
FREESUNS
SOLAR ENERGY
csem

Fundamentals and Processes for Photovoltaic Devices

Spring 2024

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STI-IEM, EPFL, Neuchâtel

Expected major learning outcome

- Have a clear view on the evolution of the price/cost of PV component and price of solar electricity
- Be familiar with the general market developments, the contribution to energy transition and technical potential, in conjunction with other sources of energy and storage
- Assess critically PV as a form of sustainable energy (energy payback time, life cycle assessment), as well as obstacles to penetration and terawatt scale deployment
- Acquire an in-depth, intuitive and quantitative understanding of how PV devices work; in particular understand the various silicon solar cell structures, the basics of thin film PV technologies, and module assembly
- Be able to perform efficiently simple simulations of solar cell devices (electrical and optical), quantify energy yields in various configurations, understand lifetime and issues with
- Understand process manufacturing chain and interlinks, from sand to PV systems; understand the dynamics of manufacturing location, dependant on policies, and why/how solar reaches the absolute lowest electricity price in some world regions

General approach of the course

x4 lectures «the big picture»:
General knowledge on solar and PV, key definitions, various big technologies, market, energy yield, systems, integration of PV, general sustainability

x4 lectures «getting to know semiconductors and solars cell device physics»
Light absorption, recombination of excited carriers in the bulk and at interface, basic rules for design of solar cells

x1 lecture «simulation of solar cells»
Learning to use a free software for simulating the properties of solar cells,
I-V curve, External Quantum efficiency, Internal Quantum effciency

x4 lectures «manufacturing and technology»
The full manufacturing sequence and linking with all previous lectures: from purifying polysilicon to wafers, from solar cell manufacturing up to reliable PV module design
+ a deeper insight into technologies beyond crystalline silicon (thin films, III-V, and perovskite)

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Support documents

FILE
Green: Review of semiconductor properties (Chapter 2)

URL
PV-Education website

URL
PV-system energy production

FILE
Interesting review paper on PV's future challenges

FILE
Commercial progress and challenges for photovoltaics

FILE
Course manuscript Spring 2025

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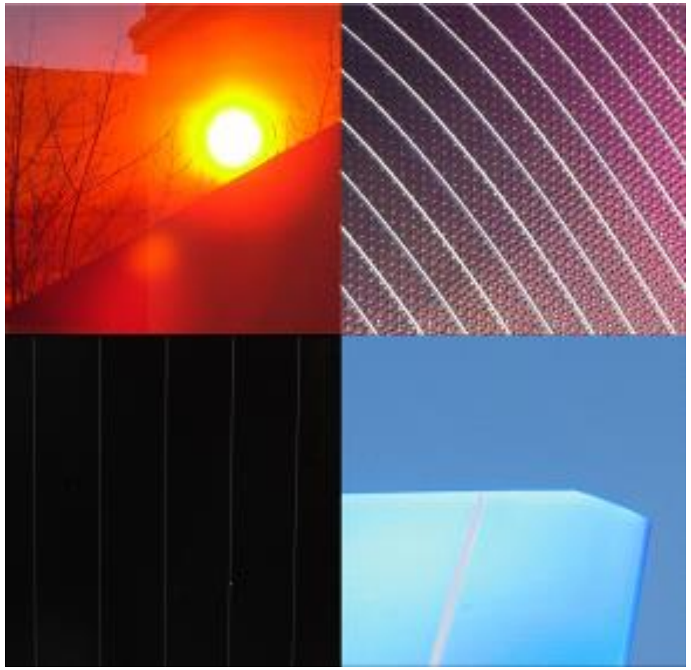
Chapter I. Basics of PV

Basic principles, potential & market



Lecture Outline

1. Basics of energy and solar energy
2. Not just PV
3. Fundamentals of PV
4. Inverters
5. PV technologies: an overview
6. PV performance and its limits
7. Challenges of PV

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1. The basics of the energy and solar energy

Reminder

- Watt [W] = power unit (instantaneous)
- Joule [J] = Energy unit
- 1 J = 1 Watt x 1 second
- 1 kWh= 1 kW x 1 hour = 3’600’000 J
- 1 TWh = 10^3 GWh = 10^6 MWh = 10^9 kWh

1GW Nuclear →
8 TWh/year
(8000 hours eq full)

1GW Solar
→ 1-2 TWh/year (1000-2000 hours eq full)

1GW Wind
→ 2-4 TWh/year
(2000-4000 hours eq full)

1. The basics of energy and the Sun

www.dashboardenergie.admin.ch/
Energy-Charts

Typical price of energy

- **1 metric ton of coal** in EU ~ 100- 120 $/t,
  → 1.2 €cts/kWh thermal (70$/t in 2019)

- **1 m³ of gas** at home for heating (methane), around 1.5 CHF, 10 kWh thermal energy
  → 15 cts/kWh of heat (increased from 10 cts/kWh in 2019)

- **1 m³ of gas** wholesale price in EU
  → 4-5 €cts/kWh thermal (2025) (2-3 €cts in 2019, up to 40 in 2021-2022))

- **1 litre of gasoline** at 1.6 CHF (n.b 50% tax included) contains 9 kWh chemical energy
  → 17 cts/kWh thermal. For mechanical energy, with 30% engine efficiency → 56 cts/kWh

- **1kWh** of electricity on the wholesale EU market
  → 6-14 €cts/kWh (4-5 €cts /kWh in 2019 and
  up to 70 €cts /kWh in 2021-2022)

- **1kWh** of electricity use at home with various taxes
  → ~ 25-40 €cts/kWh

1 kWh solar electricity in 2000 ?

100 €cts/kWh

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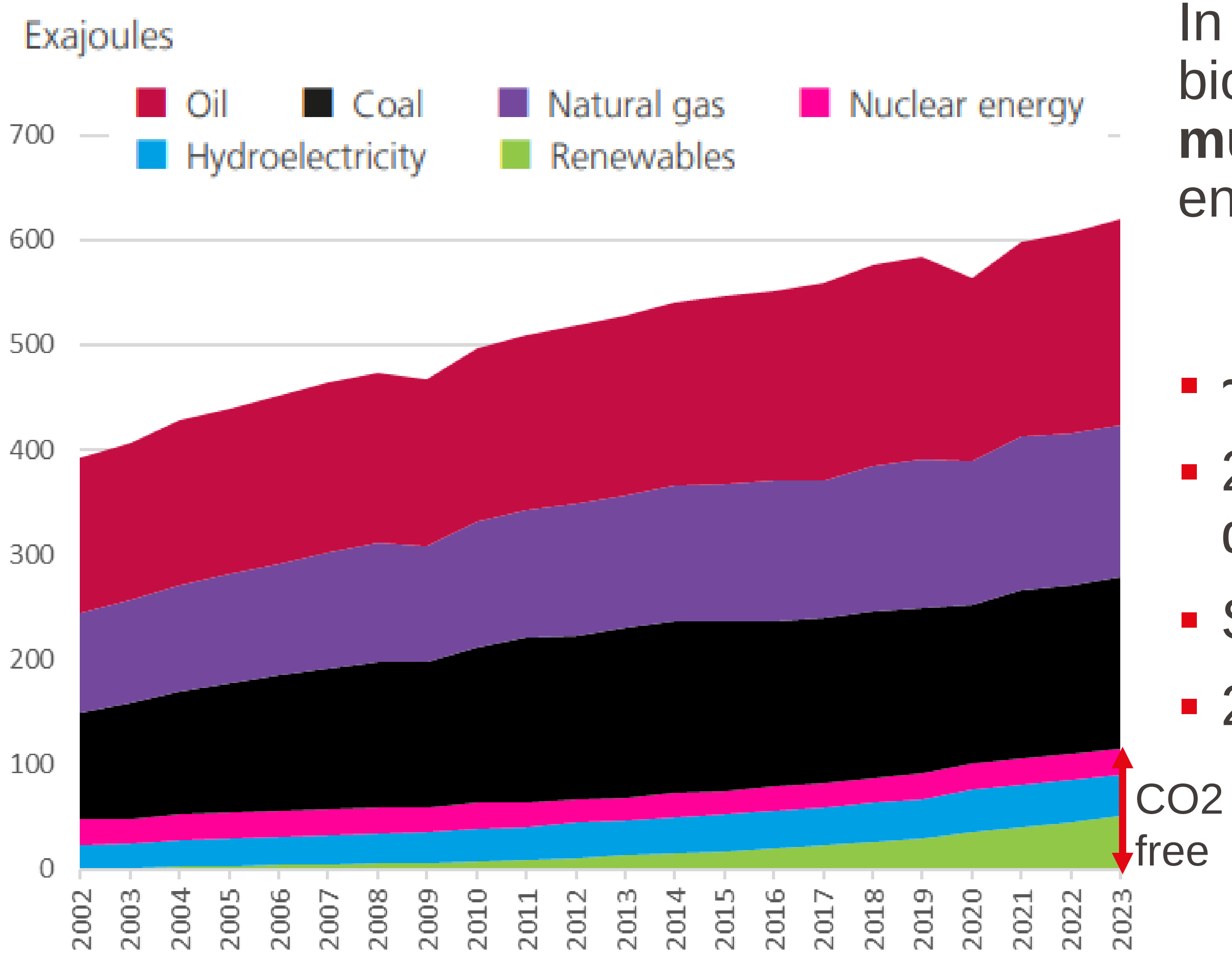
Primary energy consumption: the world challenge



In this representation: electricity in kWh of biomass, hydro, solar, nuclear wind is **multiplied by 2.5 to** be shown as primary energy source («BP» substitution method)

- ~ 172'000 TWh (CH ~ 320 TWh)
- 2% annual growth in the last 20 years driven mostly by China and India
- Still 80% fossile fuel
- 20% renewable and nuclear

Statistical review of world energy

World Energy Outlook 2024 – Analysis - IEA

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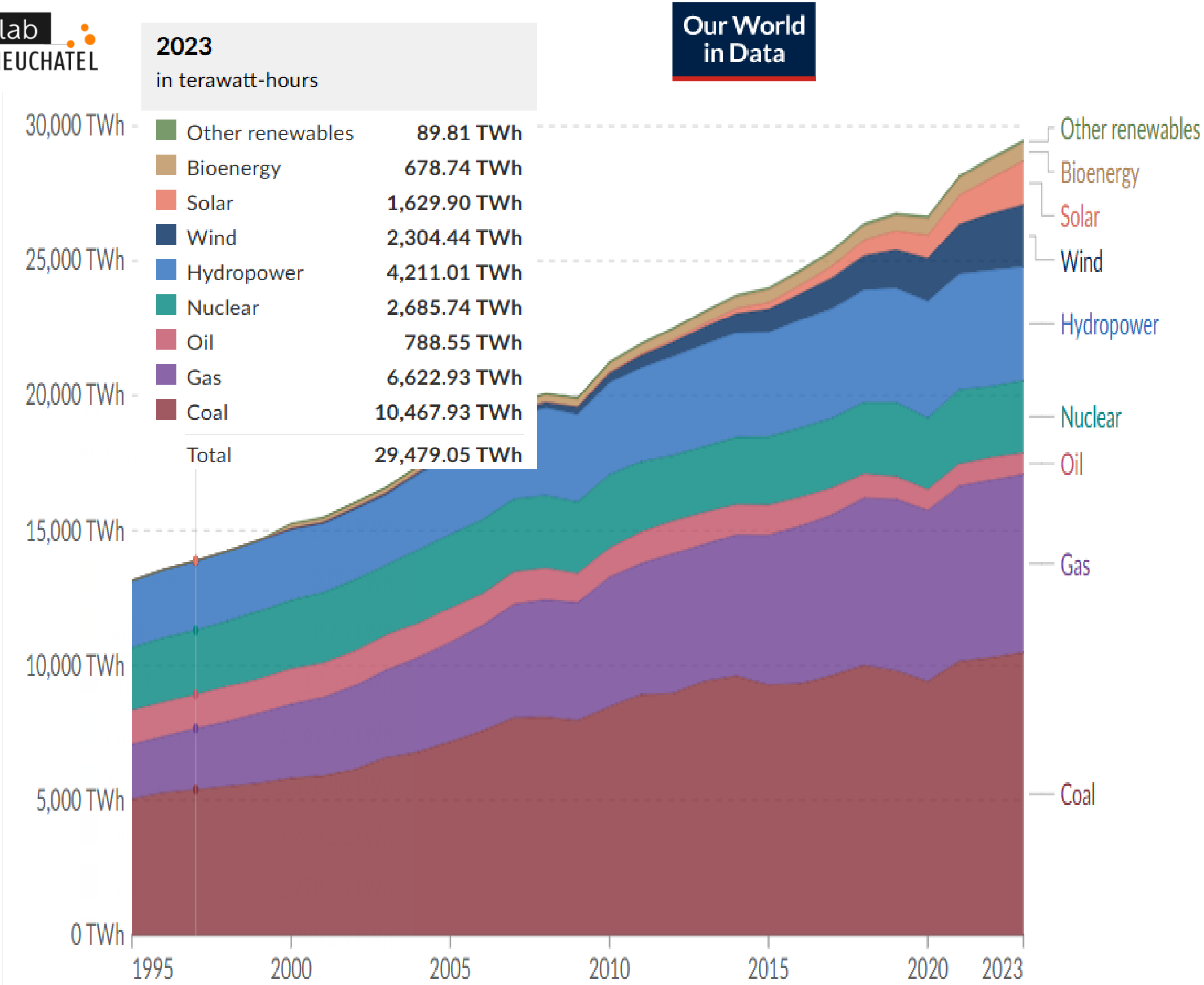
→ Each day the planet consumes an equivalent energy of around
~ 300 millions barrels of oil (1barrel=159 liters)

→ 6 liters of equivalent oil per person per day or an equivalent
thermal energy of 60 kWh,
or a continuous 60 kWh /24hrs ~2.5 kW…

(in CHF around 4000 W per person… with the same accounting…
→ 36000 kWh per person per year)

World electricity production by source 2023



- 29’470 TWh in 2023
- 2.6% annual growth over the last 20 years
- 60 % from world electricity made with fossil fuels
- Around 38% of all fossil fuels used to make electricity: most of the rest for heat and transport
- Electricity demand will accelerate (because it is the major way to decarbonise), should be in the 4% per year for two decades

https://ourworldindata.org/grapher/electricity-production-by-source

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Challenges

We have a huge triple challenge with global warming, pollution from fossil fuels (est. 5 milions dead), and a partially correlated problem with loss of biodiversity

Can photovoltaics play a significant role in decarbonizing the society? First electricity then energy?

Does it make sense economically, technically (integration) and environmentally?

Can it make the energy transition alone?

Tuoketuo Coal Power Station Mongolia 6670 MW, largest coal power plant

Cressier PV park, Suisse, 7800 kW

Rule of thumb estimations: What would you need to decarbonize the world energy system?

- With a 1.5 % growth in primary* energy need, instead of 2%... This includes efficiency gains and some sobriety in western country but still a growth in developping countries who consumes far less per habitant). It might not include additional growth linked to AI

→ **250'000 TWh primary energy** in 2050*

- **Strong electrification** of heating/mobility + biomass + rest electricity for H_2

→ **100'000 TWh** electrical production by 2050

***according to the BP substitution accounting technique**

Total 2023

29'500 TWh

- **Hydro ~ 4200 TWh**
- **Nuclear 2700 TWh**
- **Wind 2300 TWh**
- **Solar 1600 TWh**

*Global Electricity Review 2023 | Ember (ember-climate.org)

100‘000 TWh annual electricity production: 4 major options

Reminder

1GW Nuclear → 8 TWh/year (8000 hours)

1GW solar → 1-2 TWh/year (1000-2000 hours)

1GW wind → 2-4 TWh/year (2000-4000 hours)

Which can be combined with ...

- a e.g. 40‘000 GW of Solar and 15‘000 GW of Wind (+ Hydro + Biomass)
- b 13’000 x 1 GW nuclear power plants
- c Carbon sequestration behind coal
- d Don’t care (or too late…)

https://energy.economictimes.indiatimes.com/news/renewable/india-on-path-to-triple-renewable-energy-capacity-by-2030-but-faces-financing-hurdle-report/105584911

Technical question

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K owing that:

- There is enough coal (and oil and gas) for the next 100 years (cf lecture on energy)
- That no government wants to deprive its economy from energy. Means if it is not «CO_2» free, it will come from fossile.

Is it technically possible, in the next thirty years ?

- To manufacturing and install 1500 GW of PV panels per year ? And 500 GW of Wind per year ?
- Install 420 GW of new nuclear power plants every year ?
- Stop energy consumption ? (sufficiency)
- To really substitute fossile fuels


Fliegl
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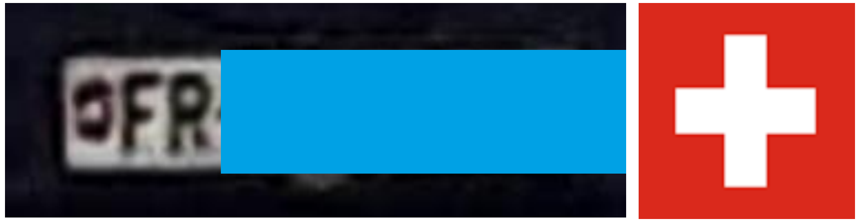
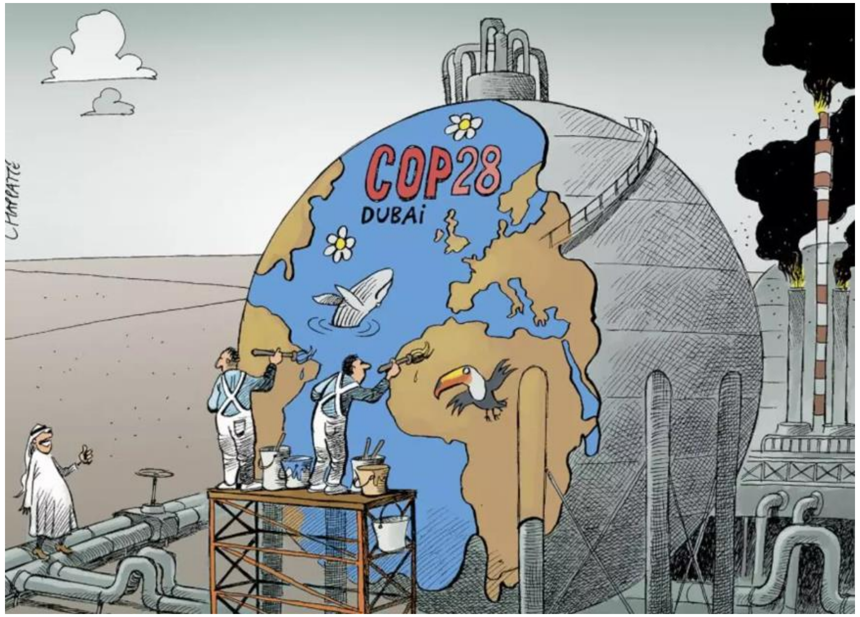
avesco
MAKE DIESEL GREAT AGAIN

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INTERVIEW

«Für die Bauern ist die Klimaerwärmung nicht schlecht», sagt der künftige SVP-Präsident Marcel Dettling

Dem Landwirt ist es lieber, wenn es wärmer wird statt kälter. Und er will sich beim Stromgesetz mit seinem Bundesrat Albert Rösti anlegen.

