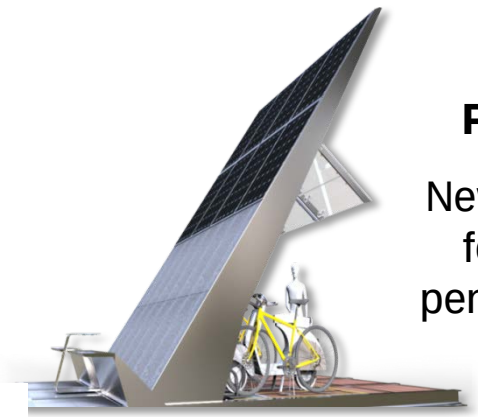
- **Smart Grids**
  - Electricity network that allows for sustainable energy sources
  - Typically characterized by incorporation of ICT
- **Multidisciplinary approach:**
  - **Electrical engineering**
    (network stability, efficiency, control, supply/demand balancing, power processing, management, devices)
  - **Computer science**
    (data collection and processing)
  - **Economics and business science**
    (services, control, management, business models)
  - **Law and society**
    (regulation, privacy, reliability, prices, fairness)

Research areas

c-Si solar cells

Large-scale cost-effective electricity generation





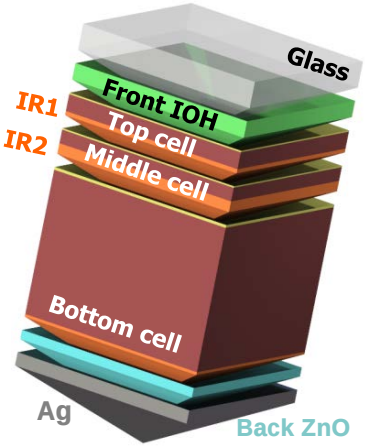
PV systems

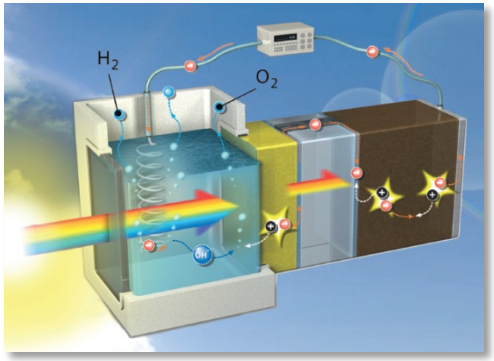
New applications for increased penetration of PV

PVMD

TF solar cells
(TF-Si, CIGS, Hybrid)

Testbed for innovation & new applications





Solar fuels

Storage for abundant solar electricity

Solar water cleaning

Facilities: From substrates to complete solar cells

Clean rooms

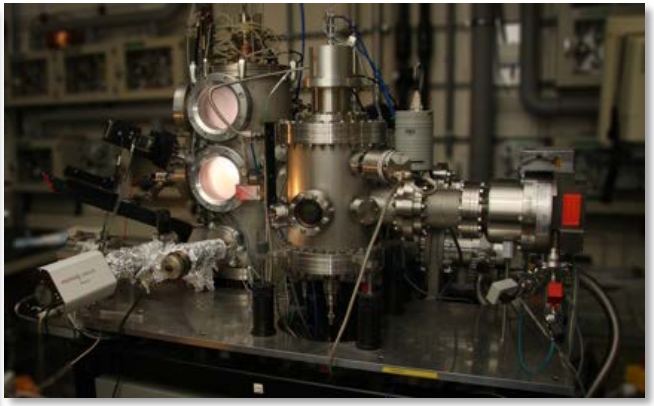
PVMD Delft University of Technology

EKL Else Kooi Laboratory

- **Fully equipped**
  - Class 100
  - Class 10.000
- **Substrates size**
  - Wafers: max 4 in
  - Quartz: max 4 in
  - Glass sheet: max 10 x 10 cm^2

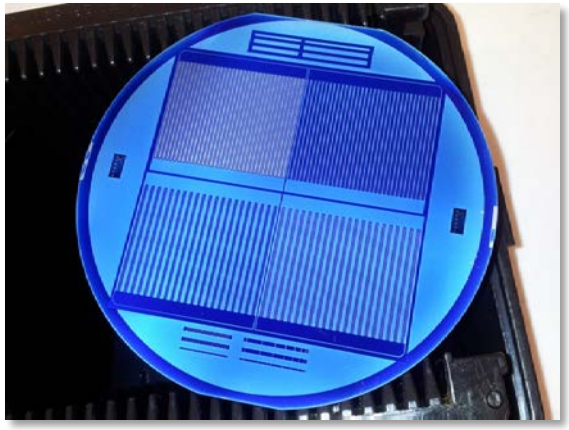
Facilities: From substrates to complete solar cells

