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Winter College on Optics and Energy

8 - 19 February 2010

Physics of Solar Cells (I)

J. Nelson

Imperial College
London
U.K.

ICTP Winter College on Optics and Energy
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Physics of Solar Cells (I)

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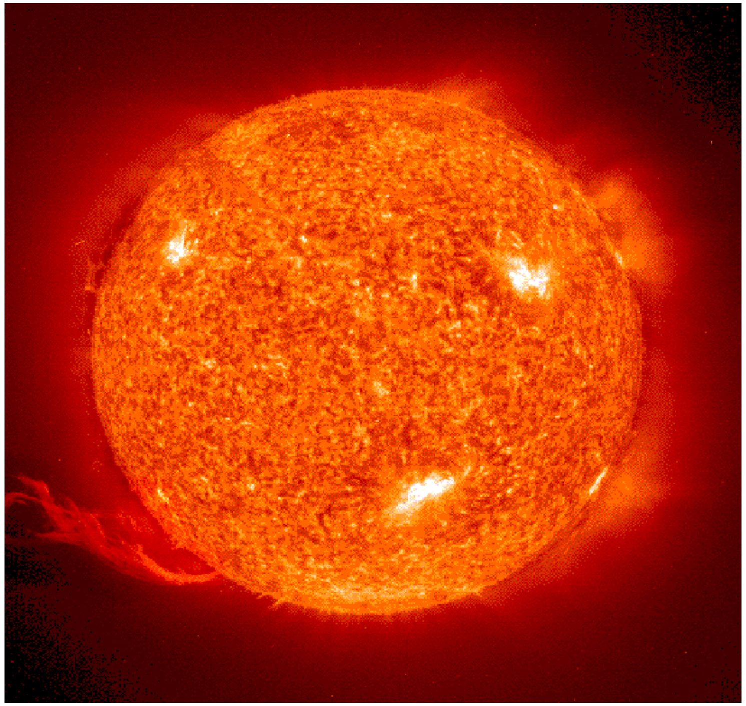
Outline

1. Photovoltaic applications
2. The solar resource
3. Photovoltaic energy conversion
4. The p-n junction solar cell
5. Solar cell performance characteristics

The solar energy resource

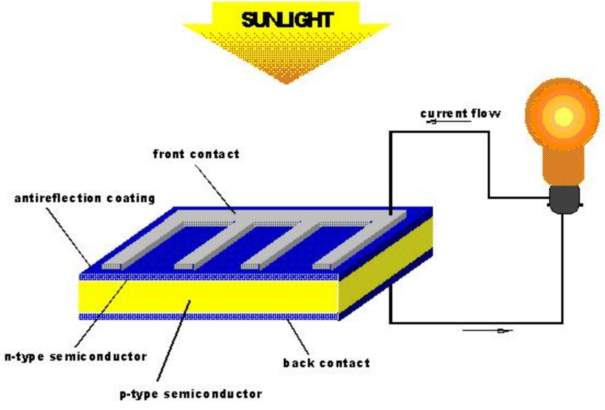
- Radiant power at Earth's surface ~ 100000 TW



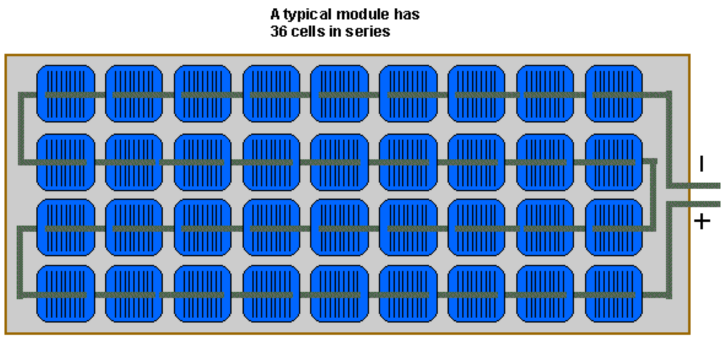
- Electricity consumption ~ 2 TW
- 80% from fossil fuels & nuclear, 0.1% from PV