René Donzé und Ladina Triaca (Interview)

17.02.2024, 18.56 Uhr 9 min

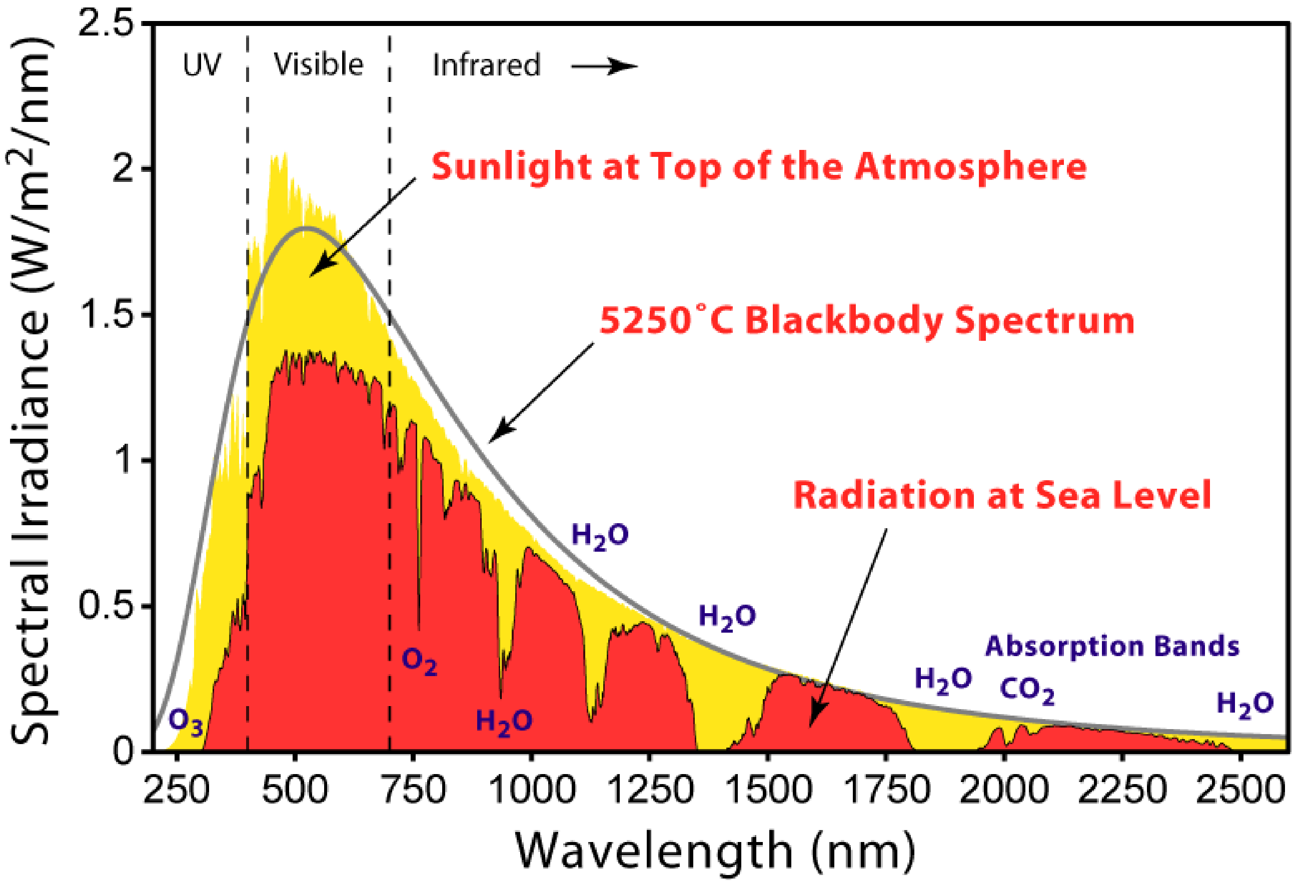
Hören Merken Drucken Teilen

??

Ich bin ein gläubiger Mensch, und ich glaube auch, dass wir nicht über alles bestimmen können.

1. The basics of solar energy

Solar irradiance spectrum



• The mean **solar irradiance** is 1366 W/m^2 in outer space

The spectrum is referred to as **AM$_0$.**

• On earth: losses by absorption (18%) and by diffusion (10%)

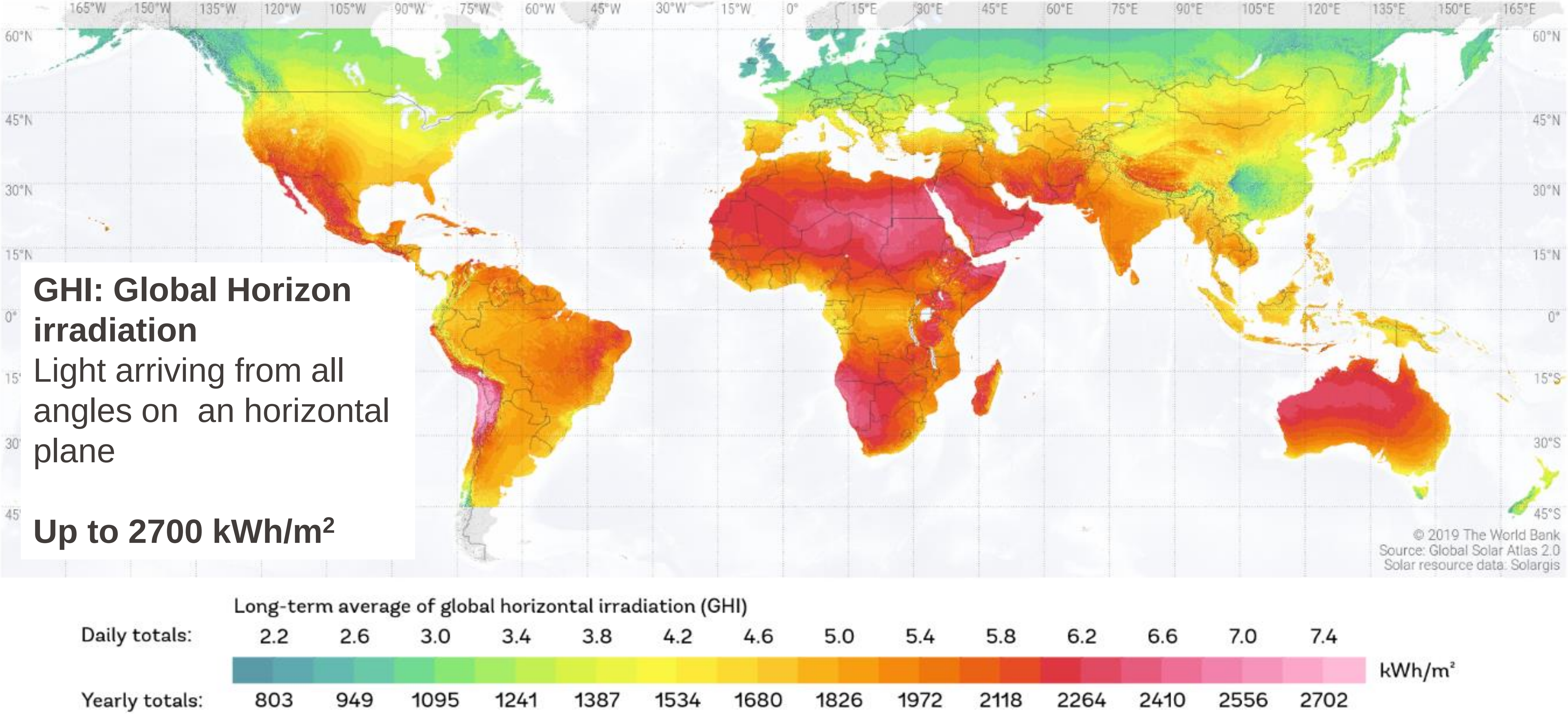
~ 970-1000 W/m^2

Direct light around 90% of total “global" light

- When the solar spectrum crosses the earth atmosphere it suffers from absorption (water vapour, ozone, dust…) and from Rayleigh scattering (diffusion… blue light is more scattered than red light).

SOLAR RESOURCE MAP

GLOBAL HORIZONTAL IRRADIATION



GHI: Global Horizon irradiation

Light arriving from all angles on an horizontal plane

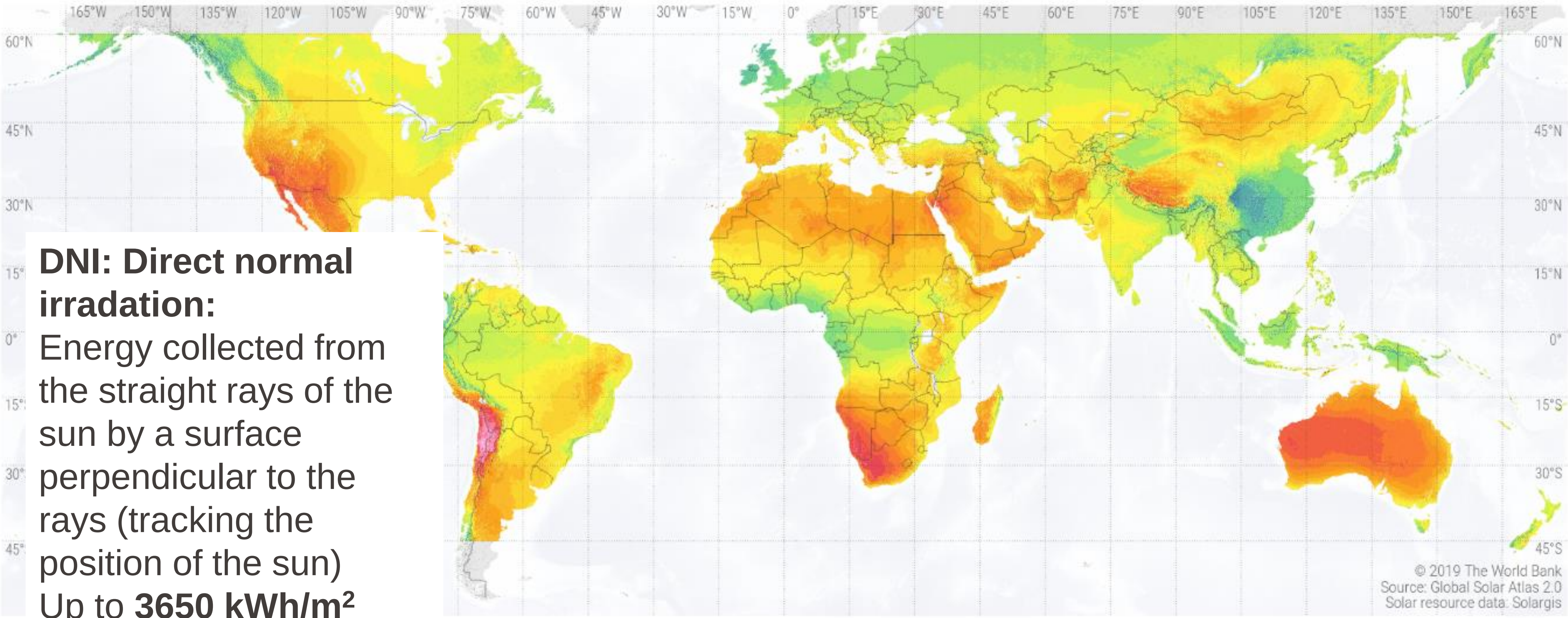
Up to 2700 kWh/m^2

This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit http://globalsolaratlas.info.

SOLAR RESOURCE MAP

DIRECT NORMAL IRRADIATION

WORLD BANK GROUP ESMAP SOLARGIS



DNI: Direct normal irradation:
Energy collected from the straight rays of the sun by a surface perpendicular to the rays (tracking the position of the sun)
Up to **3650 kWh/m^2**

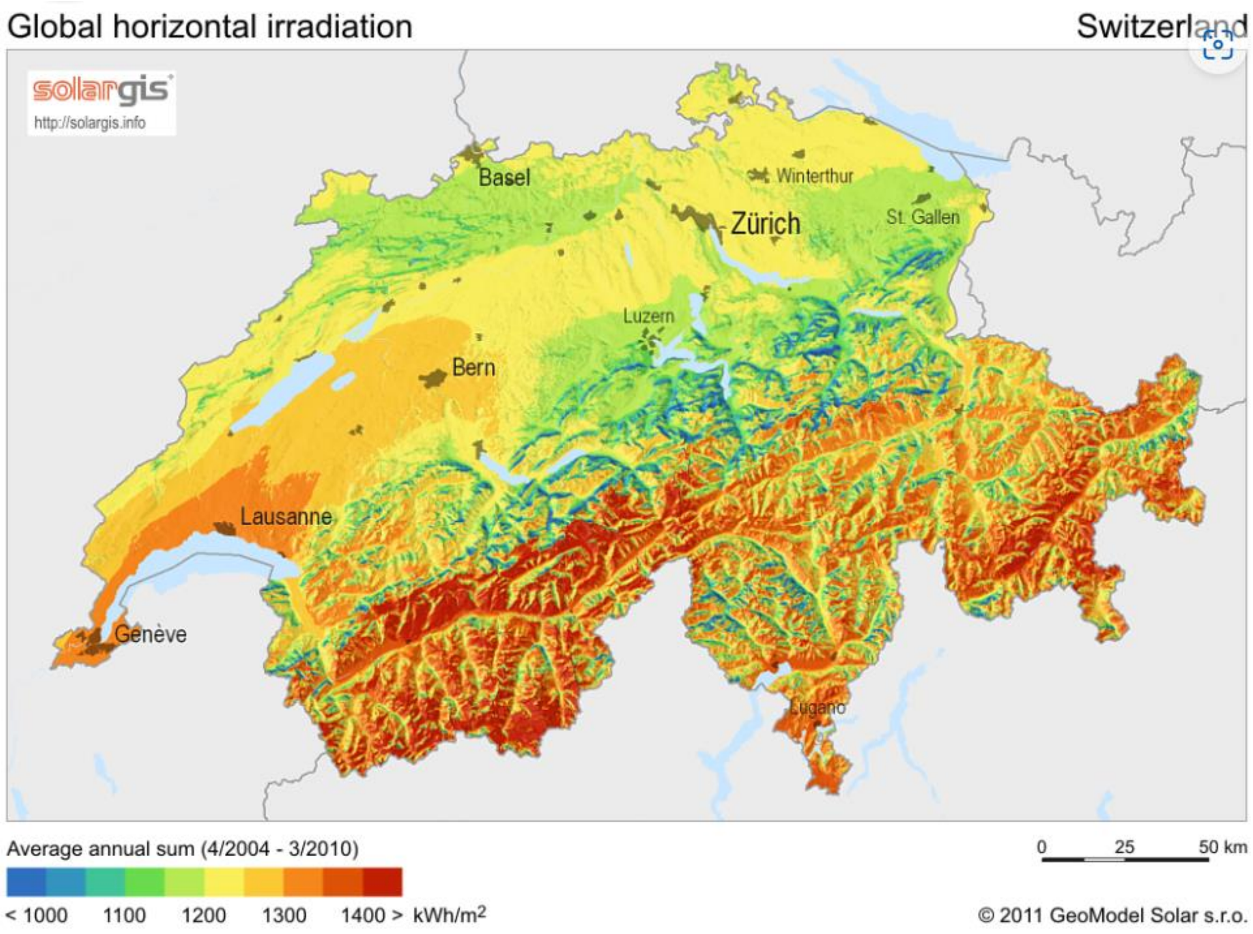
Long-term average of direct normal irradiation (DNI)

Daily totals:	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	kWh/m²
Yearly totals:	365	730	1095	1461	1826	2191	2556	2922	3287	3652	

Annual GHI in Switzerland

One year in Switzerland:
1000-1500 full hours at intensity
1000 W/m^2

1000-1500 kWh/m^2/y



Almost the same as

1 barrel/m^2/year

1 litre of oil ~9-10 kWh chemical energy

1 barrel = 159 litres

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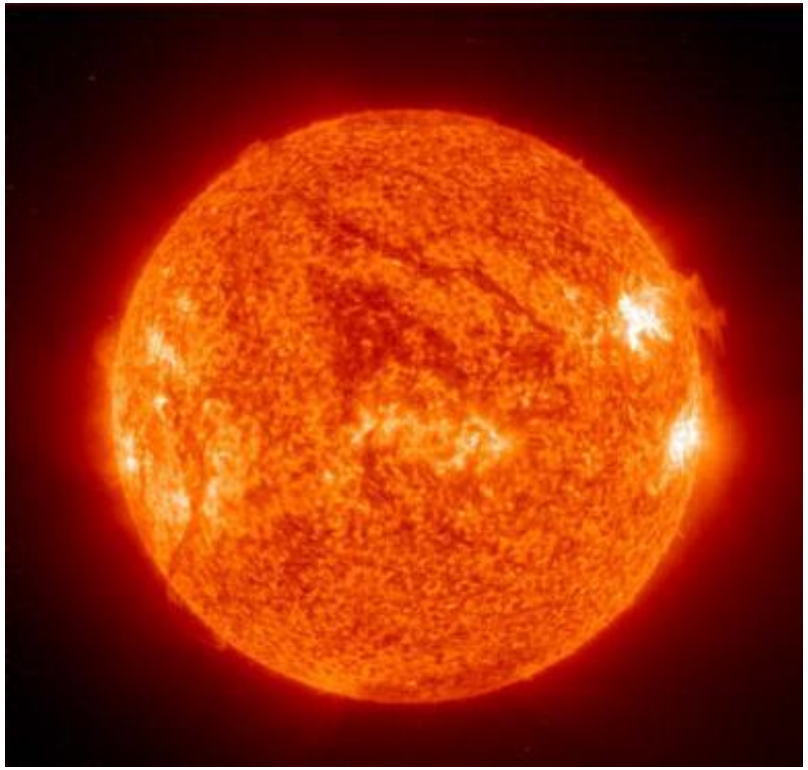
Summary

- Sun irradiance Earth ≈ 10’000 x World power consumption;
- 1 hour of sun irradiance on earth = Total annual world energy consumption;
- Irradiance at sea level ~ **1000 W/m²**;

→Typical Annual irradiation **800-2500 kWh/m² annually** depending on location (more on optimally inclined surface, and more with tracking).



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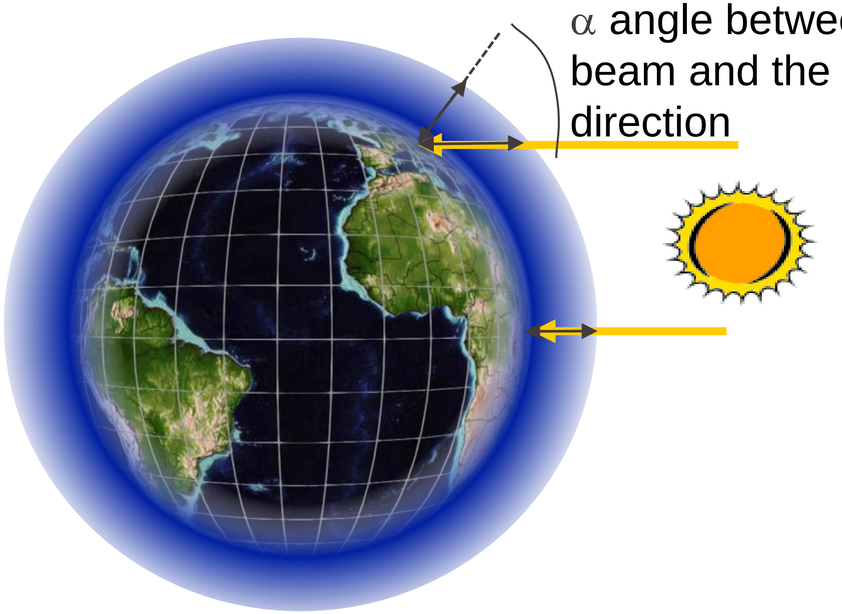
1. The basics of the Sun and energy

Air Mass - AM

AM*x* where *x* describes attenuation through the atmosphere $x = 1/\cos\alpha$ (eq. 1.1)