Clean rooms



Facilities: From substrates to complete solar cells

Clean rooms



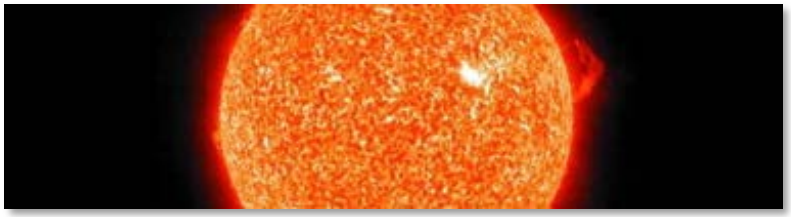
Facilities: Characterization of thin films and solar cells

❖ Materials characterization

- Structural properties: FTIR // Raman Spectroscopy
- Transport properties: I-V dark/illuminated // Sheet Resistance // Hall
- Optical: TIS // VAS // RT // OES // Pyranometer // Ellipsometry
- Electronic properties: Q-DLTS // DBP // Carrier Lifetime // SunV_{OC} // PL // PDS
- Morphology: SEM // FIB // AFM // Dektak profile-meter

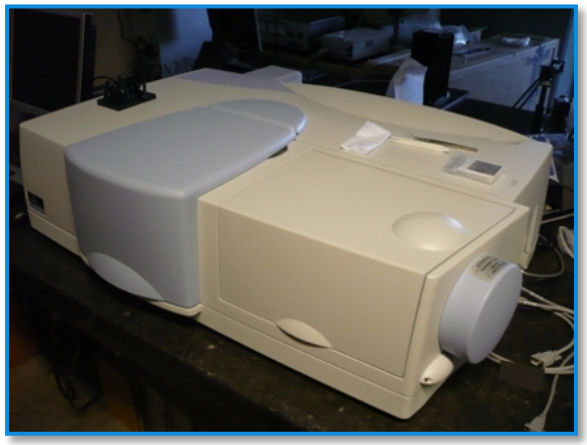
❖ Devices characterization

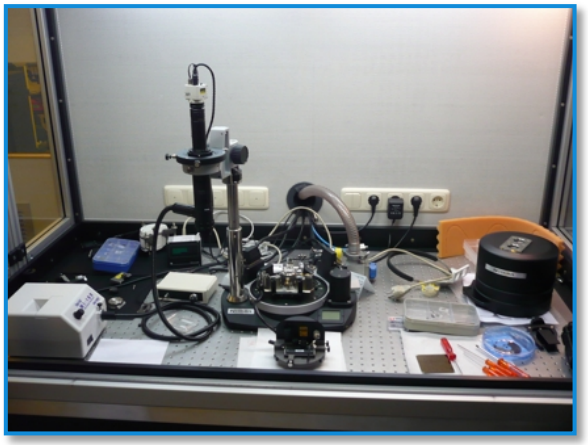
- Solar simulators: Oriel // Pasan // Wacom
- Large-area simulator EternalSun
- Degradation set-ups: standard // (3) red-led based
- SR set-up // EQE set-ups

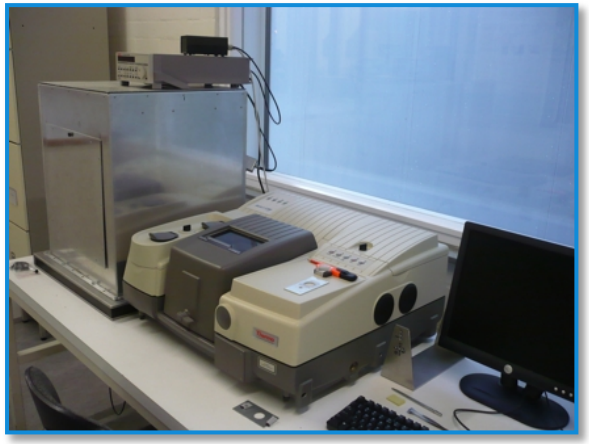


Facilities

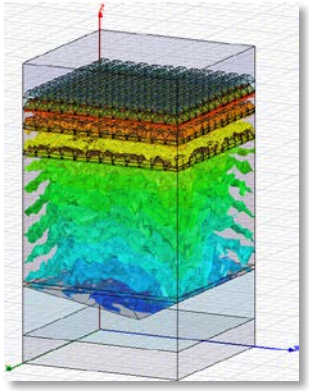
Material and devices characterization





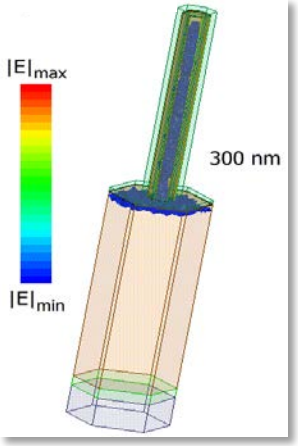


Modelling platform



❖ Opto-electrical modelling

- Software calibration
- Physical insight & Optimization
- Model available for multi-junction TF (Si) PV
- Model available for full-area (m)c-Si cells
- Model available for IBC c-Si cells