Some concepts in PV

Solar cell

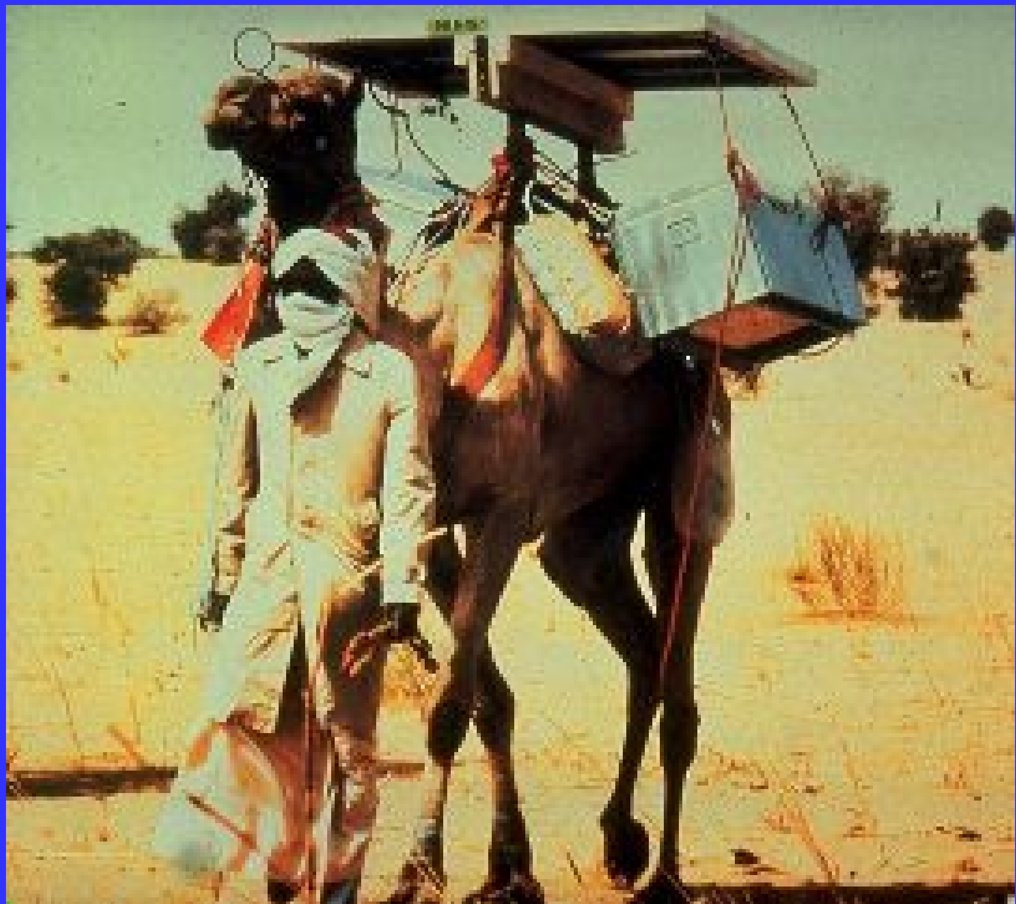


Module



System

1.1. PHOTOVOLTAIC APPLICATIONS