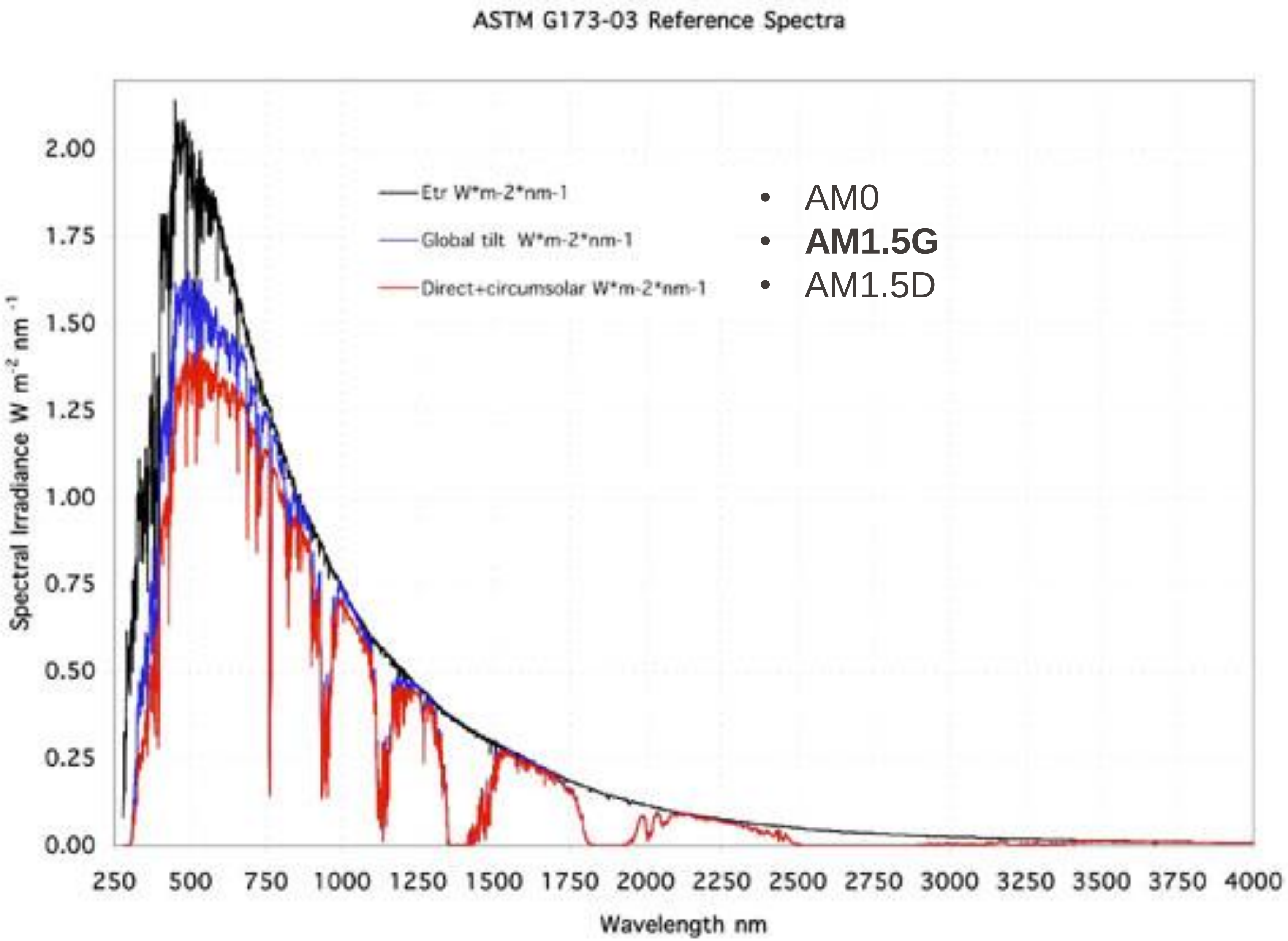
α angle between the sun beam and the vertical direction

- **AM0** solar spectrum outside of the atmosphere (1366 W/m^2)
- **AM1** solar spectrum on earth when the sun is vertically above (equator)

ASTM International G173-03 (IEC 60904-3) defines the spectra used for measurement of solar cells:

- AM1.5
  - ~970-1000 W/m2
  - spectrum after passing 1.5 times the atmosphere thickness
  - (solar zenith angle α = 48.19°)
- **AM1.5G**
  - Including diffuse radiation
  - Normalised to 1000 W/m2
- AM1.5D
  - Only direct radiation
  - 900 W/m2 (direct + 2.5° circumsolar component)

Standard spectra



- AM0
- **AM1.5G**
- AM1.5D

2. Not just photovoltaic

Various ways to use solar energy

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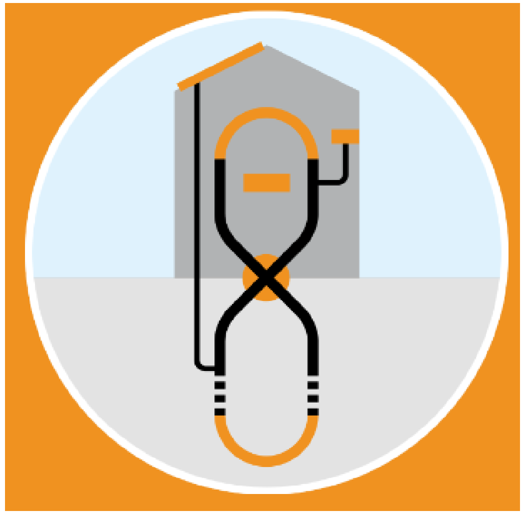
Passive solar

[Swiss Solartank - Deutsch (jenni.ch)](jenni.ch)

Solar thermal with seasonal storage

Solar thermal



Soltar thermal (or PV)
With ground heat storage

www.2sol.ch

2. Not just photovoltaic

Various ways to use solar energy

- Sanitary water 1 m^2/person (CH)
- Can support heating needs in winter
- Efficiency 50-70% (high T, or low T heat)
- Thermal 8-15 cts/ kWh for small/medium size systems (a few kW)
- Often in competition with PV+heat pump (with similar global efficiency)

Solar thermal systems: light - heat

- Seasonal storage up to large scale heat storage in 200’000 m^3 in Denmark (and low storage seasonal costs)
- Possible higher temperature for industrial heat or district heating

TVP Solar (Geneva), up to 200°c large plant at down to 4€cts/kWh thermal

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2. Not just photovoltaic: Electricity from heat

Concentrated Solar Thermal

- Focus light on receiver (e.g. tower or tube)
- Create high temperature (300-600°C)
- Run turbine with heated gas
- Likely to disappear, all replaced by PV+batteries

- Extend production toward night (heat storage, e.g. with molten salt)
- Short term perspective for electricity at < 7-9 €cts/kWh with partial storage (Morocco, Dubai)
- Complex systems, global efficiency 17-20%

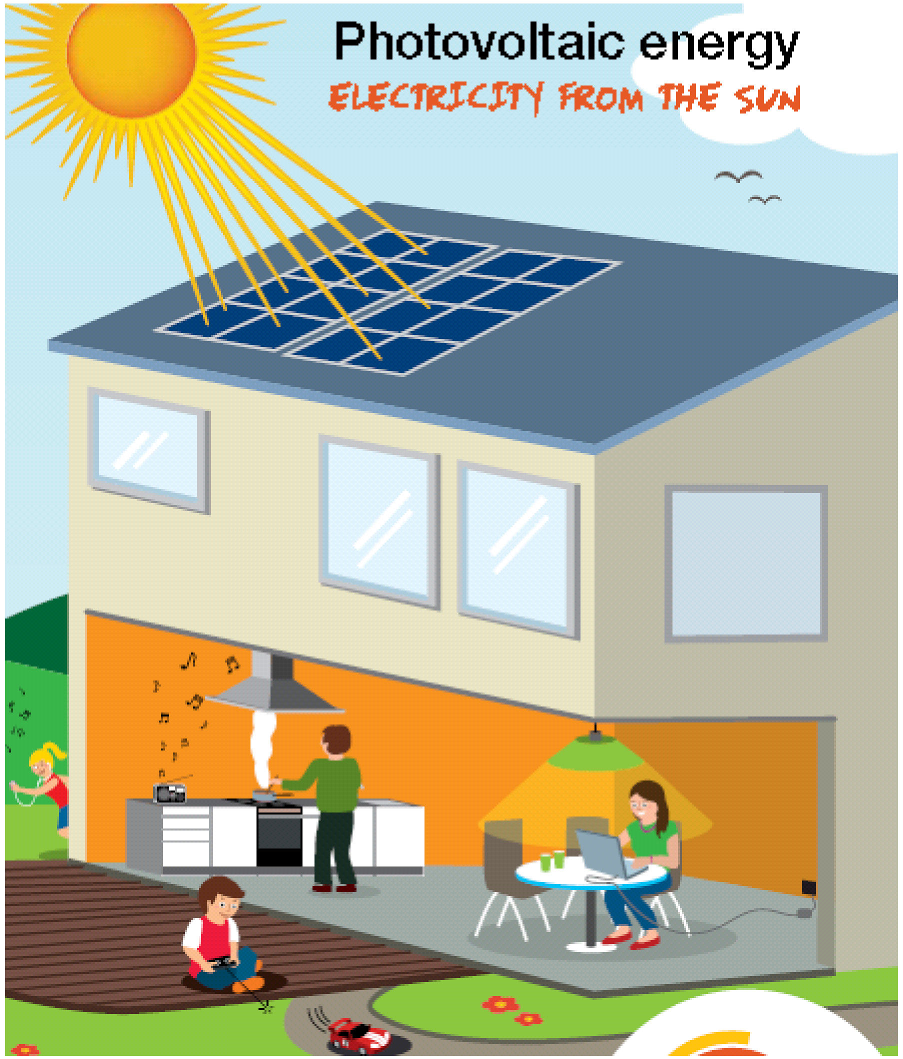
This alien-like field of mirrors in the desert was once the future of solar energy. It's closing after just 11 years

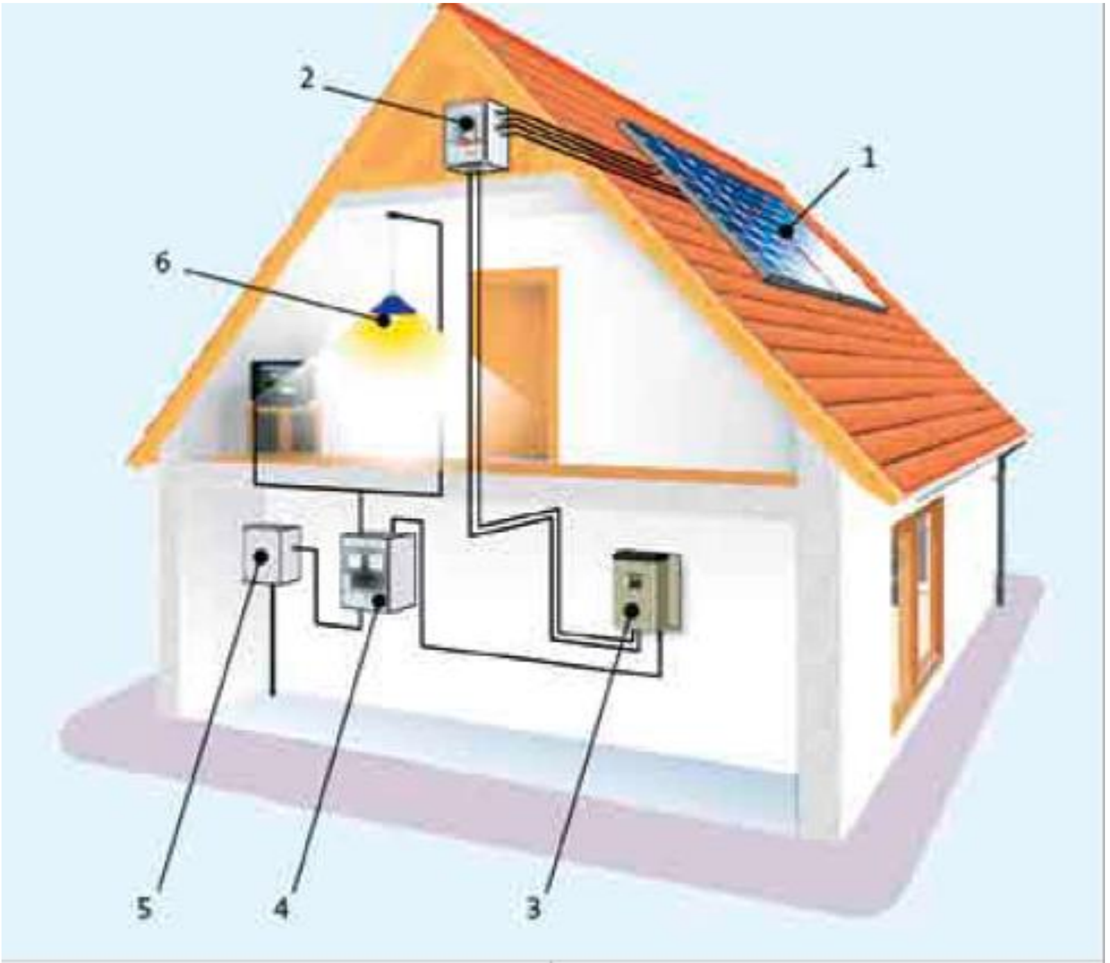
By Laura Paddison, CNN

4 minute read · Published 6:00 AM EST, Thu February 13, 2025

3. Fundamentals of PV

Photovoltaic energy = direct light - electricity conversion





1 PV array
2 PV array combiner / junction box
3 Grid-tied inverter
4 Import / Export meter
5 Connection to the grid
6 Load

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3. Fundamentals of PV

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A brief history…

1839, at the age of 19

Edmond Becquerel, the French experimental physicist, discovered the photovoltaic effect while experimenting with an electrolytic cell made up of two metal electrodes placed in an electricity-conducting solution-generation increased when exposed to light.

E. Becquerel, 'On electron effects under the influence of solar radiation.' Comptes Rendus 9, 561.

Edmond's Son, Henri, discovers radioactivity in 1896 !

http://www.pvresources.com/en/introduction/hist
http://www.pvpower.com/pvhistory.html

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3. Fundamentals of PV

A brief history

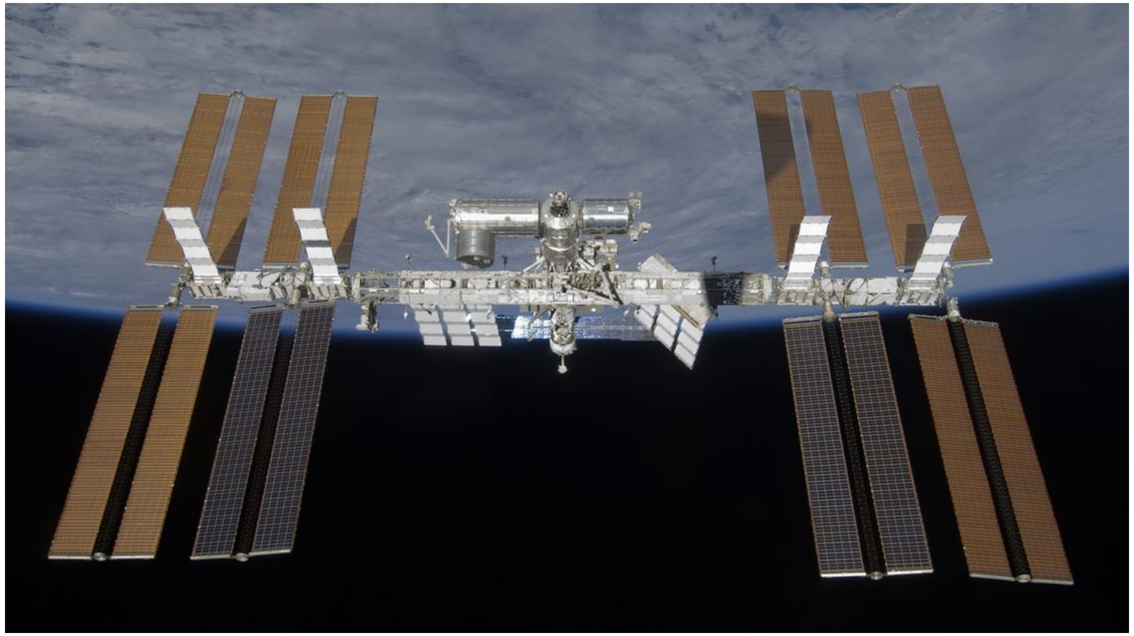
1883 : Charles Fritts, an American inventor, described the first solar cells made from selenium wafers

1954: Bell Laboratories, D.M. Chapin, C.S. Fuller, and G.L. Pearson published the results of their discovery of **4.5%** efficient silicon solar cells--raised to 6% only a few months later

From the mid-50

Market driven by space applications (military, communication)

Challenge at that time = high radiation tends to "kill" the solar cells. What counts is the "end of life efficiency" in space



3. Fundamentals of PV

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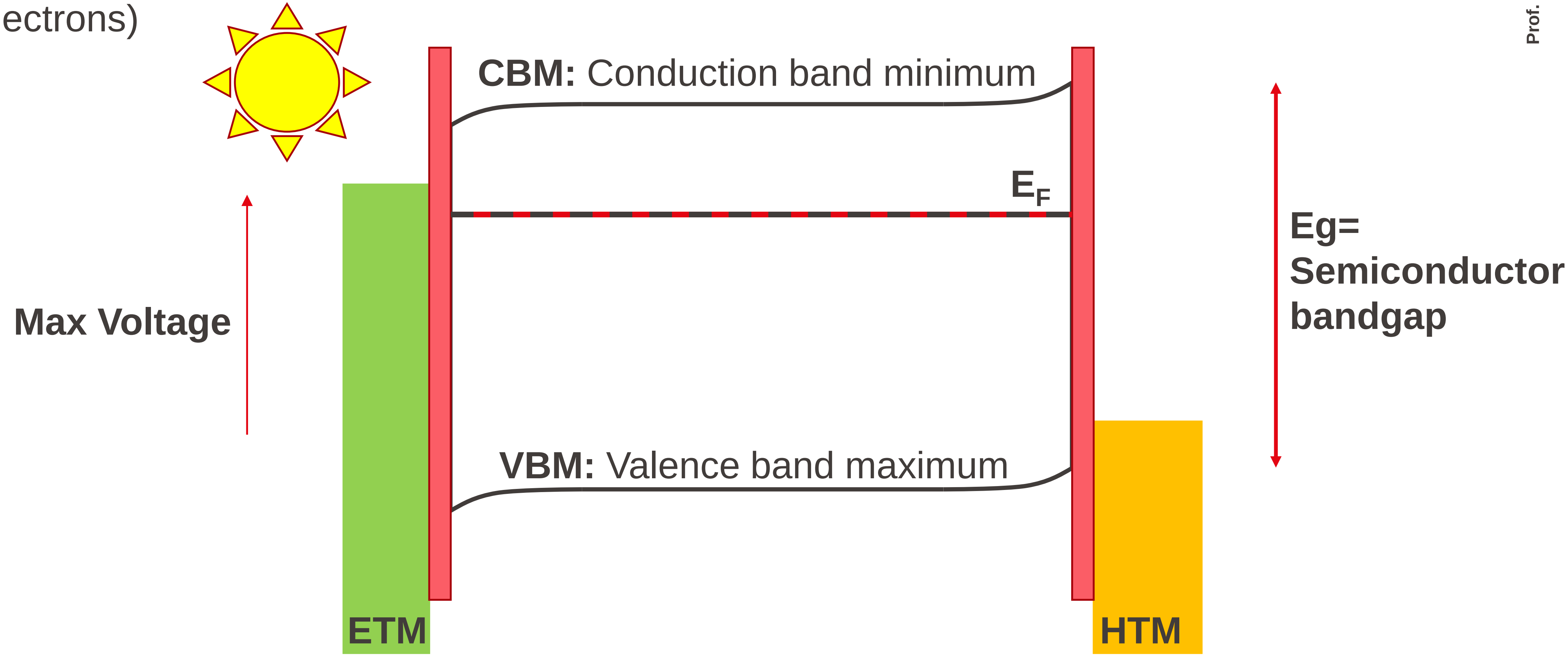
Ideal solar cells : a photon absorber (a semiconductor with a bandgap) with two membranes: one to extract electrons and another one to extract holes (or inject electrons)



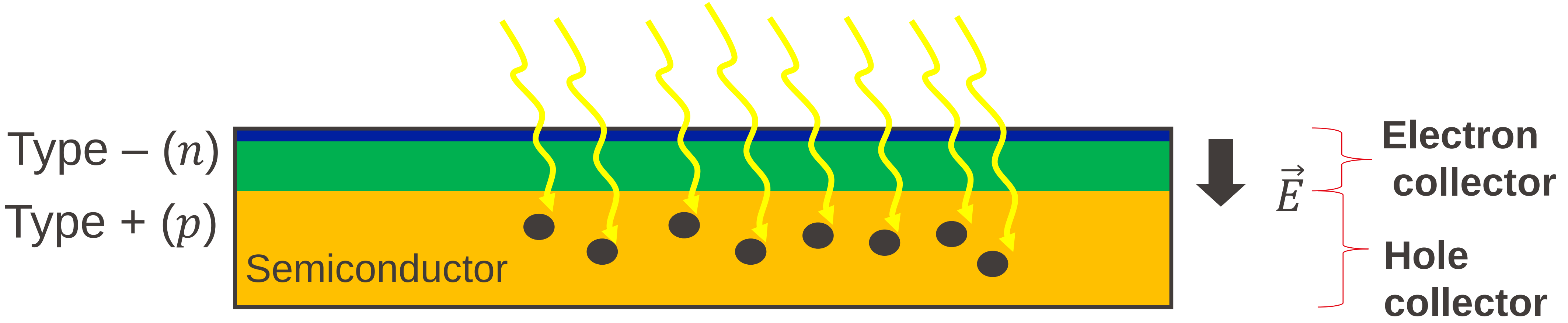
ETM or ETL: electron transport material or layer: collects excited electron