❖ Full 3D Maxwell Equation solvers

- HP-Z800 (dual quad-core) - 12 Gb RAM
- Dell Inspiron (dual six-core) - 128 Gb RAM
- Dell Inspiron (48-core) - 128 Gb RAM
- OS: UNIX OS // Win7 64 bit
- Software: COMSOL, SYNOPSYS, lumerical, ANSYS

@ UniCal

❖ In-house developed opto-electrical simulators

- Advanced Semiconductor Analysis 6.0 (beta) with GP4
- Ray-tracing with coherent propagation based on AFM data input

ASA LUX
SunRay

Recent results

World record in its category

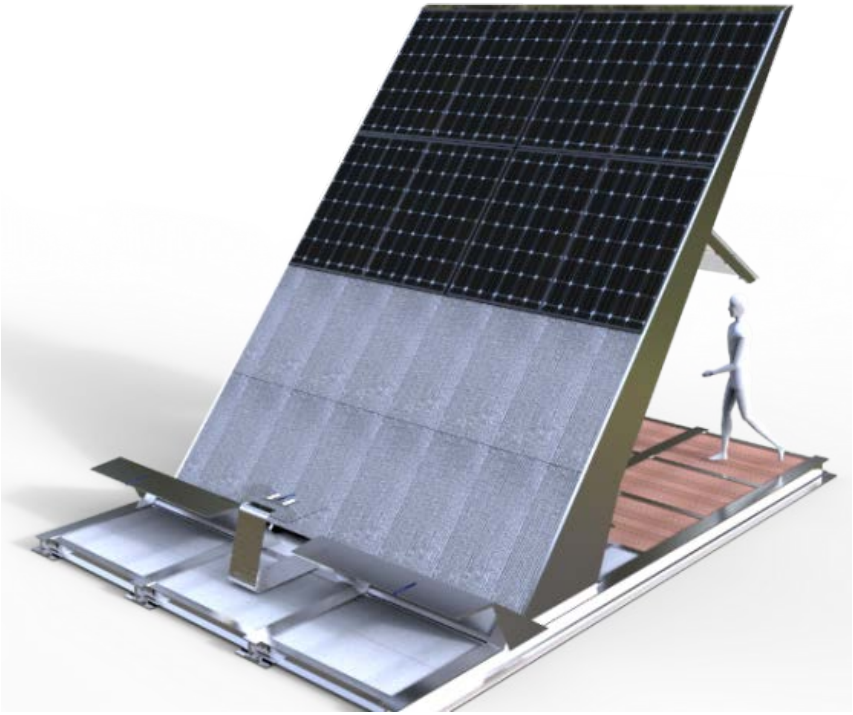
Cell type	Area (cm^2)	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)	η_{in} (%)
PIN a-SiO_x	0.16	1026	10.6	73.0	7.9
PIN a-Si	0.16	882	17.4	72.3	11.1
PIN nc-Si	0.16	559	27.3	71.2	10.9
NIP nc-Si	0.25	533	27.5	72.7	10.6
a-Si/nc-Si (w ARC)	**0.16**	**1424**	**14.0**	**74.4**	**14.8**
a-Si/a-Si/nc-Si	0.16	1971	9.4	68.4	12.7
a-SiO_x/a-Si/nc-Si	0.16	2375	7.27	72.0	12.4
a-SiO_x/a-Si/2 x nc-Si	0.16	2841	5.40	73.7	11.3
CIGS (1 µm, text)	0.36	620	31.4	76.1	14.8
CIGS (1.5 µm, flat)	0.36	623	33.5	74.7	15.6
a-Si/CIGS	0.36	1230	12.0	64.6	9.5
a-Si/OPV	**0.16**	**1550**	**11.5**	**68.0**	**12.1**
a-Si/a-Si/OPV	**0.16**	**2330**	**8.50**	**67.0**	**13.2**