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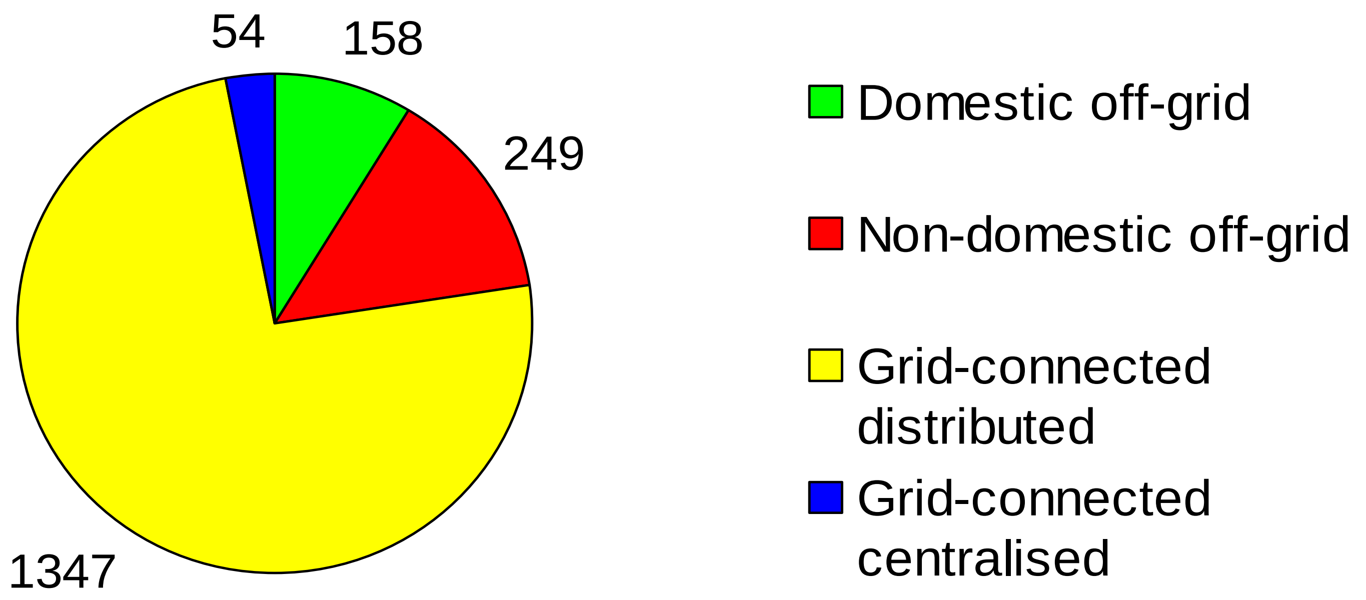
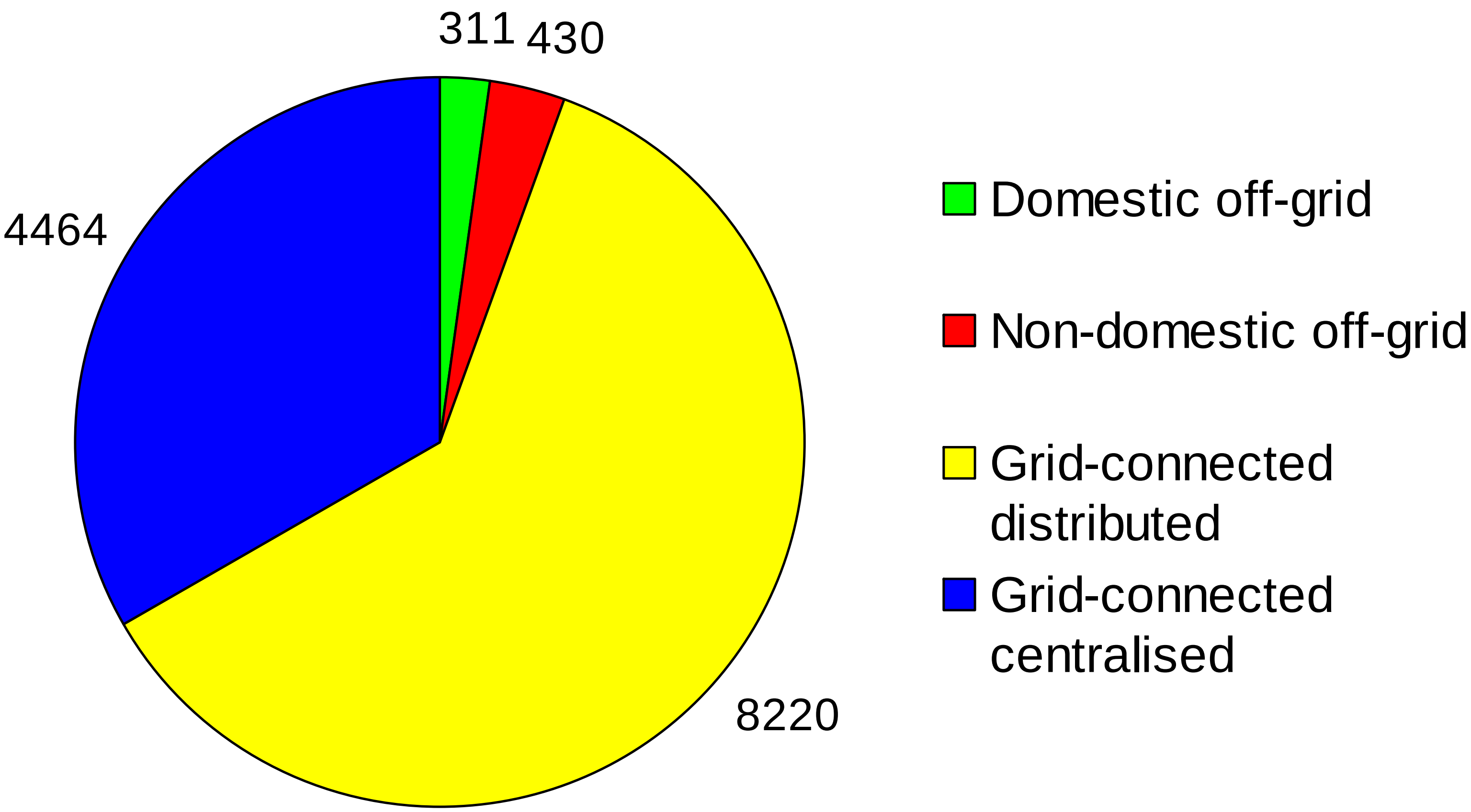
Photovoltaic applications