HTM or HTL: hole transport material or layer: collects excited holes

3. Fundamentals of PV

Basic design of a solar cell : p-n junction

- → Intrinsic (pure) semiconductor material (e.g. Si, CdTe,…)
- → Doping with chosen impurities → becomes conductor with + (p) or – (n) charges transporting the current
- → If a p-zone is in contact with an n-zone → diffusion of charges and creation of an electrical field $\vec{E}$
- → Under light: absorption of photons if $h\nu > E_g$ (E_g: semiconductor bandgap)
- → Photons absorbed in p-zone transfer their energy to electrons (in n-zone to holes)
- → Photogenerated carriers move towards the junction and cross it



3. Fundamentals of PV

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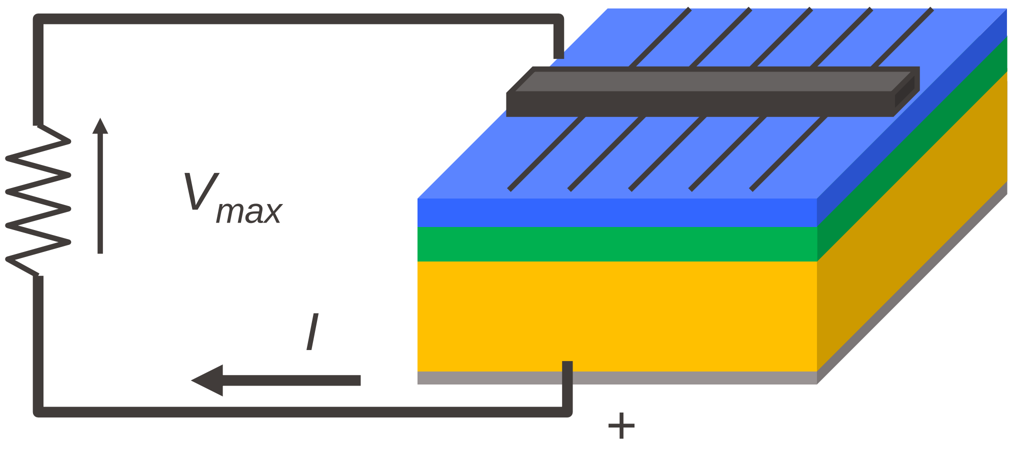
Extraction of current

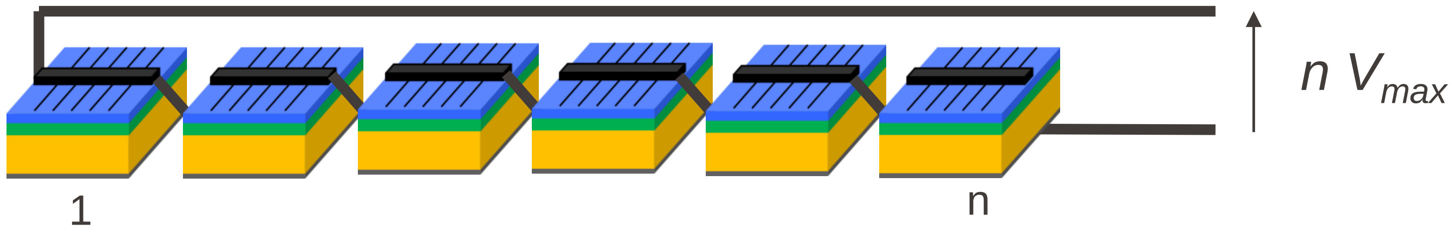
Metallic contacts (and/or transparent conductive contacts) extract the current

- Voltage depends on bandgap (Eg)
  - **~0.7 V for crystalline Si, 1.1 V for GaAs**
- Current depends on Eg and is proportional to the surface area
  - **Typical ~ 40 mA/cm^2 c-Si, or 10 A for a 6" inch square cell (16x16 cm^2)**

Useful power dissipated on R_M



- To get high voltage → connect cells in series



! If one cell is not illuminated
It will block the full chain !
Usually a «by-pass diode»
will « protect a chain of cells»

3. Fundamentals of PV

First approximation : a basic solar cell can be seen **as a p-n diode** with a current source in parallel (current proportional to light intensity)

kT=
26 mV at 25°K
q= electron charge
I_o= saturation current

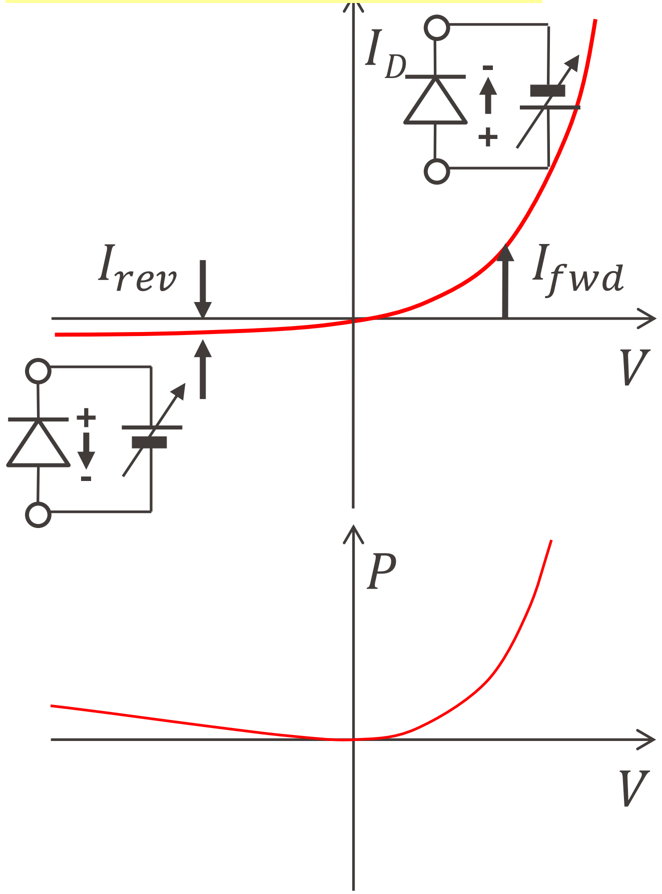
Dark

$$I_D = I_0\left[\exp\left\{\frac{qV}{kT}\right\} - 1\right] \quad (1.2)$$

Illuminated

$$I_L = I_D - I_{ph} = I_0\left[\exp\left\{\frac{qV}{kT}\right\} - 1\right] - I_{ph} \quad (1.3)$$

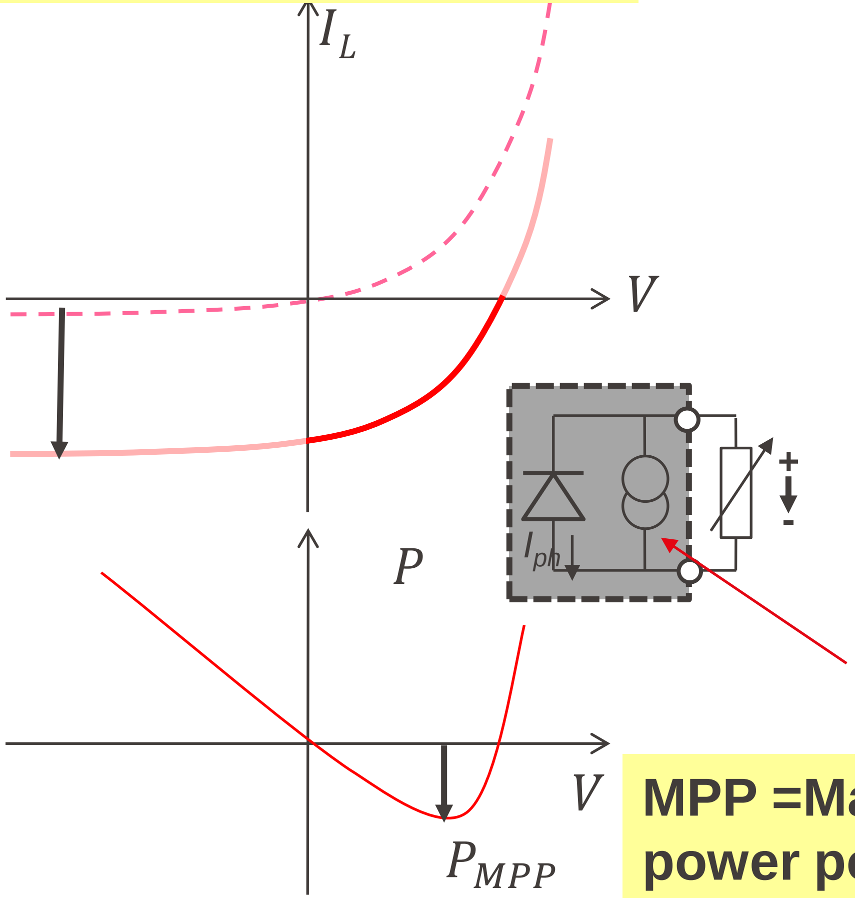
P= VI



consuming

sign convention

producing



Current source

MPP =Maximum power point

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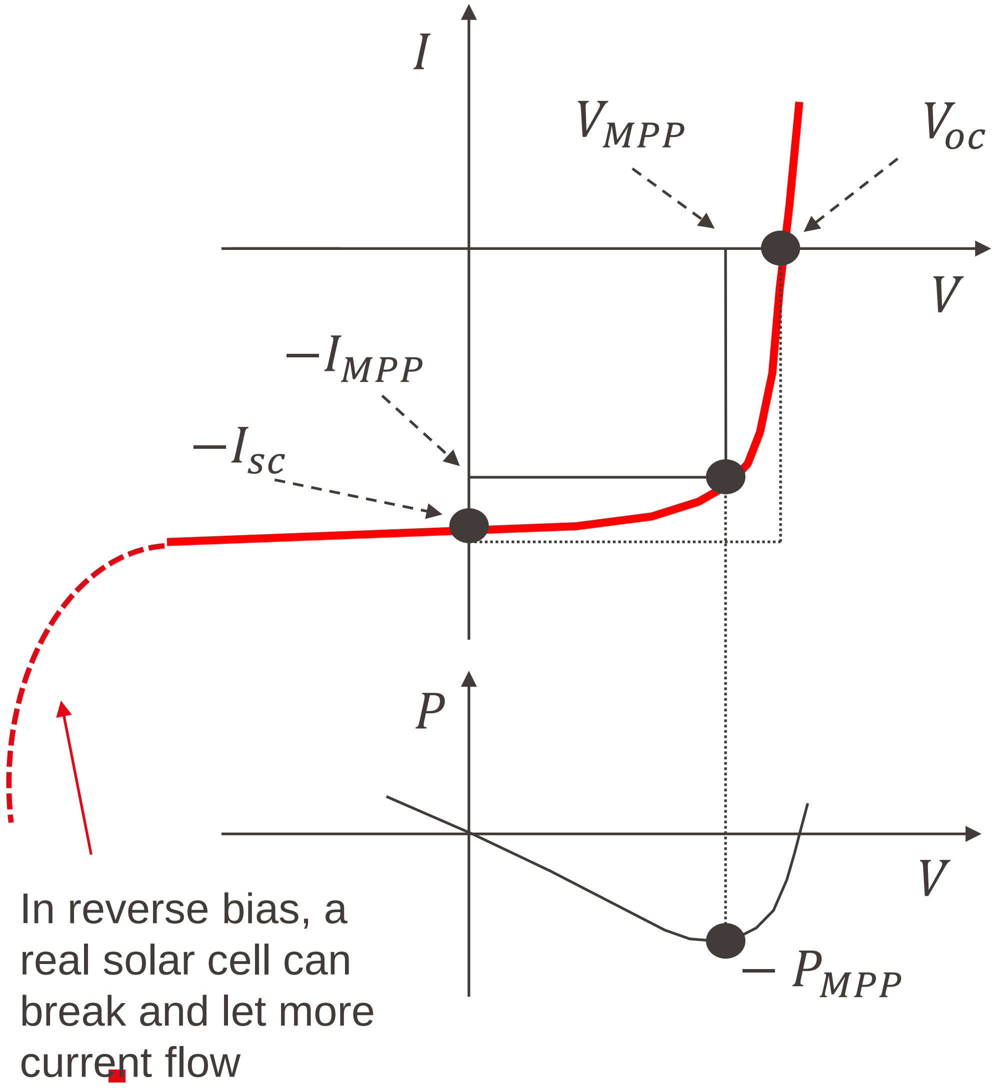
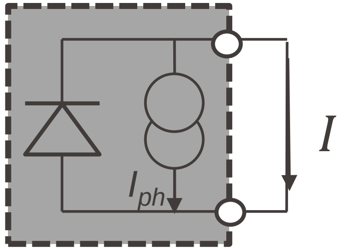
3. Fundamentals of PV

Special points of the $I(V)$ curve

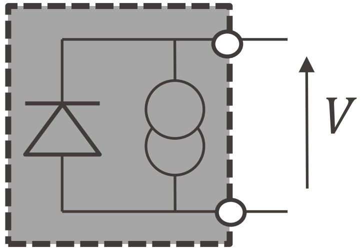




Short-circuit conditions

$V = 0 \Rightarrow -I_{sc} = I_{ph}$

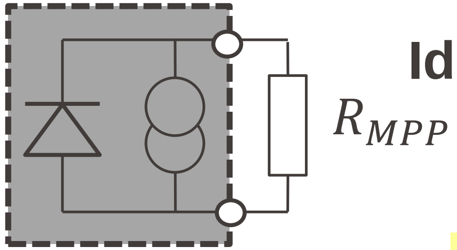
I_{sc} = Short circuit current



Open-circuit conditions

$I = 0 \Rightarrow V = V_{oc}$

V_{oc} = Open circuit voltage



Ideal power dissipation on R_{MPP}

$R_{MPP} = V_{MPP}/I_{MPP}$

Fill factor ($\boldsymbol{FF}$) given by:

$$FF = \frac{P_{MPP}}{I_{sc}V_{oc}} = \frac{I_{MPP}V_{MPP}}{I_{sc}V_{oc}} \quad (1.4)$$

**FF indicates how «square» the I-V curve is !
An ideal FF would be 100%. Usually the higher the Voc the higher the FF**

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3. Fundamentals of PV

Power or efficiency of a cell or module under defined ***standard test conditions* (*STC*)**

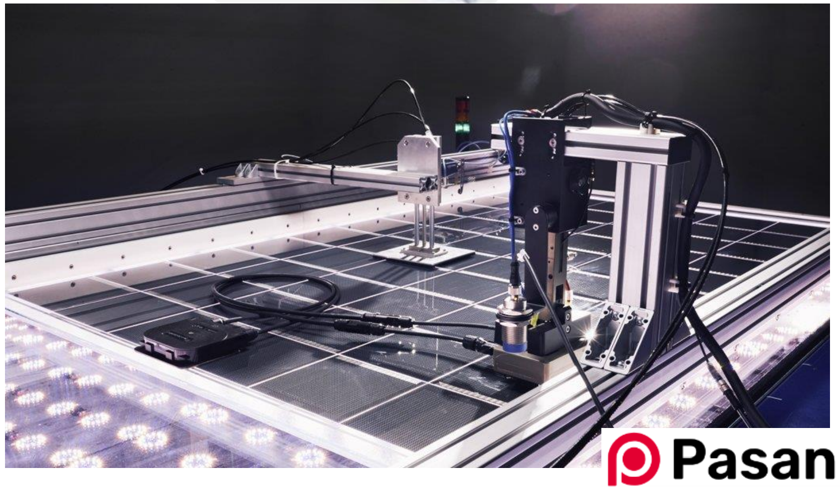
- Cell or module at 25°C
- Spectrum AM1.5G (global)
- ght intensity 1000 W/m2

$$\eta_{STC} = \left.\frac{P_{MPP}}{P_{light}}\right|_{STC} \quad (1.5)$$

Efficiency at STC

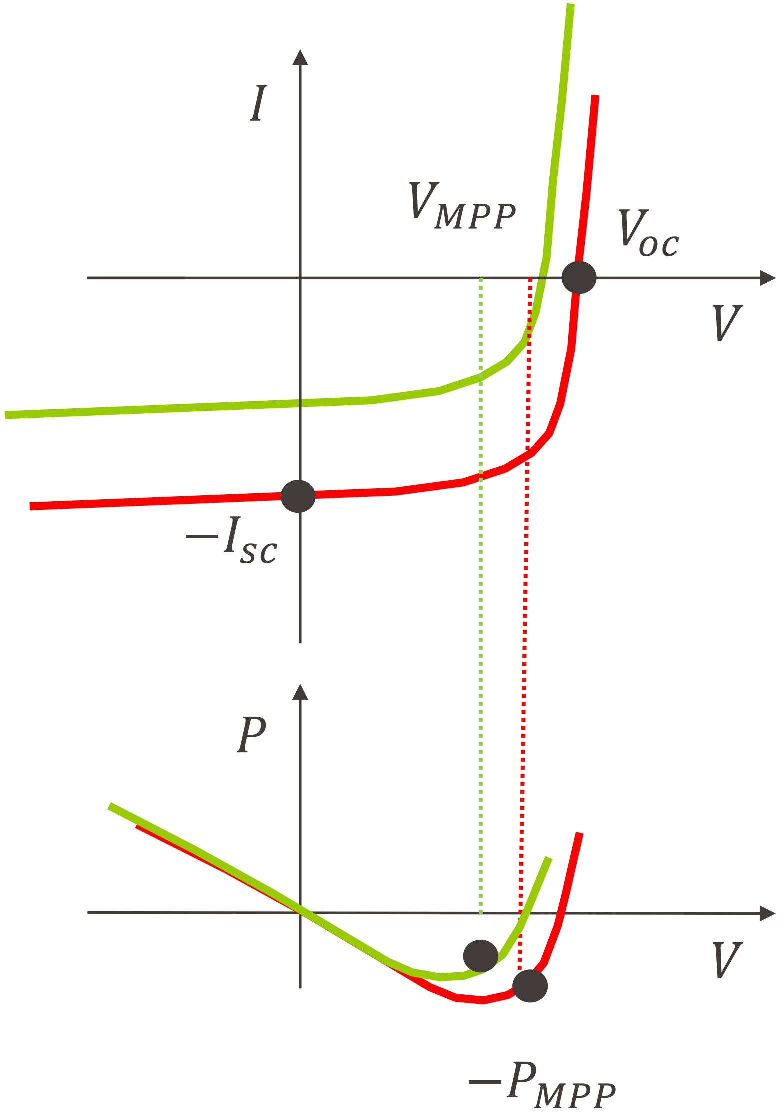
Modules of Area ***A*** are sold according to their Nominal power in **W or Wp (=Watt peak output)**, with respect to STC

$$Wp = \eta_{STC} \text{ x A} \quad (1.6)$$



A modern LED measurement table for c-Si modules

Maximum Power Point Tracker (MPPT)



A maximum power point tracker (or MPPT) is a high efficiency DC to DC converter that presents an optimal electrical load to a solar panel or array and produces a voltage suitable for a consumer (e.g. a battery system or an a DC/AC converter).