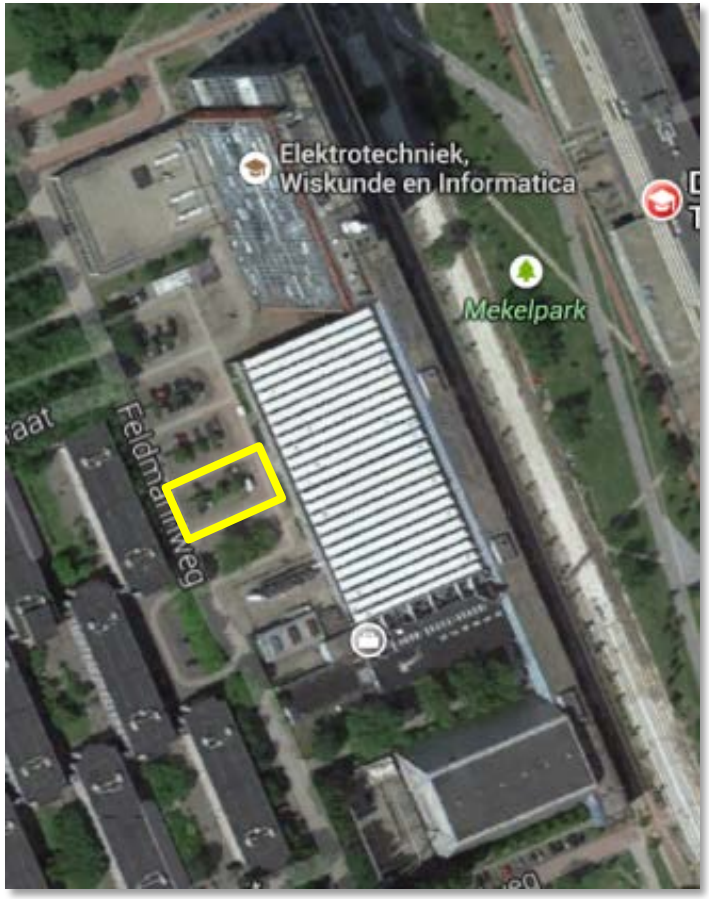
Cell type	Area (cm^2)	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)	η (%)
HTJ (n - textured)	4.00	682	39.9	78.4	21.3
HMJ (p - textured)	9.00	618	39.0	80.0	19.3
HMJ (n - IBC)	9.00	639	41.0	76.9	20.2
PolySi IBC (n - flat)	9.00	680	35.9	74.5	18.2

PV for smart cities applications

Solar Powered Electrical Bike and Scooter Charging Station

- **3 students involved**
  - Industrial design
  - Photovoltaic technology
  - DC systems





PV for smart cities applications

Solar Powered Infotainment Spot

- **Demonstrator for a lively campus**
  - Solar powered rugged tablet
  - Kiosk software
  - USB plugs for free energy

PV Technologies: SolaRoad

TNO + partners

World's first solar cycle path:

- 2.5 by 3.5 meter slabs of concrete
- Integrated layer of c-Si solar cells
- top layer of translucent, tempered safety glass (~1cm thick)
- 30 percent less energy than rooftop solar panels
- Utilise up to 20 percent of the 140,000km roadway
- Many challenges

PVMD contribution:

- Energy yield prediction
- Choice of PV technology

PV Technologies: Thin-film Si foil

HyET Solar Powerfoil ®

PVMD contribution:

- Material development
- Light trapping

The modules have the unique properties:

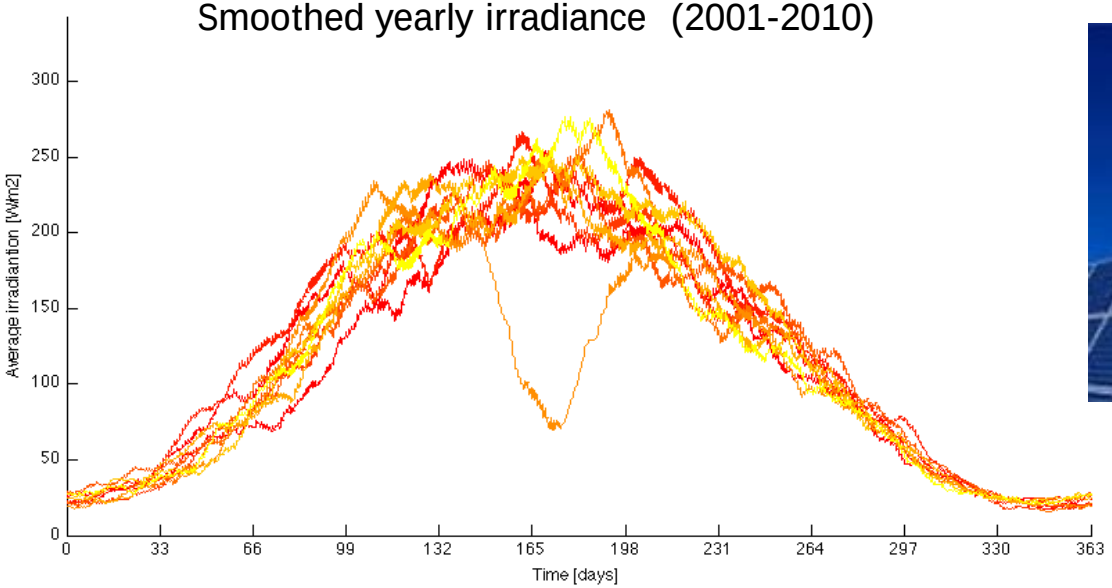
- Lightweight
- Unbreakable
- High efficiency
- Low installation costs

Versatile applications:

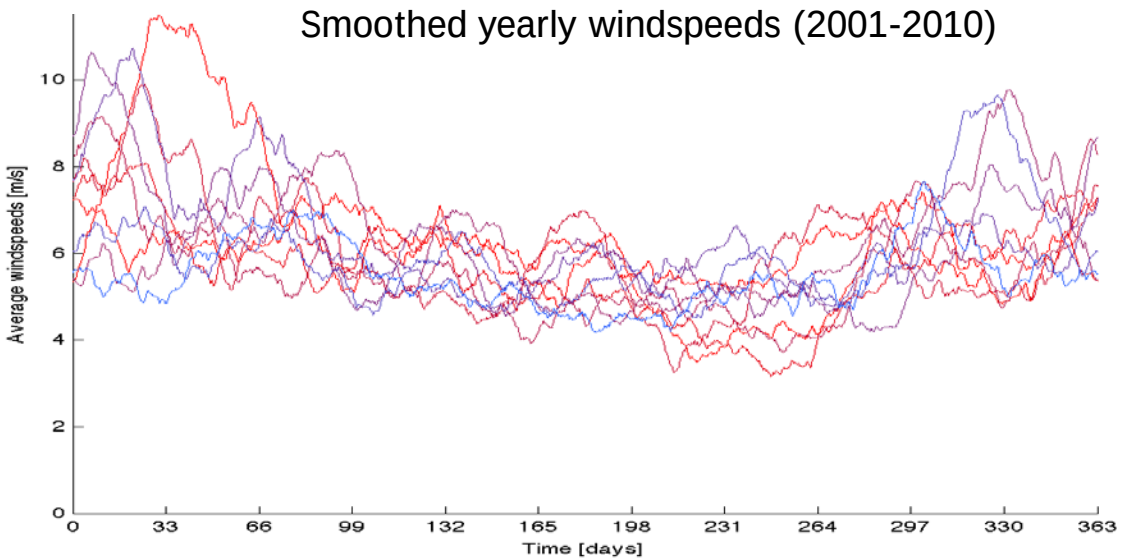
- Building integrated roof tops
- Steel building panels
- Highly curved surfaces
- Mobile applications
- Road applications?

Application of RES in Rotterdam

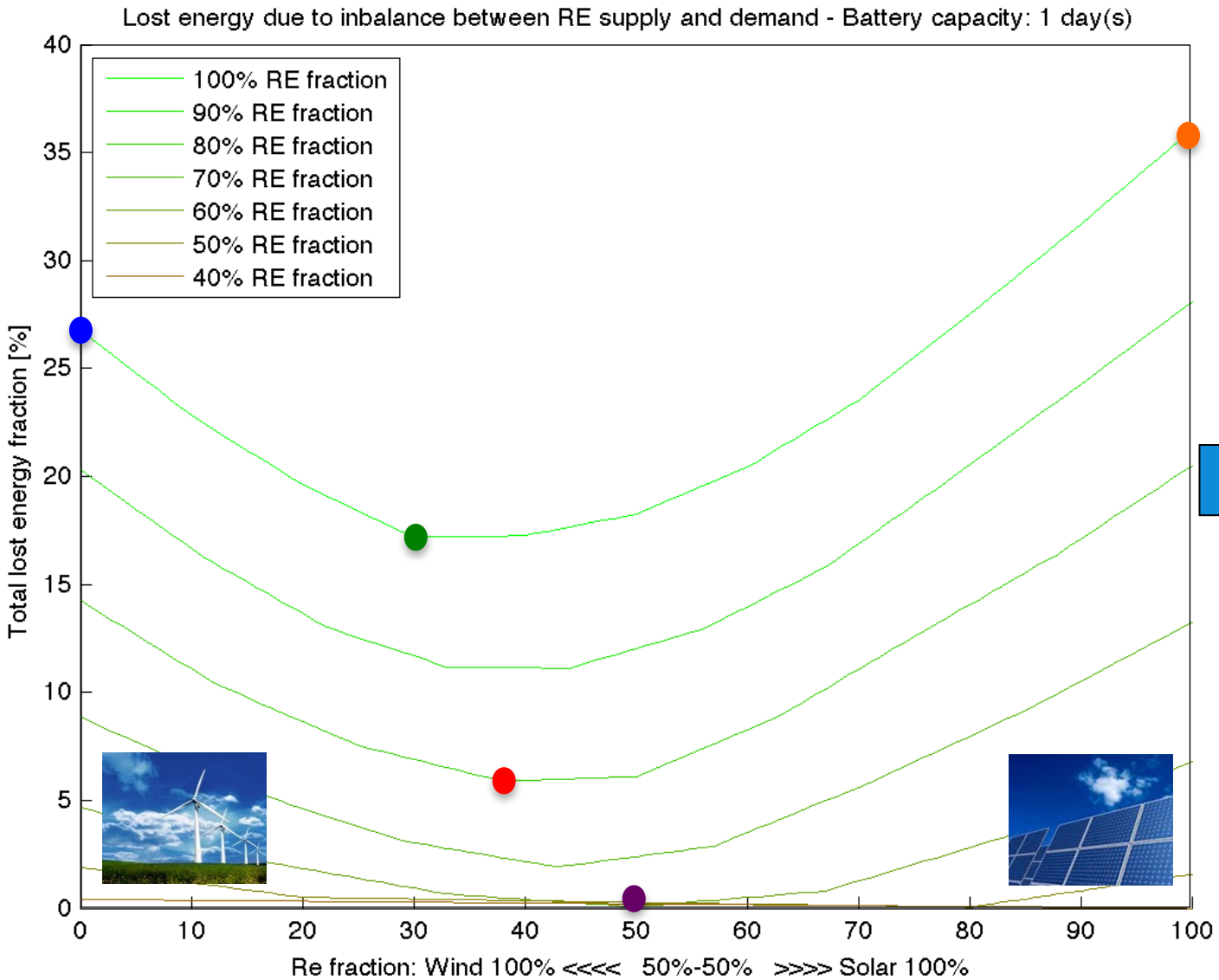
Smoothed yearly irradiance (2001-2010)