It uses e.g. a *perturb and observe* algorithm:
- apply higher voltage
- check whether power increases
- repeat until power decreases
- It helps find the **optimum working point**

Note: From the diode equation, Voc changes little with light intensity (logarithmic dependence), whereas current is proportional… This helps for control !
For real modules, sometimes complex I-V curves ! (step-wise)

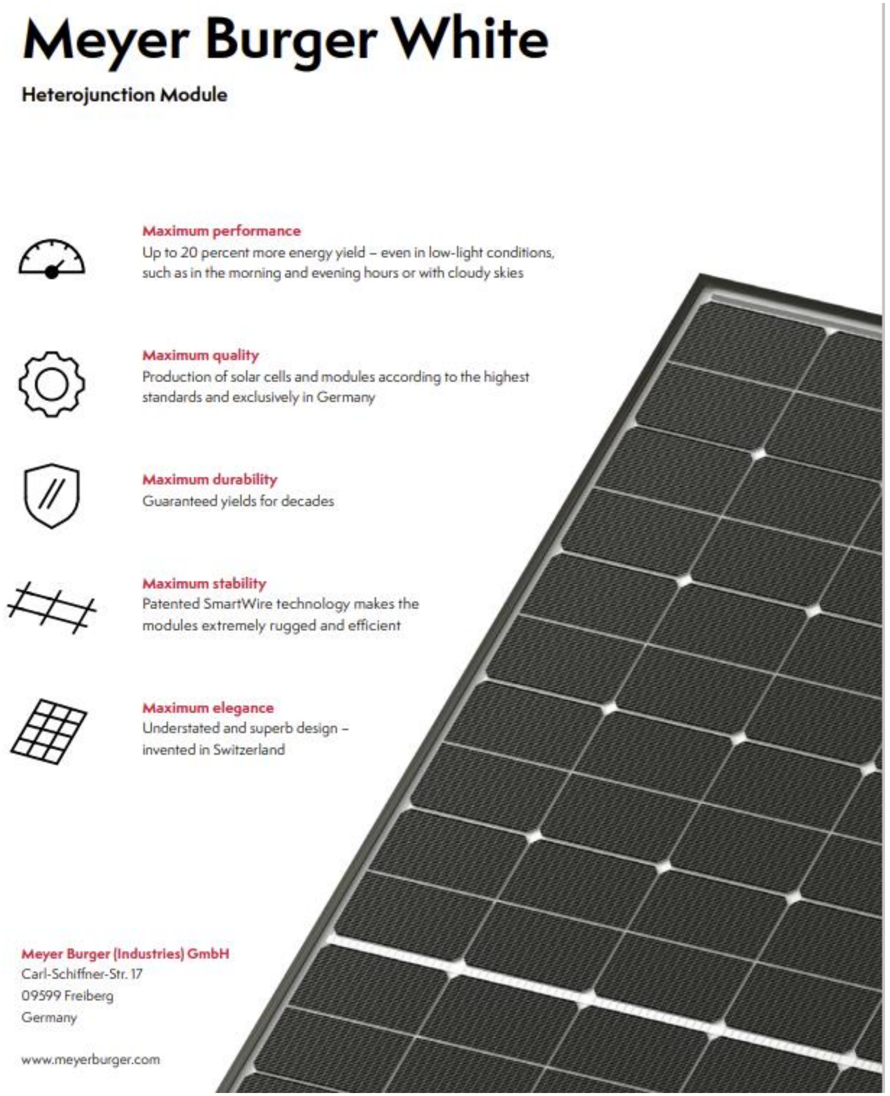
Real modules: a sum of diodes with current sources

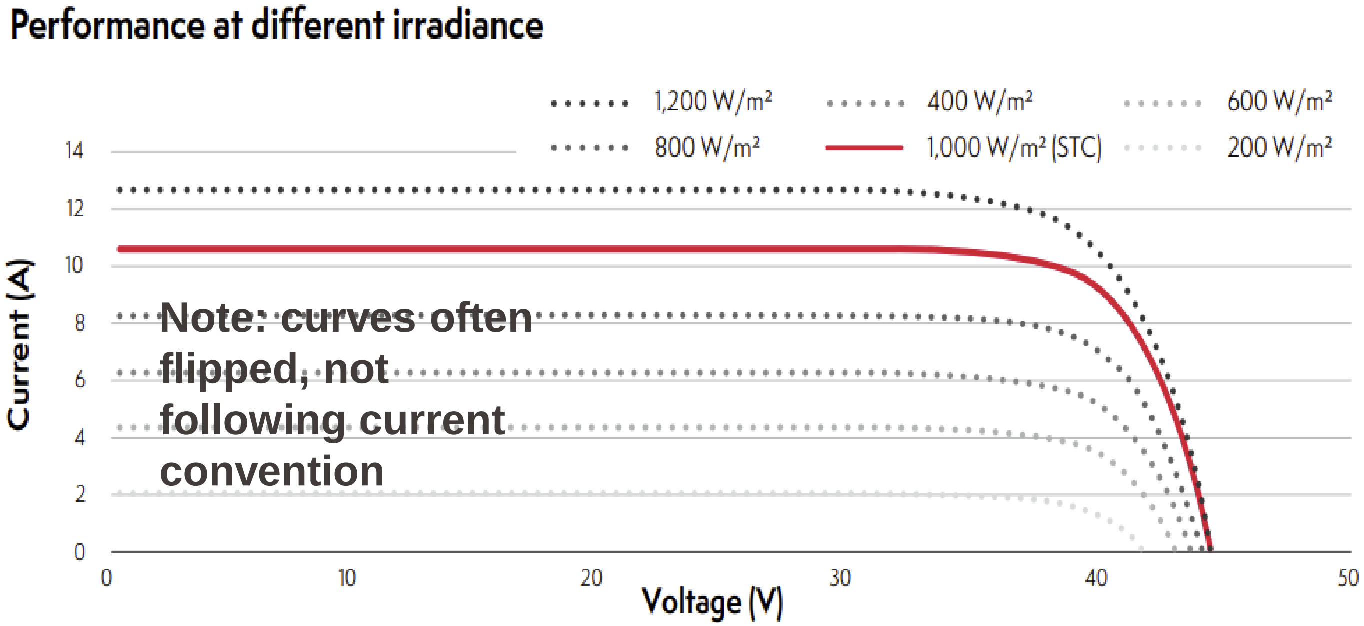
Module datasheet allows a reconstruction of important cell parameters

Example: 390 W modules of Swiss Comp MB (21.7%, 2022) 120 solar cells (1/2 solar cells of 166x83 mm2). 60 solar cells in series, two series in parallel.

→ **Voc= 44.5 V** (742 mV per cell)

→ **Isc=10.9 A (~39.5 mA/cm²), Pmax= 390 W (datasheet). Calculated FF= 80.4%, cell efficiency in module of 23.5%.**





Note: curves often flipped, not following current convention

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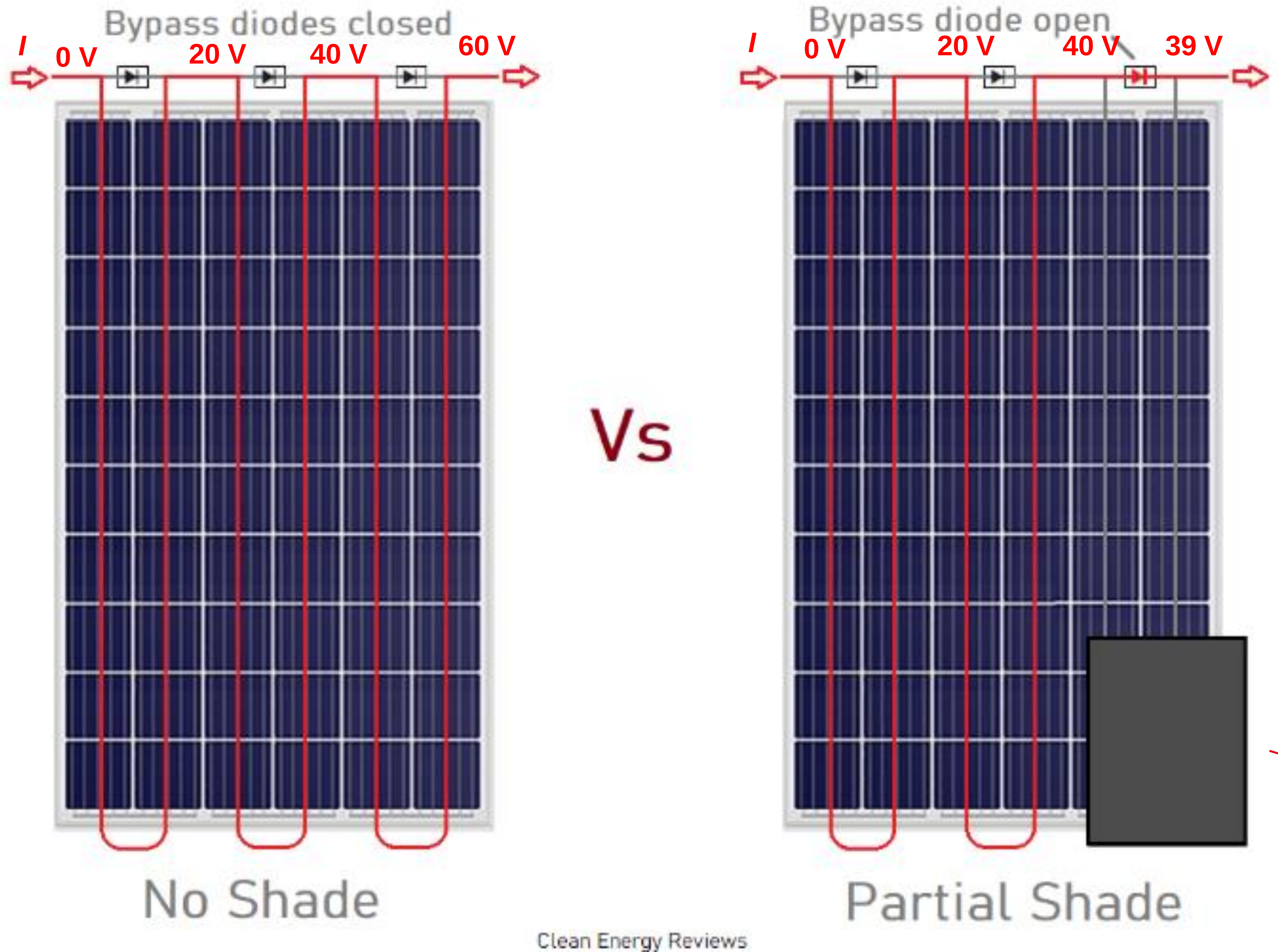
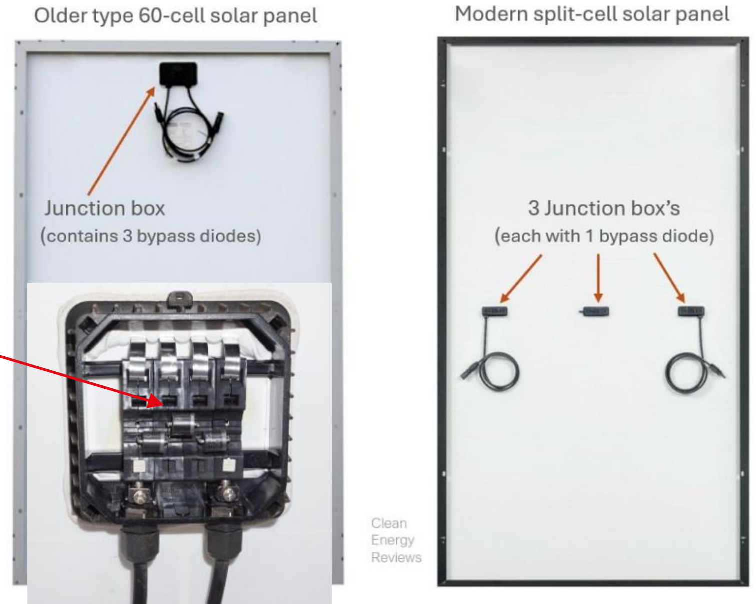
Bypass diode: keep current flowing/protect cells



With no bypass diode,

- likely working point is all cells at Voc and no current → no power out, no danger for the module
- Or that all the voltage provided by the other cells applies in reverse onto the shaded cells (breakdown and local heating)



4. Inverters

Inverters (including an MPPT): grid injection

An inverter is an electrical device that converts DC to AC current.
PV inverters usually include an MPPT tracker.

Mounted inverters close to PV modules

SMA «sunny boy» 3kW inverter

ABB 5 MW inverter

$\eta = 98.6\%$

Emphase Micro-inverter (one module)

- Entrance voltage into inverters up to 1000, or even 1500 V obtained by strings of modules (typically 30 to 50 modules in series)
- With mass manufacturing: large inverters down to low cost 4-10 cts/W
- Typical efficiencies 96-99%

Important estimation

Standard c-Si modules at 21 % efficiency → 210 Wp/m^2 (Watt peak)

Rule of thumb:

- **1 Wp produces 1.0-1.5 kWh/year** in CH corresponding to 1000 h of ideal sunshine per year. In mountain regions more hours because of less fog and, sometimes, higher irradiation intensity because of reflection from snow

- **1 Wp produces 1.5 to 2.0 kWh/year** in sunny climates Southern Europe, Southern US, Australia etc.

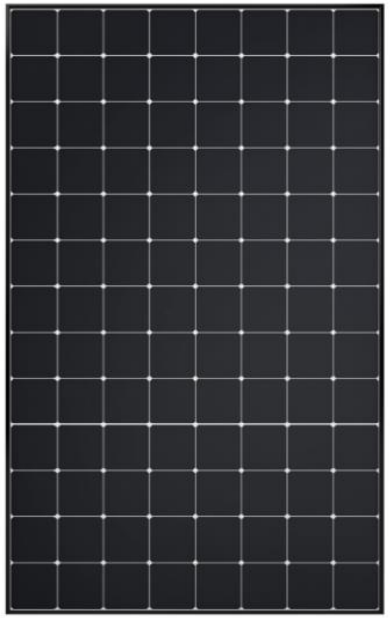
- **1 Wp can produce up to 2.5- 3 kWh/year** when in perfectly sunny area mounted on tracking system with "bifacial" systems

Energy Density of PV

With 22.6% panels in CH, per year;

13.2 m^2 → 3000 Wp → 3200 kWh → typical electricity needs of a family (without heating)

8.6 m^2 → 2000 Wp → 2100 kWh → drive 12’000 km by electrical car (17 kWh/100 km ~ 2 L oil /100 km)



MAXEON® 3 | 400 W

DC Residential Solar Panel

One of today’s most efficient commercial terrestrial PV modules

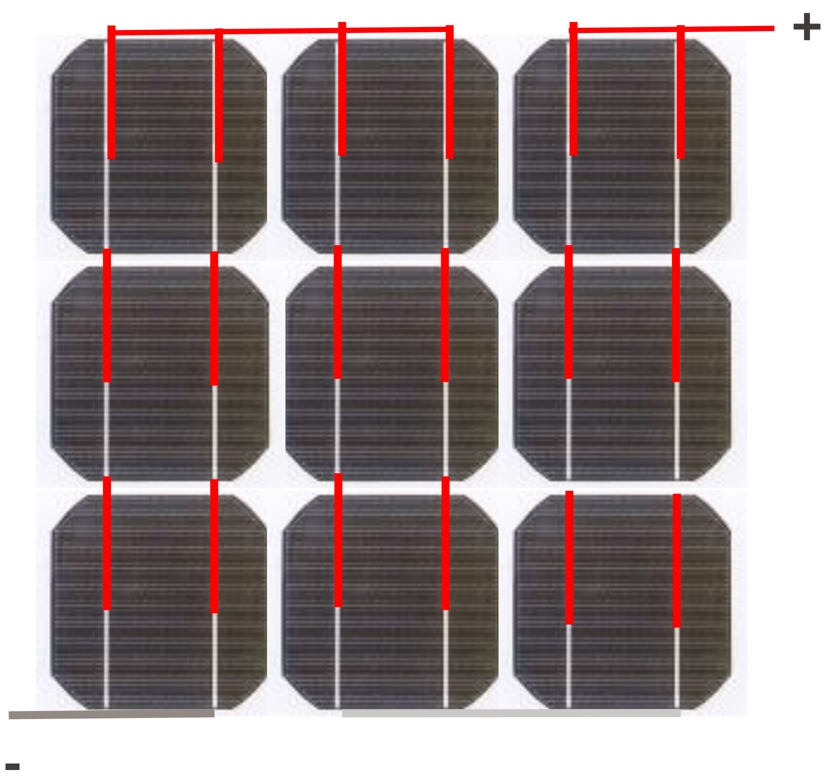
22.6% by Sunpower
Guaranteed for 40 years (previously 25 years) at 88% nominal power

5. PV Technologies: First overview

Wafers vs Thin Films or a combination of thin film on wafers

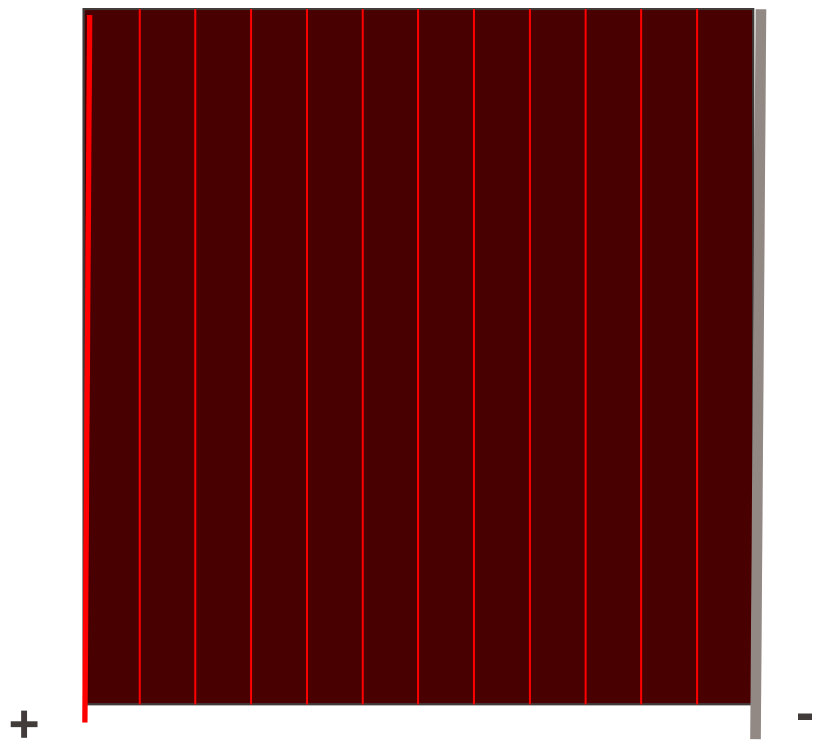
Wafer based (bulk semiconductor)

- Processing of wafers (typ 100-400 microns)
- Series connection of individual solar cells



Thin films

- Depositions of thin cells (micron) on large area substrate
- "monolithic series integration" of the cells (typically by lasering) for high V_{oc} and low I_{sc}



- **Or deposit thin film on plates and/or wafers and interconnect (e.g. space solar cells)**

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5. PV Technologies: an overview

Crystalline silicon
Mono and multicrystalline
Status: main market share (Mostly Mono)

Thin films
CdTe, CIGS, a-Si
Status: 3-5% market share (mostly CdTe)

III-V solar cells (GaAs based)
Space application

Market

Concentrator technologies

Status: failed market entrance
New innovative concepts

Other technologies
Organic-Polymer, Dye sensitized, nano-inorganic
Status: niche application, failed market entrance
Perovskite: R&D with challenges

Novel PV concepts
Quantum dots, intermediate band…
Status: attempt of demonstration

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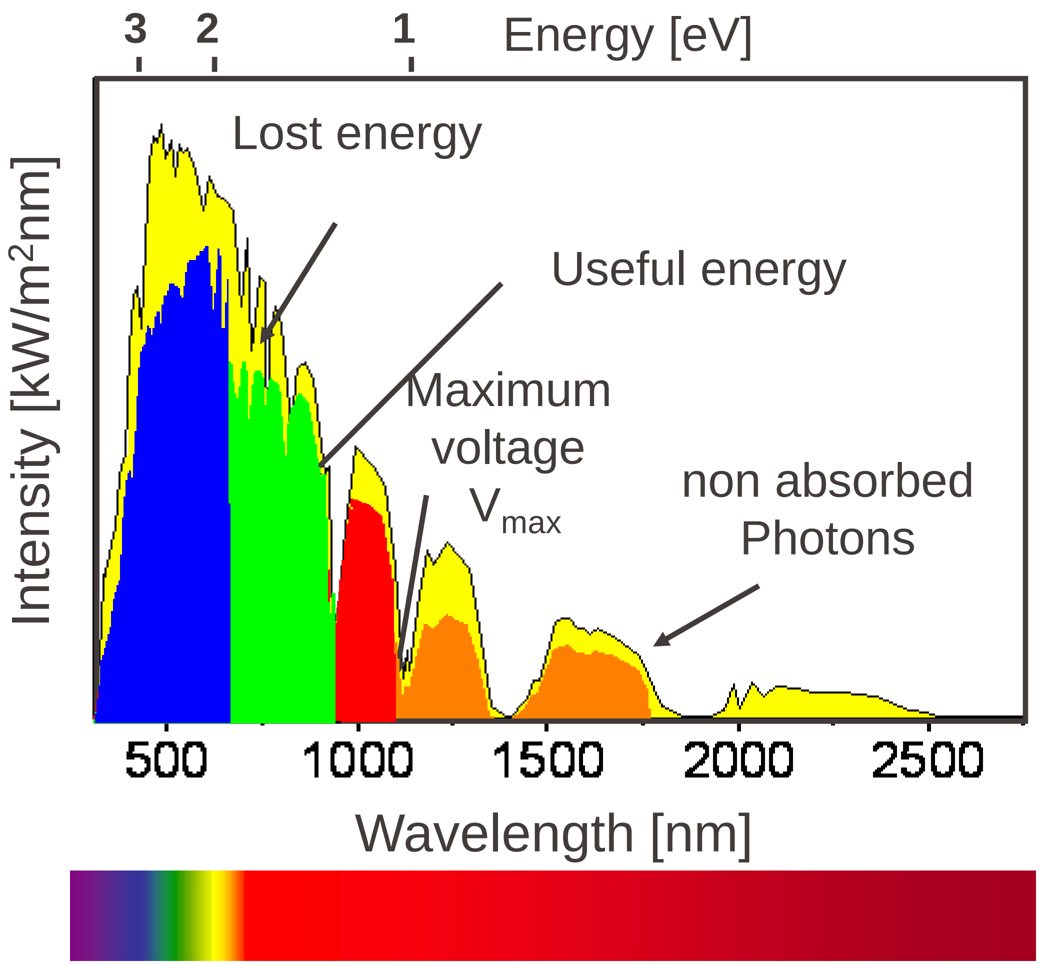
6. PV performance and its limits

Prof. Christophe Ballif

Voltage and current

A ***semiconductor with a bandgap*** E_g absorbs only photon with $E>E_g$
e.g., photons below the wavelength λ corresponding to the bandgap

$$\lambda[nm] = \frac{1240}{E(\lambda)[eV]} \quad (1.7)$$



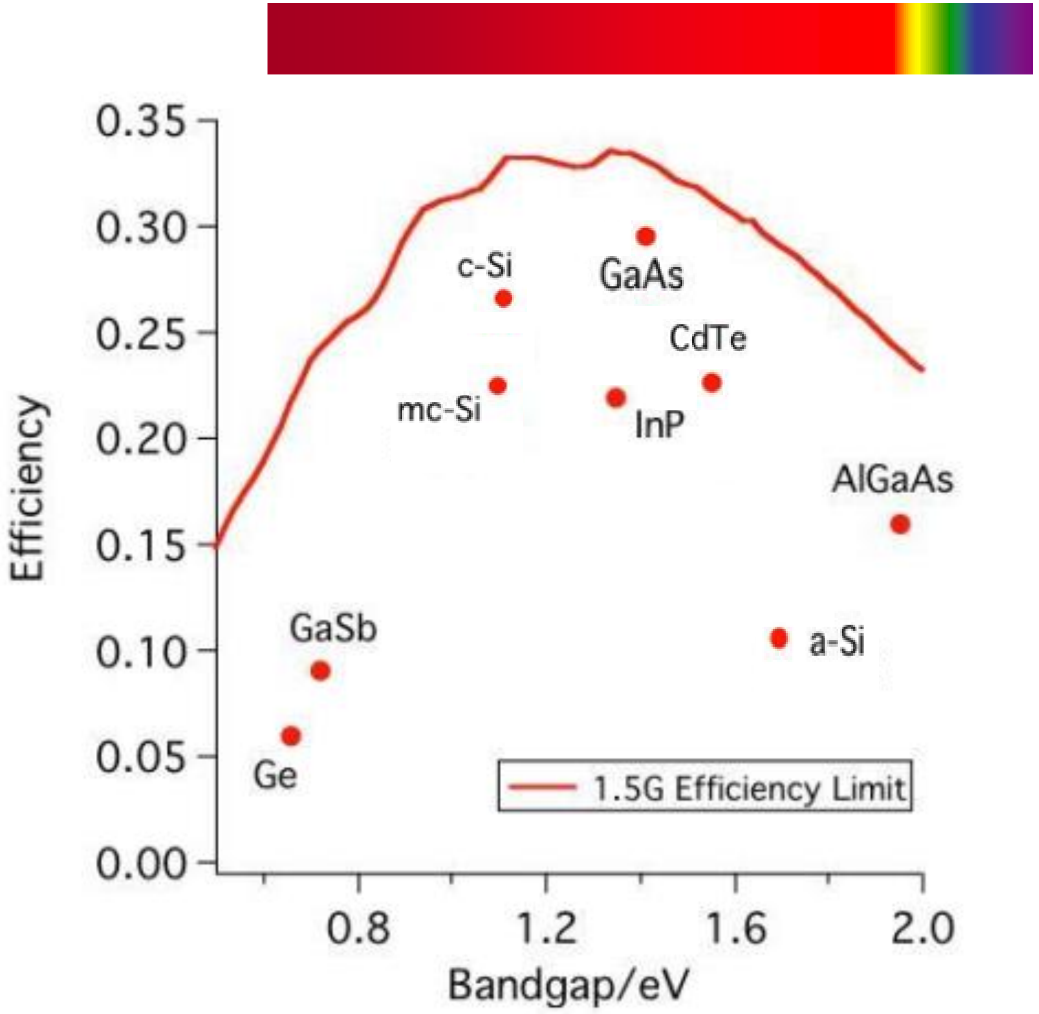
$V_{max} \leq E_g$ **The voltage is lower than the bandgap**

- Ge, E_g = 0.8 eV
- c-Si, μc-Si:H , E_g= 1.12 eV
- GaInAs, E_g = 1.3 eV
- a-Si:H, E_g = 1.7 eV

Compromise between current and voltage → Efficiency limit for single junction ~31-33%

6. PV performance and its limits

Limit of efficiency for single junction solar cell



Adapted from UNSW, Sydney

Single junction ***Shockley-Queisser radiative limit*,***** *:*

*R*adiative equilibrium of cell under AM1.5 or one sun for a single junction. Ideal bandgap around 1.1 to 1.5 eV (IR to close to visible)

→ **limit of 31-33%**

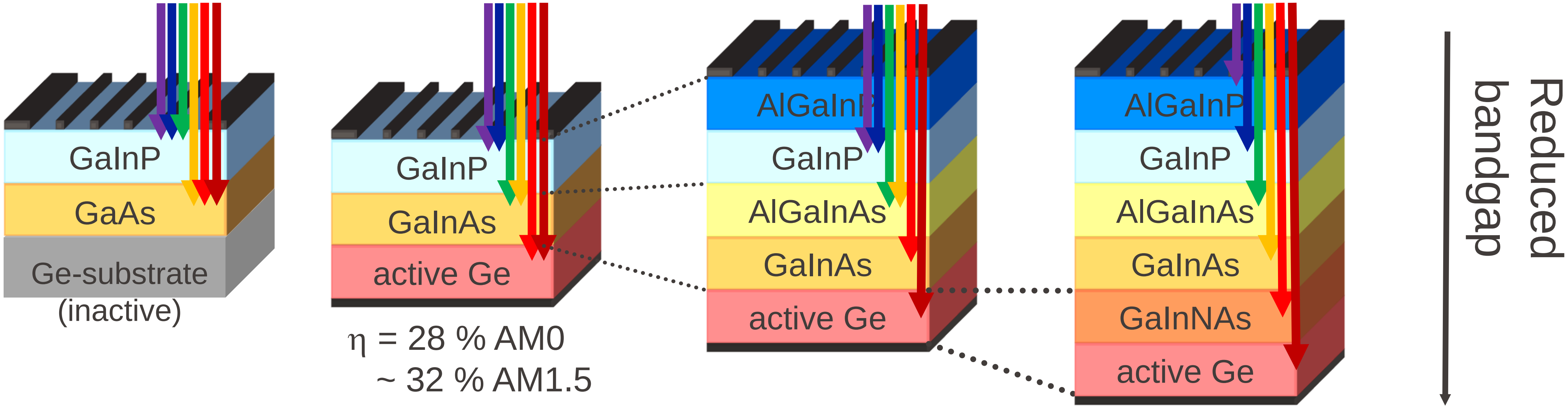
Beware: this limit is for non-concentrated light (equivalent to light from all angles accepted….)

Radiative Recombination Limit:
** Shockley and Queisser, J. Appl. Phys. 32, 510 (1961)*
*** For a modern interpretation: Jean-Francois Guillemoles Nature Photonics 13 (2019)501–5*

6. PV performance and its limits

How to break the *Shockley-Queisser* limit ? **tandem & multi-junction**

tandem → triple-junction → 5-cells → 6-cells



η = 28 % AM0
~ 32 % AM1.5

- **Current divided between the cells**
- **Voltages are added !**

3-6 Junction Photovoltaic Cells For Space And Terrestrial Concentrator Applications
F. Dimroth et al. Proc 31st IEEE, 2005

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Towards highest efficiency

1 Sun : efficiency gain with multi junction

n	η (%)	E_{g1} (eV)	E_{g2} (eV)	E_{g3} (eV)	E_{g4} (eV)
1	30	1·3	—	—	—
2	42	1·9	1·0	—	—
3	49	2·3	1·4	0·8	—
4	53	2·6	1·8	1·2	0·8
∞	68				

With 2 junctions, ***Shockley-Queisser radiative limit***

→ *~ 42%*

3 junctions 49%

Infinity 68%

6. PV performance and its limits

Towards highest efficiency

1 Sun : efficiency gain with multi junction

n	η (%)	E_{g1} (eV)	E_{g2} (eV)	E_{g3} (eV)	E_{g4} (eV)
1	30	1·3	—	—	—
2	42	1·9	1·0	—	—
3	49	2·3	1·4	0·8	—
4	53	2·6	1·8	1·2	0·8
∞	68				

45900 Suns: maximum concentration

n	η (%)	E_{g1} (eV)	E_{g2} (eV)	E_{g3} (eV)	E_{g4} (eV)
1	40	1·1	—	—	—
2	55	1·7	0·8	—	—
3	63	2·1	1·2	0·6	—
4	68	2·5	1·6	1·0	0·5
∞	86.6				

By increasing light intensity → increase in V_{oc} . Better use the photon energy !
Can be understood from the diode equation

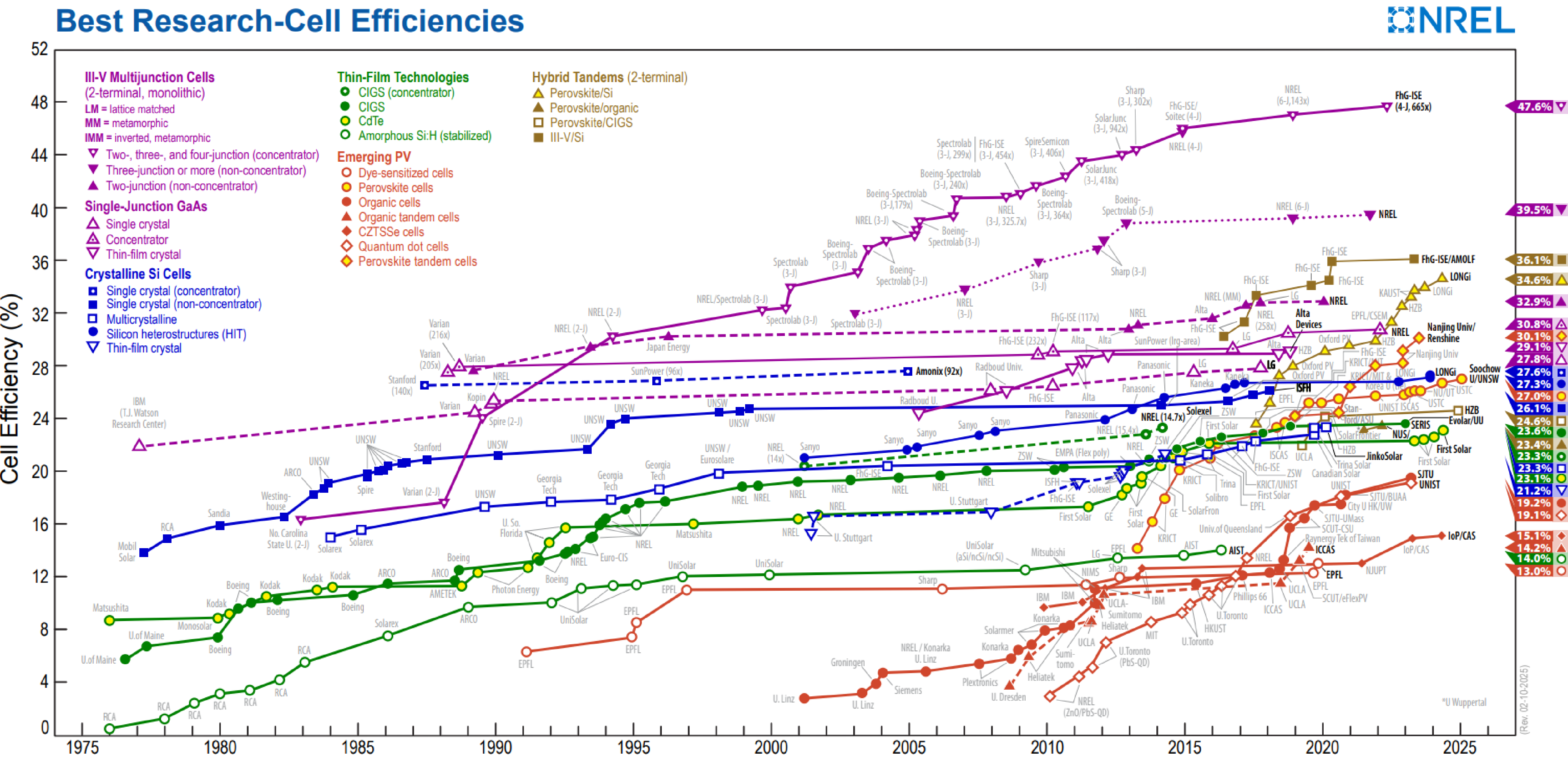
$$I_L = I_0 \left[\exp\left\{ \frac{qV}{kT} \right\} - 1 \right] - I_{ph}$$

$$V_{oc} \approx \frac{kT}{q} \ln \left\{ \frac{I_L}{I_0} \right\} \qquad (1.8)$$

Example: Voc gain of 170 mV for a 1000X concentrated light

Alexis De Vos, Detailed balance limit of the efficiency of tandem solar cells J. Phys. D: Appl. Phys., 13 (1980) 83946.

https://www.nrel.gov/pv/cell-efficiency.html

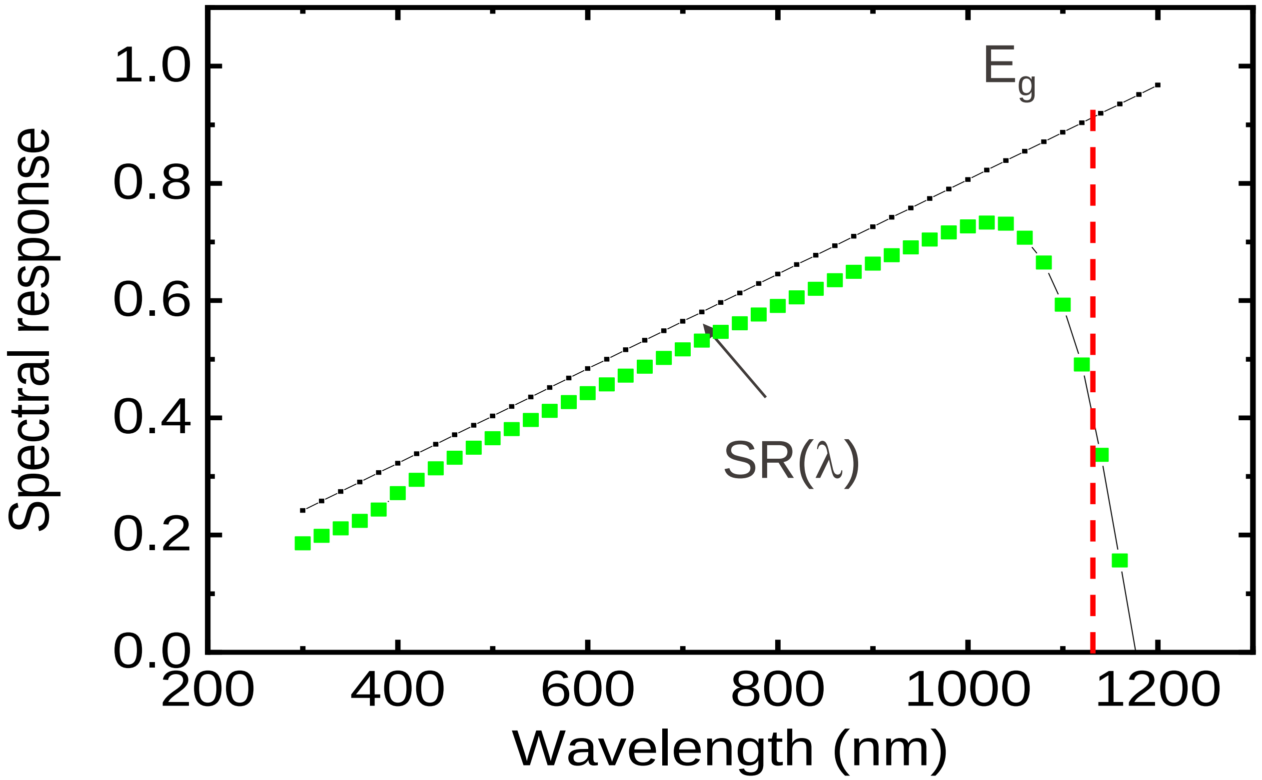


Definition of spectral response (SR)

Spectral response SR(λ):
The current [A] in short-circuit conditions per incident power [W] as function of wavelength.