Smoothed yearly windspeeds (2001-2010)



Application of RES in Rotterdam

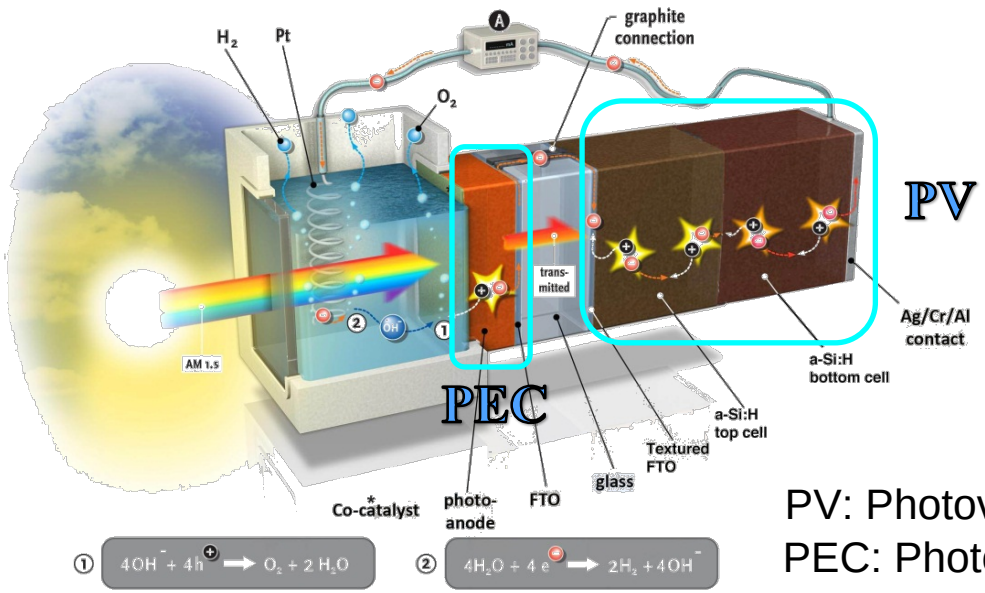


Fuels

Solar fuels

Lihao Han (PhD student PVMD group in cooperation with TNW faculty)