If the spectral response, illumination intensity spectrum Spec(λ) [W/m²/nm] and the cell area A are known, it is possible to calculate the solar cell current delivered by the solar cell*

$$I_{CELL,Spec} = A \int_{300}^{1200} Spec(\lambda) SR(\lambda) d\lambda \quad (1.9)$$



Typical SR of a c-Si cell

* This holds providing all signals are linear with light intensity…Otherwise SR, EQE, IQE are ill-defined

6. PV performance and its limits

Definition of EQE, IQE

External Quantum Efficiency (EQE):
Ratio of collected electrons per incident photons at short circuit

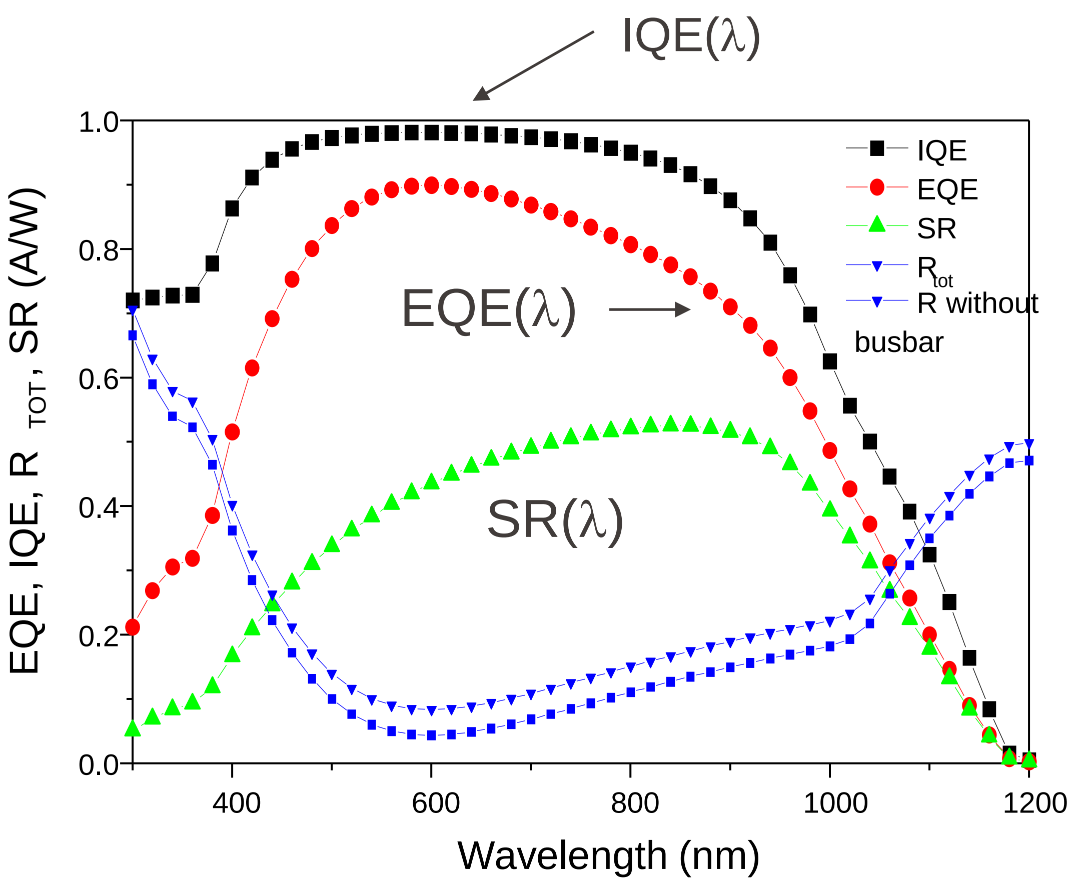
$$EQE(\lambda) = \left.\frac{[electrons]}{[photons]}\right|_{I_{sc}} \quad (1.10)$$

The EQE allows a direct visualization of current losses at different wavelengths (a perfect silicon cell with no reflection would have an EQE of unity at all wavelengths between 300 and 1200 nm)

$$EQE(\lambda) = SR(\lambda) \cdot E(\lambda)/q \quad (1.11)$$

Internal quantum efficiency (IQE):
Ratio of collected electrons per absorbed photon.

$$IQE(\lambda) = \frac{EQE(\lambda)}{1 - R(\lambda)} \quad (1.12)$$

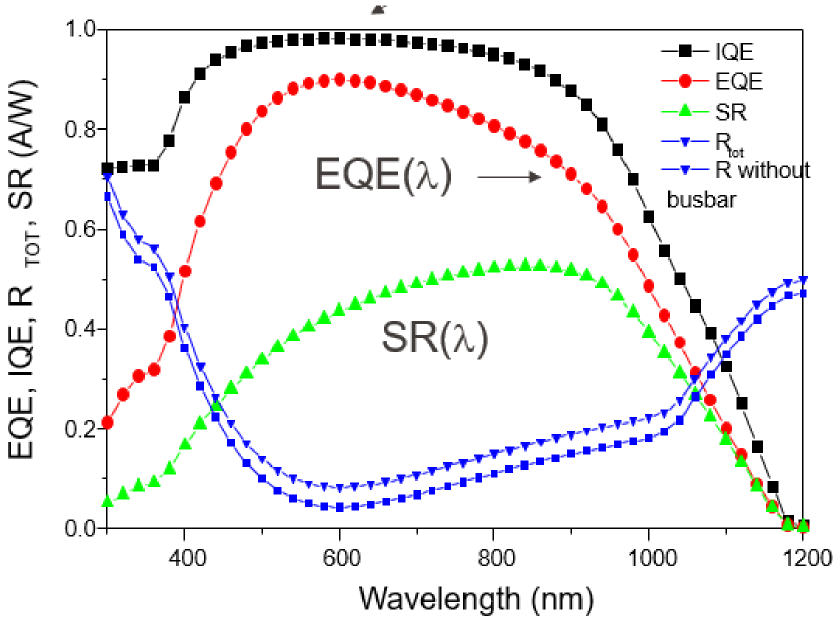


Typical SR, EQE, IQE of c-Si cell

Example of application

If you know the SR or the EQE, and if you know the IV curve for a specific light source.
Then from (1.3)

$$I_L = I_D - I_{ph} = I_0\left[\exp\left\{\frac{qV}{kT}\right\} - 1\right] - I_{ph} \qquad (1.3)$$



you can find out I_o, and then you can recalculate the efficiency for different spectrum or intensity !

Exemple: If the cell above has a Voc of 630 mV , and a current of of 35,4 mA/cm2, in STC, the it would have

- 18% efficiency under AM1.5G
- 16.9% efficiency under AM0
- 12,7 % under 1 W/m2, spectrum AM1.5g (low illumination)
- 6% under blue 400 nm monochromatic light at 1W/m2.
- ~ 7% for indoor neon lighting

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QUIZ

Question 1

What is the nominal power of a 23% efficient 3.1 m^2 module?

a) 731 W_p
b) 7310 W_p
c) It depends on the temperature

Question 2

An energy careful family needs 3000 kWh + 3000 kWh for its electrical heat pump, and drives 15’000 km by electric car (20 kWh/100 km)

How many square of 20% solar panel does it need to provide the same amount of electricity ?

a) 45 m2
b) 90 m2
c) 900 m2

QUIZ

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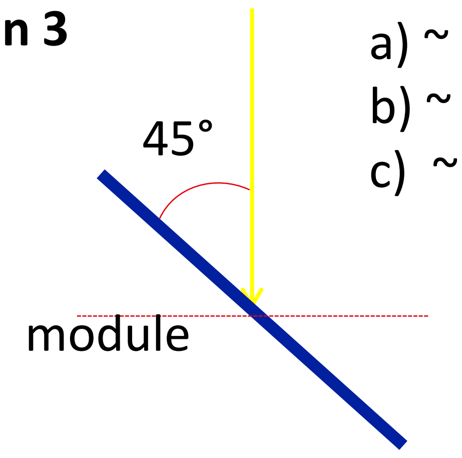
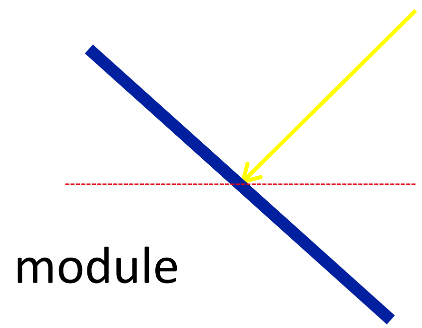
What is the intensity of light in [W/m^2] onto the various modules for a house located at sea level in a sunny day?

Question 3



a) ~ 1000 W/m^2
b) ~ 1360 W/m^2
c) ~ 700 W/m^2

Question 4



a) ~ 1000 W/m^2
b) ~ 1360 W/m^2
c) ~ 700 W/m^2

Question 5

If the module is perpendicular to the light rays and the sun is positioned as it is in question 3 and 4:

a) There is slightly more intensity and the spectrum is more reddish (for situation 4)

b) There is slightly more intensity and the spectrum is more reddish (for situation 3)

c) There is slightly more intensity and the spectrum is more bluish (for situation 3)

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QUIZ

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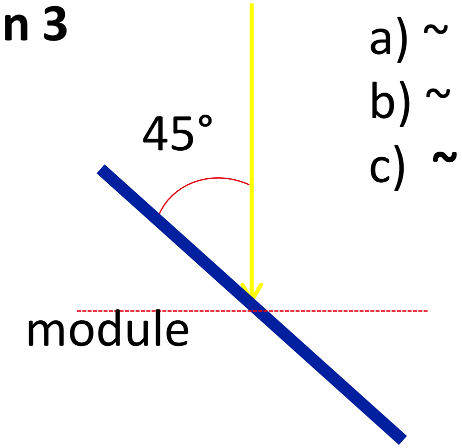
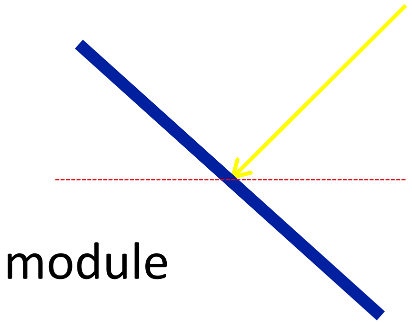
What is the intensity of light in [W/m²] onto the various modules for a house located at sea level in a sunny day?

Question 3



a) ~ 1000 W/m²
b) ~ 1360 W/m²
c) **~ 700 W/m²**

Question 4



a) **~ 1000 W/m²**
b) ~ 1360 W/m²
c) ~ 700 W/m²

Question 5

If the module is perpendicular to the light rays and the sun is positioned as it is in question 3 and 4:

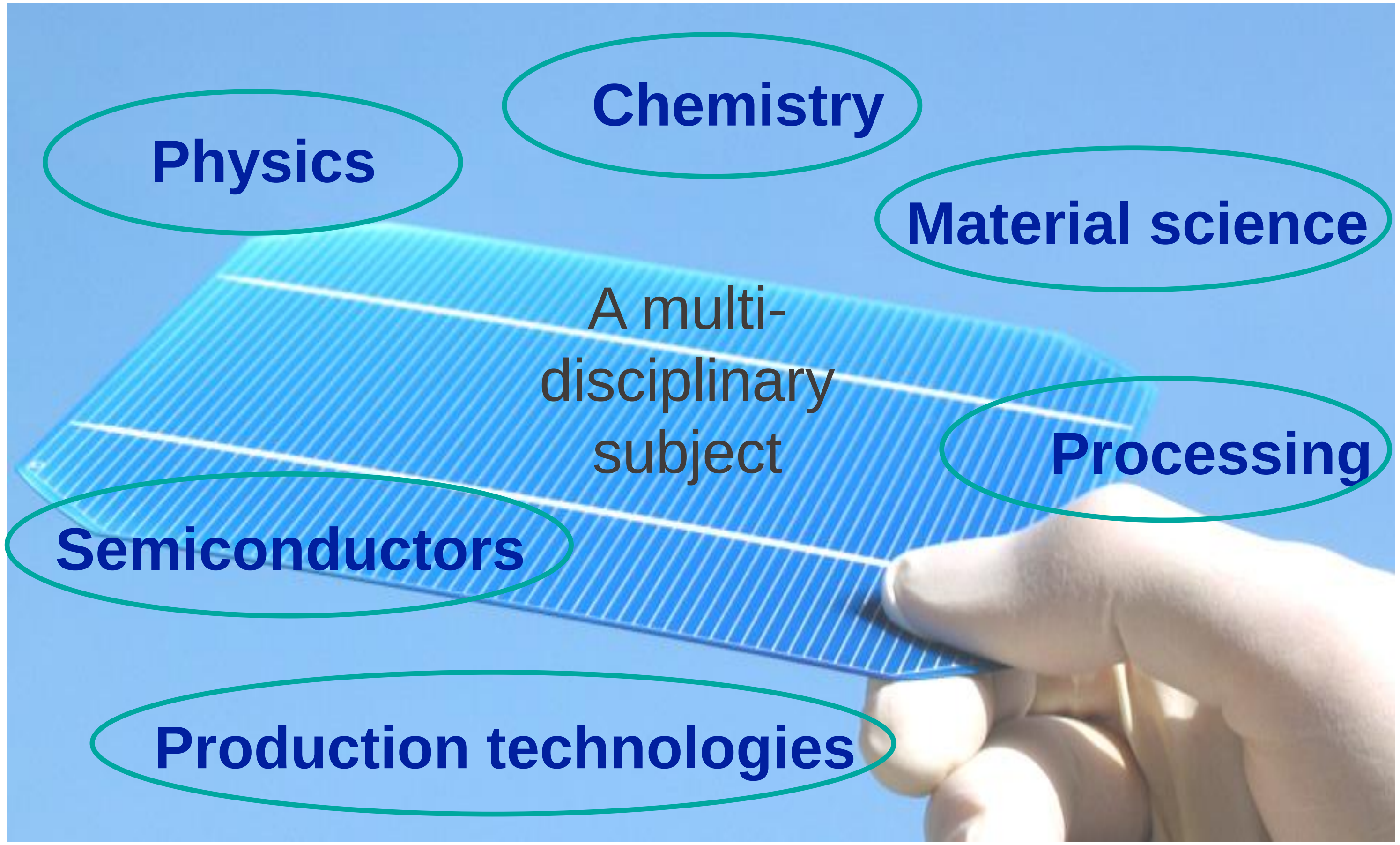
a) There is slightly more intensity and the spectrum is more reddish (for situation 4)

b) There is slightly more intensity and the spectrum is more reddish (for situation 3)

c) There is slightly more intensity and the spectrum is more bluish (for situation 3)

7. Potential and challenges of large-scale PV

Photovoltaics = direct conversion of light to electricity



7. Potential and challenges of large-scale PV

Space requirements for PV

In most countries huge potential from roofs. Not always used or priviledged (some prefers large plants with control of it)

Additional potential, on unconventional spaces such as parking, infrastructure, or directly on the ground.

Typically 30X to 100X more efficient than biomass per m^2 (final electricity consumption)

Ballif

7. Potential and challenges of large-scale PV

Potential of PV Energy: some rough estimation

With 20% efficiency module

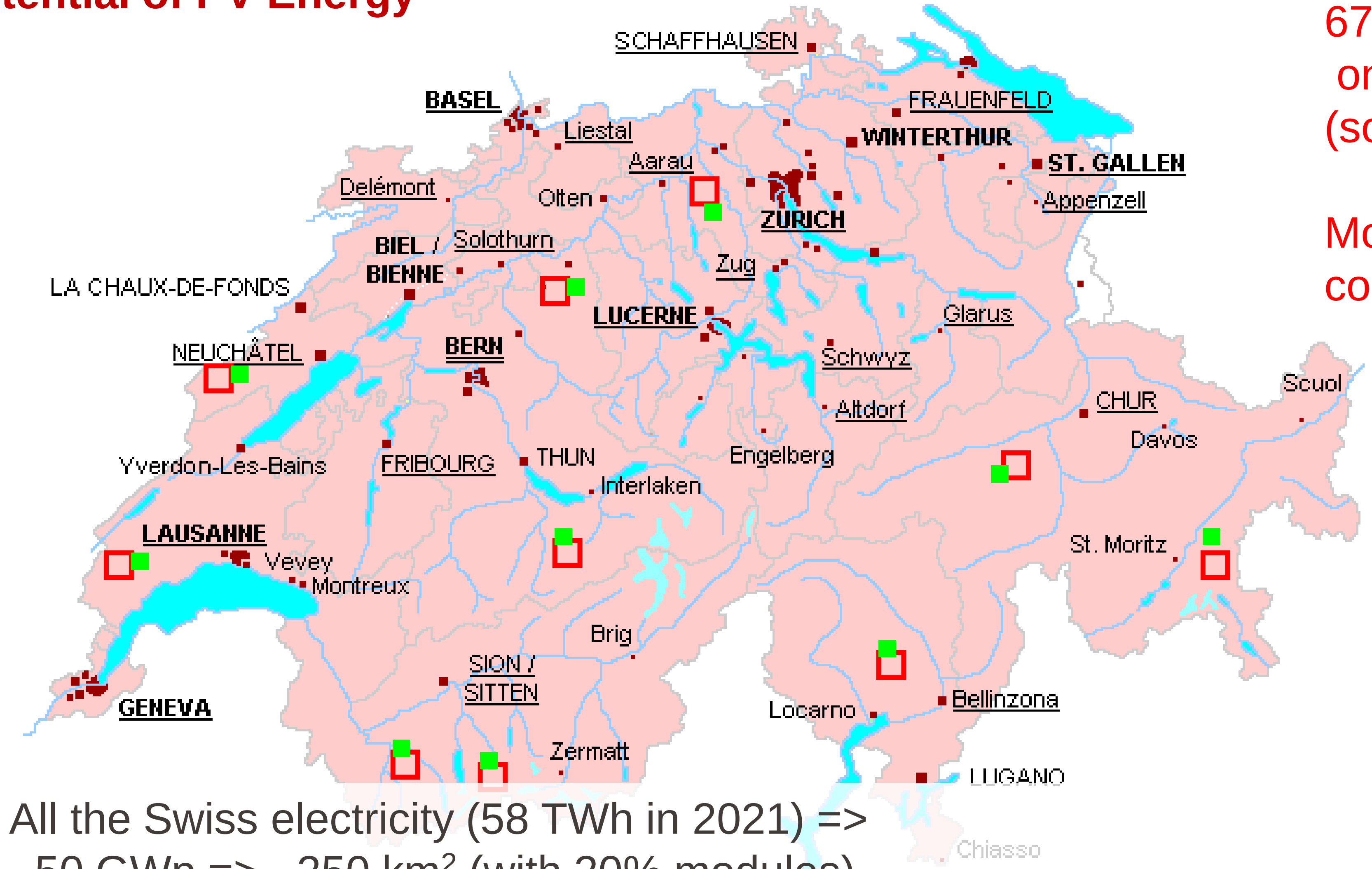
All the electricity of USA (3900 TWh in 2021)

All the energy of USA

= Area of Switzerland, to scale

7. Potential and challenges of large-scale PV

Potential of PV Energy



67 TWh potential on buildings ! (source: SFOE)*

More than current consumption

- All the Swiss electricity (58 TWh in 2021) => ~50 GWp => ~250 km^2 (with 20% modules)
- All the Swiss energy (with 10% modules)

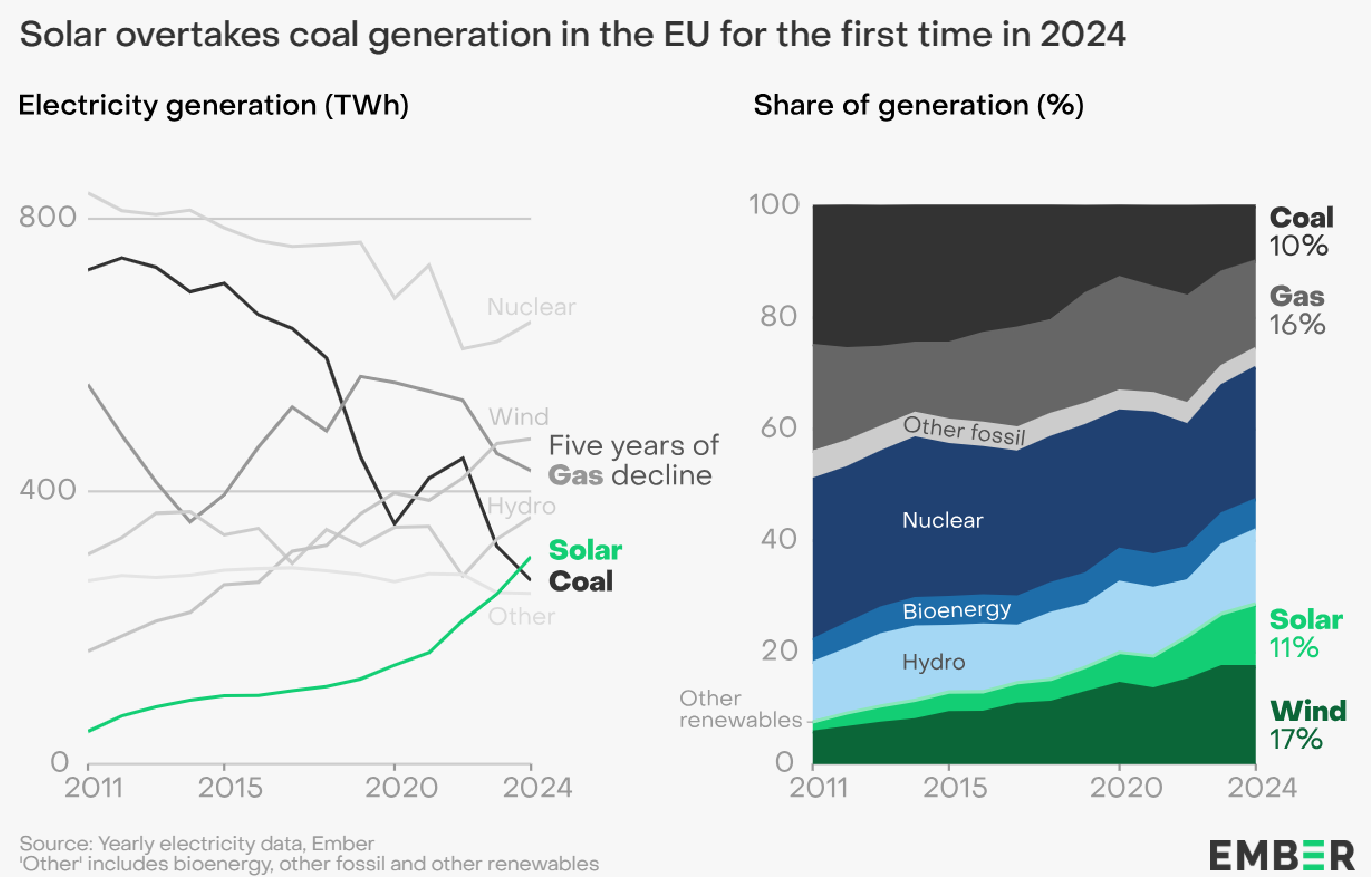
https://www.admin.ch/gov/fr/accueil/documentation/communiques.msg-id-74641.html

7. Potential and challenges of large scale PV

- **Space is not a direct issue!**
- The «real» challenge is to **displace fossil fuels** (not to substitute nuclear which will be able to contribute even though to a lower extent to the energy transition)
- Question: how to scale up PV technology to produce and install more than > 1 TW or 1000 GW per year
- How to guarantee a reasonable grid integration with other electricity and other energy vectors, While also keeping the costs of integration in the energy system acceptable
- Which future PV technologies will dominate, and what are also the negative impacts

(grey energy, mining).

A positive note on renewable share in Europe Electricity mix



Prof. Christophe Ballif

Wrap-up: key elements

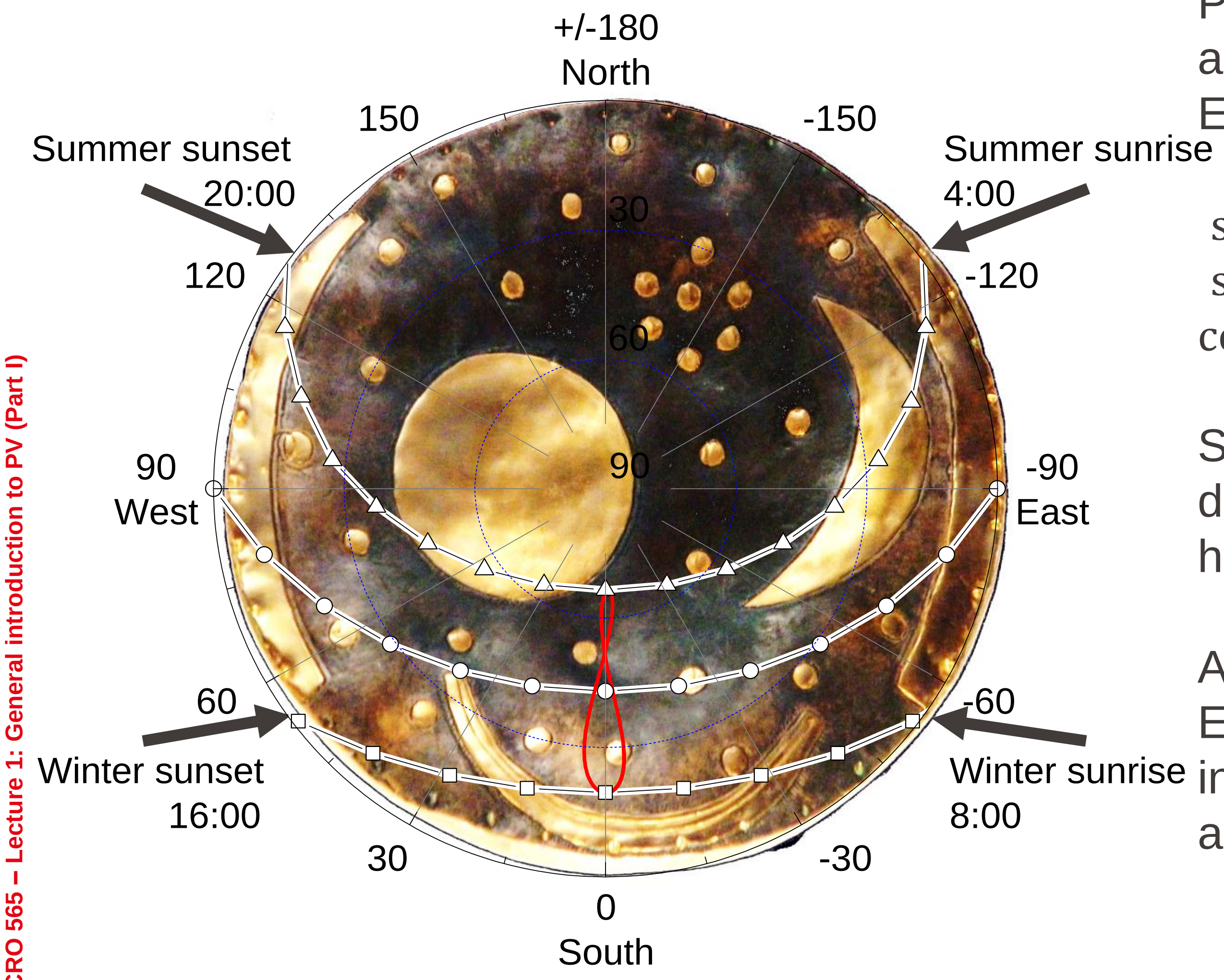
- Diode + current source in series
- Module = sum of cells, with by-pass diode
- Typical values for irradiance, typical production with one watt of module
- STC definition, AM1.5g, AM0
- SR, EQE, IQE
- From single to multi-junction, max efficiency of single junctions
- Scale to decarbonise the world
- At least electricity sector decarbonised in Europe thanks to wind and solar

Lecture I. Appendix

1. The basics of the sun and energy

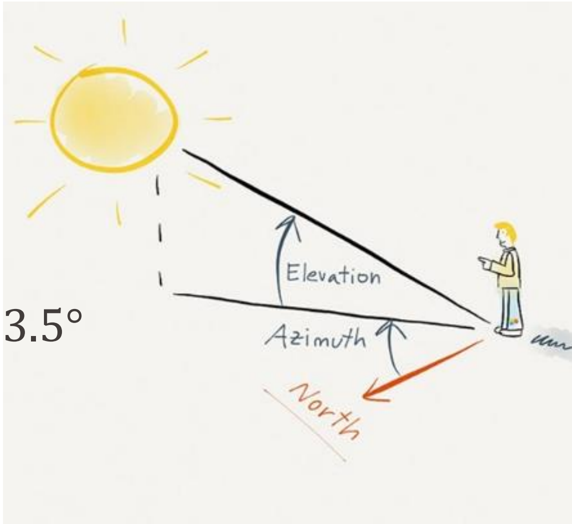
Information only

Solar Chart



Plot of azimuth Φ and elevation angle α for given location on Earth

$\sin\Phi = \cos D \sin t \,/\, \cos\alpha$
$\sin\alpha = \sin L \sin D +$
$\cos L \cos D \cos t$



Switzerland: latitude $L = 47°$
declination $D = -23.5°$ ... $+ 23.5°$
hour angle t

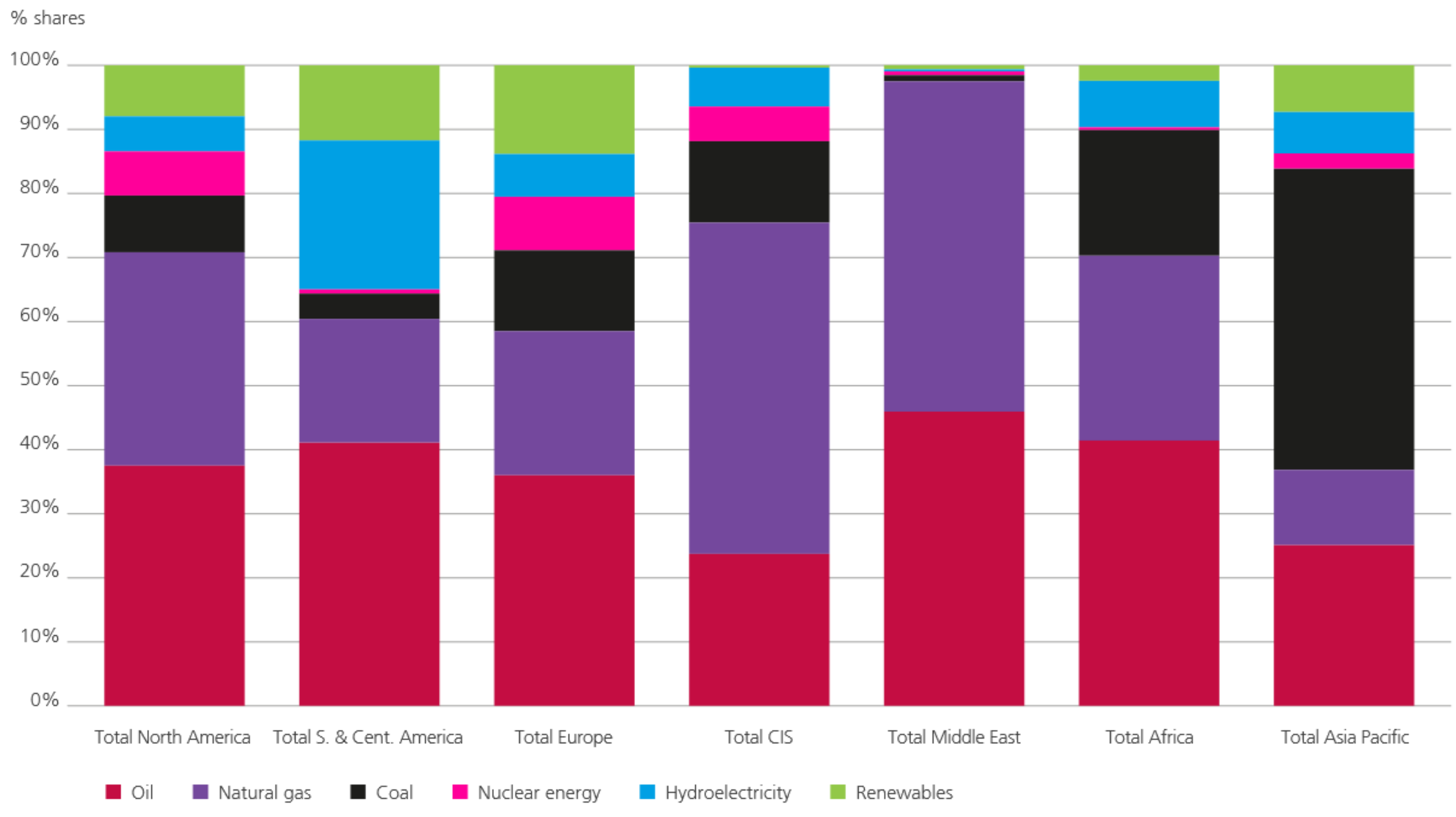
Additional correction for t:
Equation of Time (elliptic orbit, inclination of earth axis) => analemma (8-shaped path)

Image: Sky Disc of Nebra (DE), showing sunset/sunrise at solstice for $L = 51°$, ca. 2000 BC

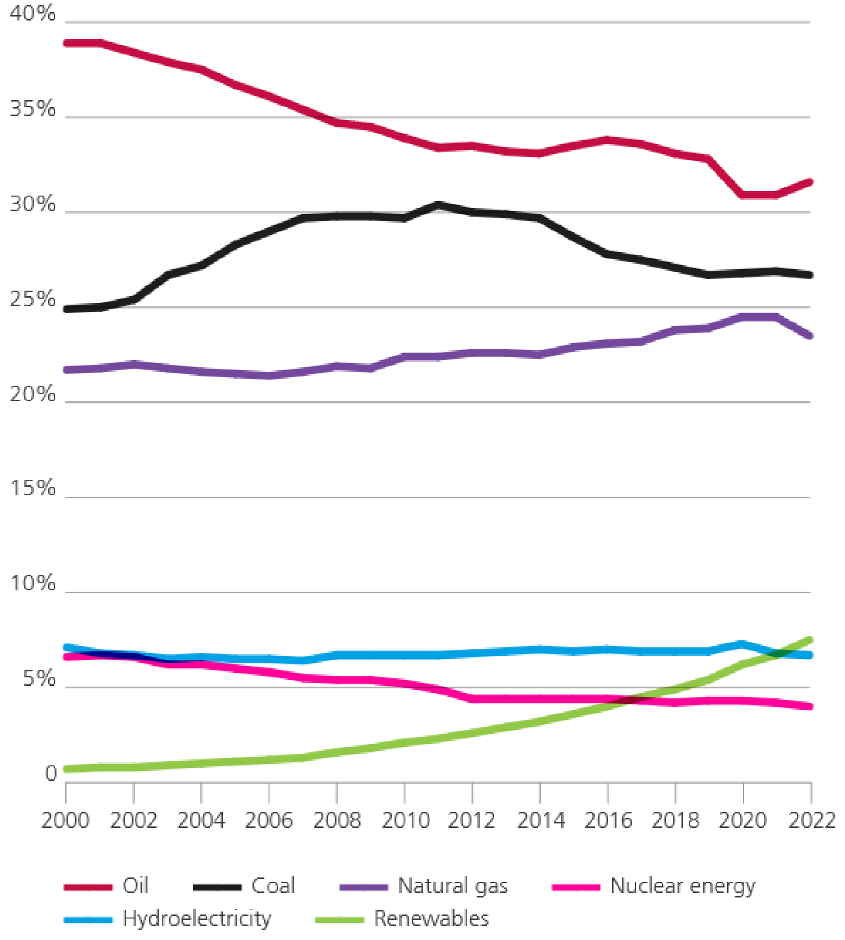
Primary energy consumption: the world challenge (cont.)

Information only

Regional consumption pattern 2022



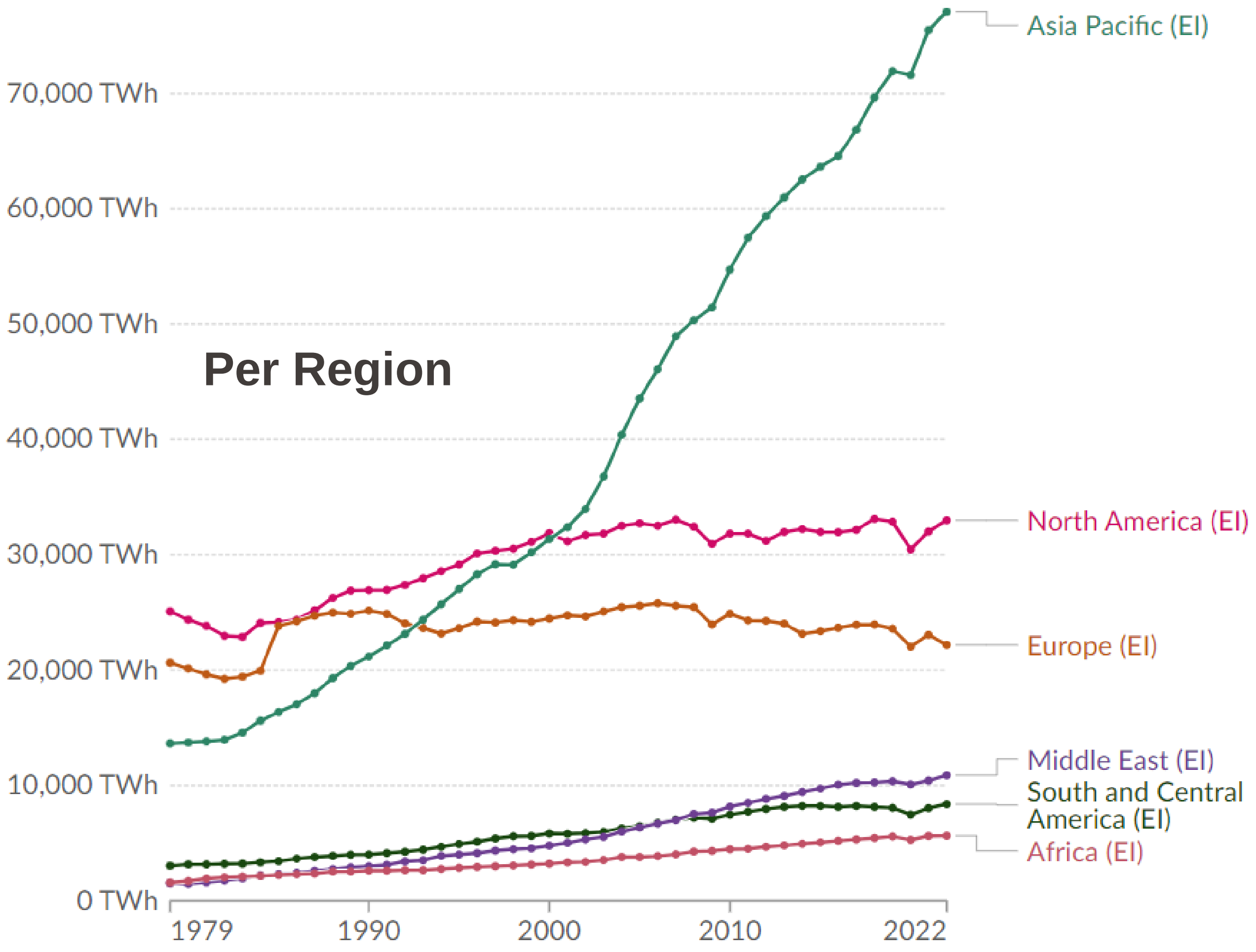
Share of global primary energy

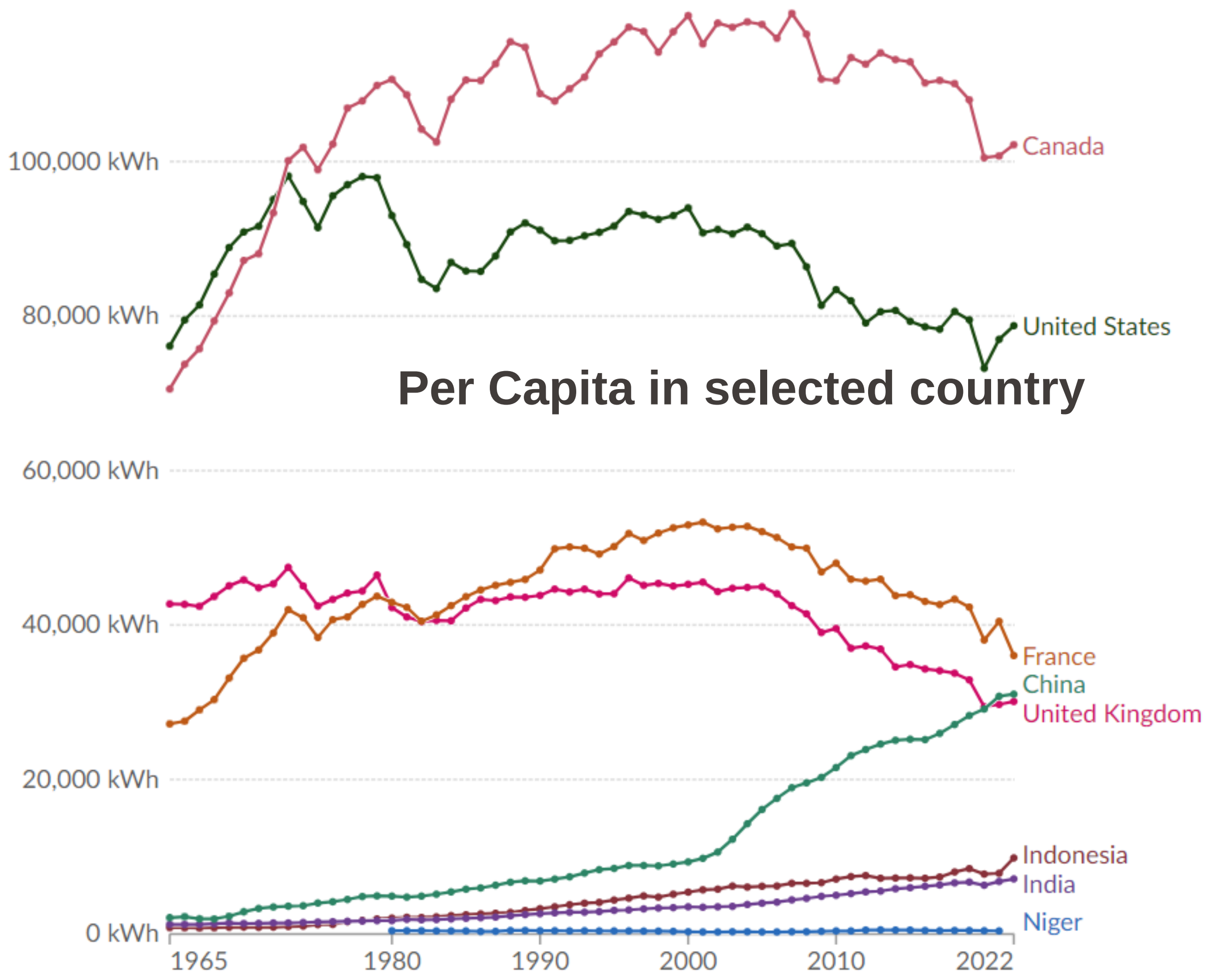


https://www.energyinst.org/__data/assets/pdf_file/IEA *World Energy Outlook 2023*

Primary energy in the substution method

Information only





- [Primary energy consumption by world region (ourworldindata.org)]