World record: Conversion efficiency solar energy into hydrogen



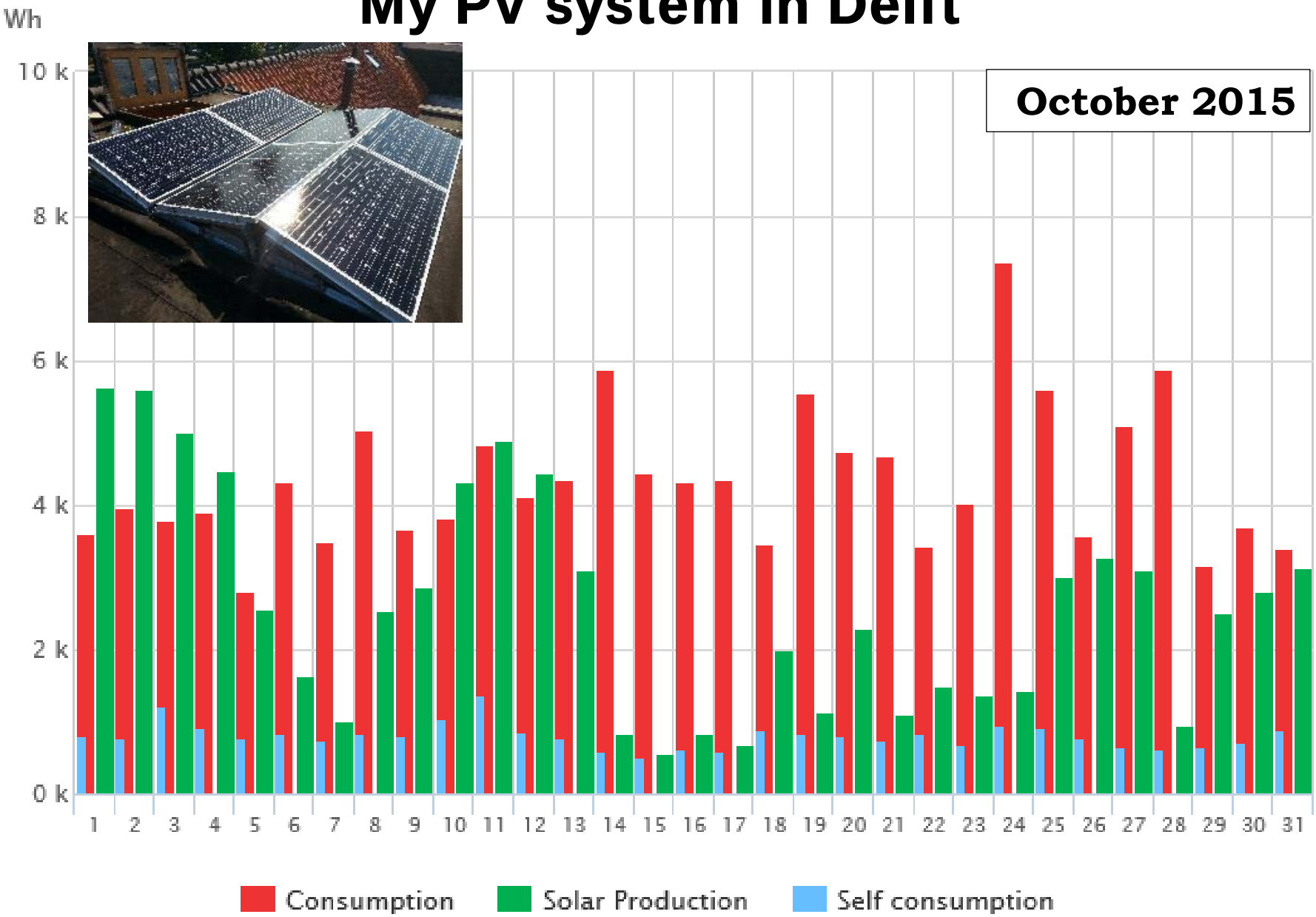
>5% efficiency light to hydrogen

PV: Photovoltaic device

PEC: Photoelectrochemical device

Fatwa F. Abdi, Lihao Han, Arno H.M. Smets, Miro Zeman, Bernard Dam and Roel van de Krol, **Nature Communications**, 4:2195 doi: 10.1038/ncomms3195 (2013).

My PV system in Delft



Photovoltaics

Cost development

2008: PV electricity will not be economical

- It is too expensive, too expensive!

2013: Coal and gas electricity is not economical

- PV electricity is too cheap, too cheap!

Technisch Weekblad / Nieuwsarchief / RWE sluit Nederlandse centrales

RWE sluit Nederlandse centrales

22 januari 2014 • Herman Damveld

De algemeen directeur van het elektriciteitsbedrijf RWE, Peter Terium, heeft de sluiting van een aantal gas- en kolencentrales in Duitsland en Nederland aangekondigd.

Volgens Terium zijn de gemiddelde winstmarges van fossiele centrales fors gedaald.
De gascentrale Moerdijk 2 met een vermogen van 430 MW gaat al dit jaar uit bedrijf maar wordt wel in stand gehouden met het oog op de toekomst. De kolencentrale Amer 8 van 610 MW gaat begin 2016 definitief uit bedrijf.

Terium rekent voor dat ook de winstmarges van de nog in bedrijf zijnde Duitse kerncentrales bijna nul zijn. Ook hun bedrijfsvoering komt daarom in gevaar.

Photovoltaics

Solar cell and module price

Solar PV Cell Weekly Spot Price

Item	High	Low	Average	AvgChg	AvgChg %
Multi Cell Price Per Watt	0.39	0.28	0.313	↑ 0.001	↑ 0.32%
Taiwan Poly Cell Per Watt	0.39	0.29	0.316	↑ 0.001	↑ 0.32%
156 mm Multi Solar Cell	1.75	1.16	1.364	↑ 0.01	↑ 0.74%
156 mm Mono Solar Cell	2.25	1.45	1.618	– 0	– 0%
125 mm Mono Solar Cell	1.37	0.85	0.975	– 0	– 0%

Solar PV Module Weekly Spot Price

Item	High	Low	Average	AvgChg	AvgChg %
Poly Silicon Solar Module	0.78	0.48	0.554	↑ 0.001	↑ 0.18%
ThinFilm Solar Module	0.79	0.47	0.592	– 0	– 0%

Unit: USD / Watt more *Last Update:* 2015-09-09

Photovoltaics

Solar cell and module price

Solar PV Cell Weekly Spot Price

Item	High	Low	Average	AvgChg	AvgChg %
Multi Cell Price Per Watt	0.50	0.36	0.399	– 0	– 0%
156 mm Multi Solar Cell	2.25	1.48	1.705	– 0	– 0%
156 mm Mono Solar Cell	2.75	1.88	2.215	– 0	– 0%
125 mm Mono Solar Cell	1.67	1.10	1.335	– 0	– 0%
Unit: USD	more			*Last Update:* 2014-02-26	

Solar PV Module Weekly Spot Price

Item	High	Low	Average	AvgChg	AvgChg %
Silicon Solar Module	0.96	0.55	0.675	↓ -0.005	↓ -0.74%
ThinFilm Solar Module	0.91	0.49	0.590	↓ -0.003	↓ -0.51%
Unit: USD / Watt	more			*Last Update:* 2014-02-26	

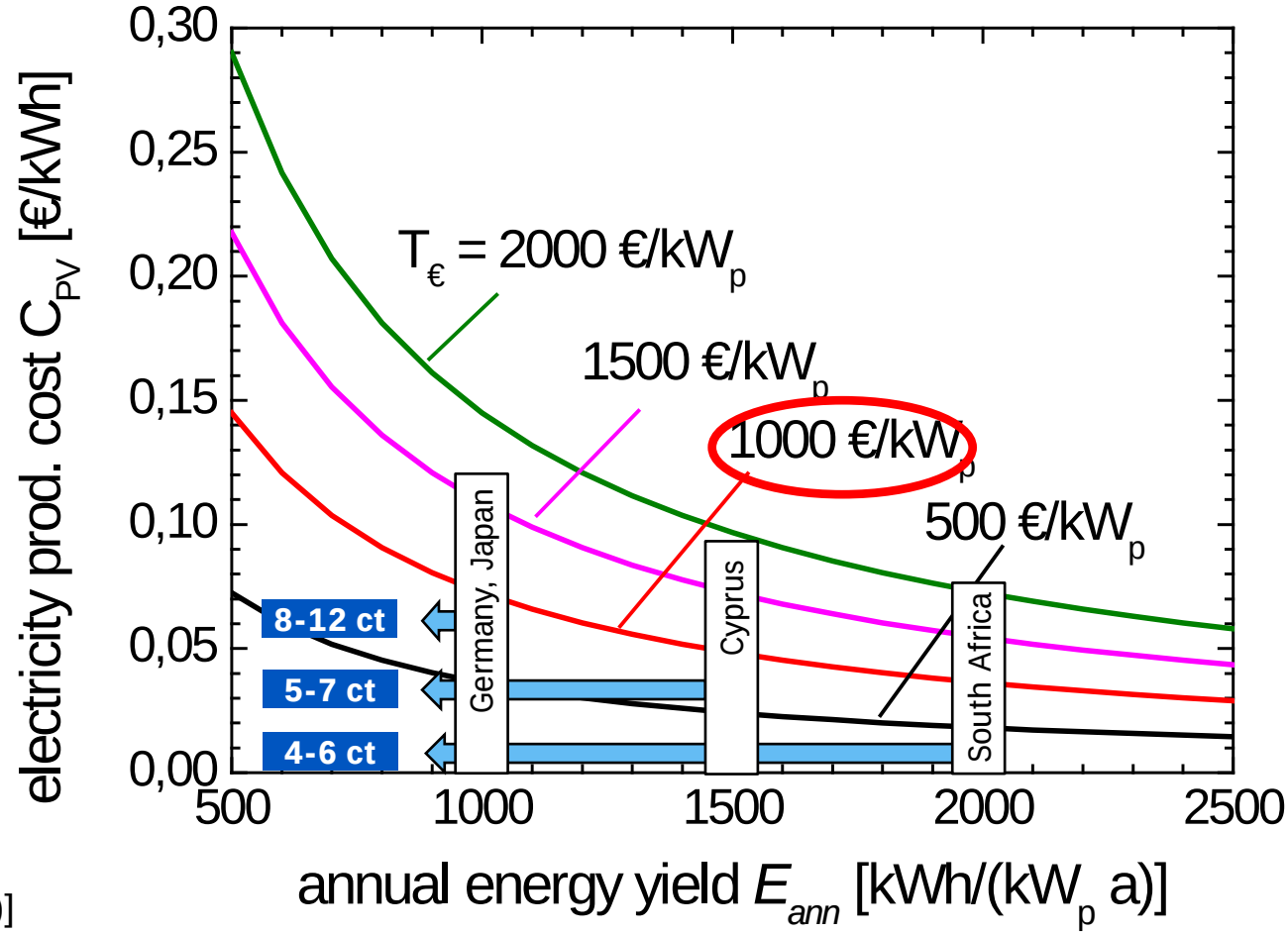
Photovoltaics

PV electricity production costs (C_{PV})

$$C_{PV} = \frac{T_€}{E_{ann}} K$$

$$K = \frac{i}{1-(1+i)^{-n}}$$

n = 20 *years*
i = 6 %



Annuity K
Years n
Interest Rate i
Electricity Cost C_{PV} [€/kWh]
Total investment $T_€$ [€/kW$_p$]
Annual Yield E_{ann} [kWh/(kW$_p$ × a)]

J. Werner, Int. Symp. on Innovative Solar Cells, Tokyo, 2014 (Un of Stuttgart)

Important message for you!

- Talk to your friends and neighbors
- Invest in a PV system and become entrepreneur
- Earn money instead of paying for electricity