Cumulative PV capacity 2003 (MW): 1.8 GW_p

Photovoltaic applications



Cumulative PV capacity 2008 (MW): 13.4 GW_p

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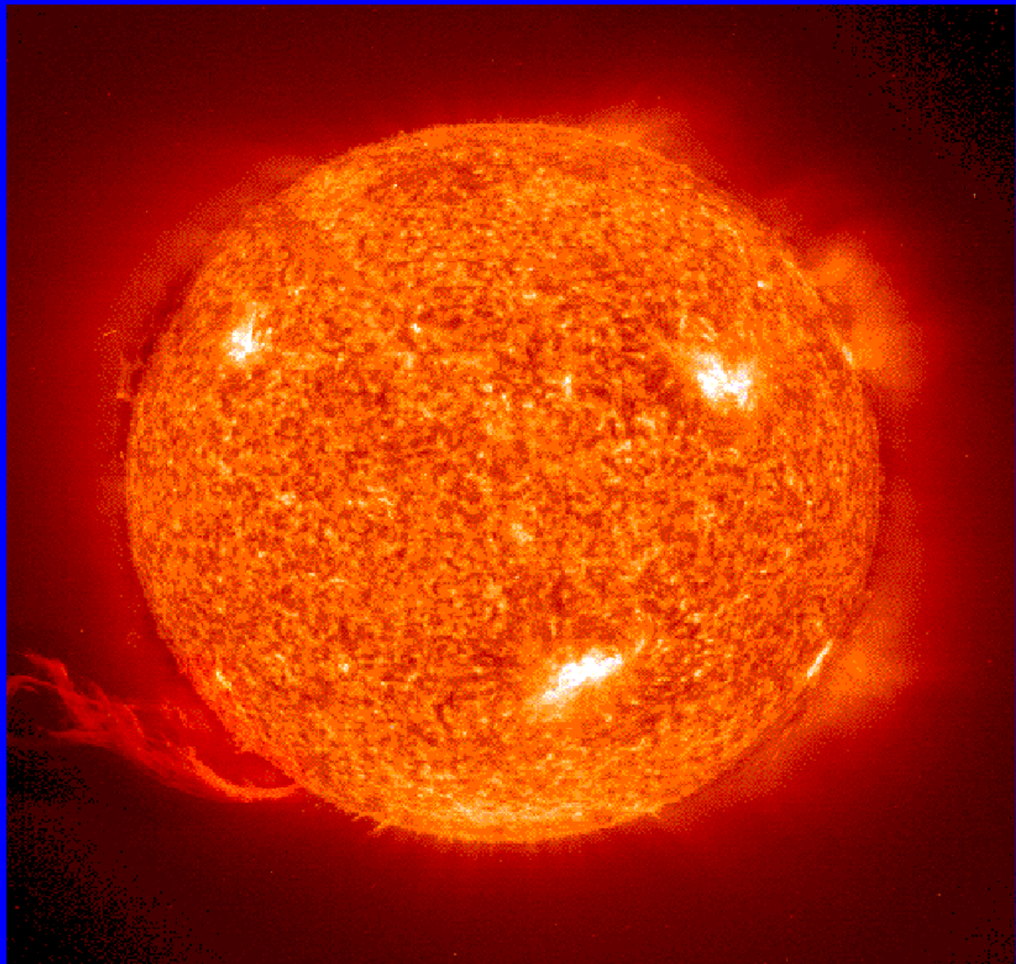
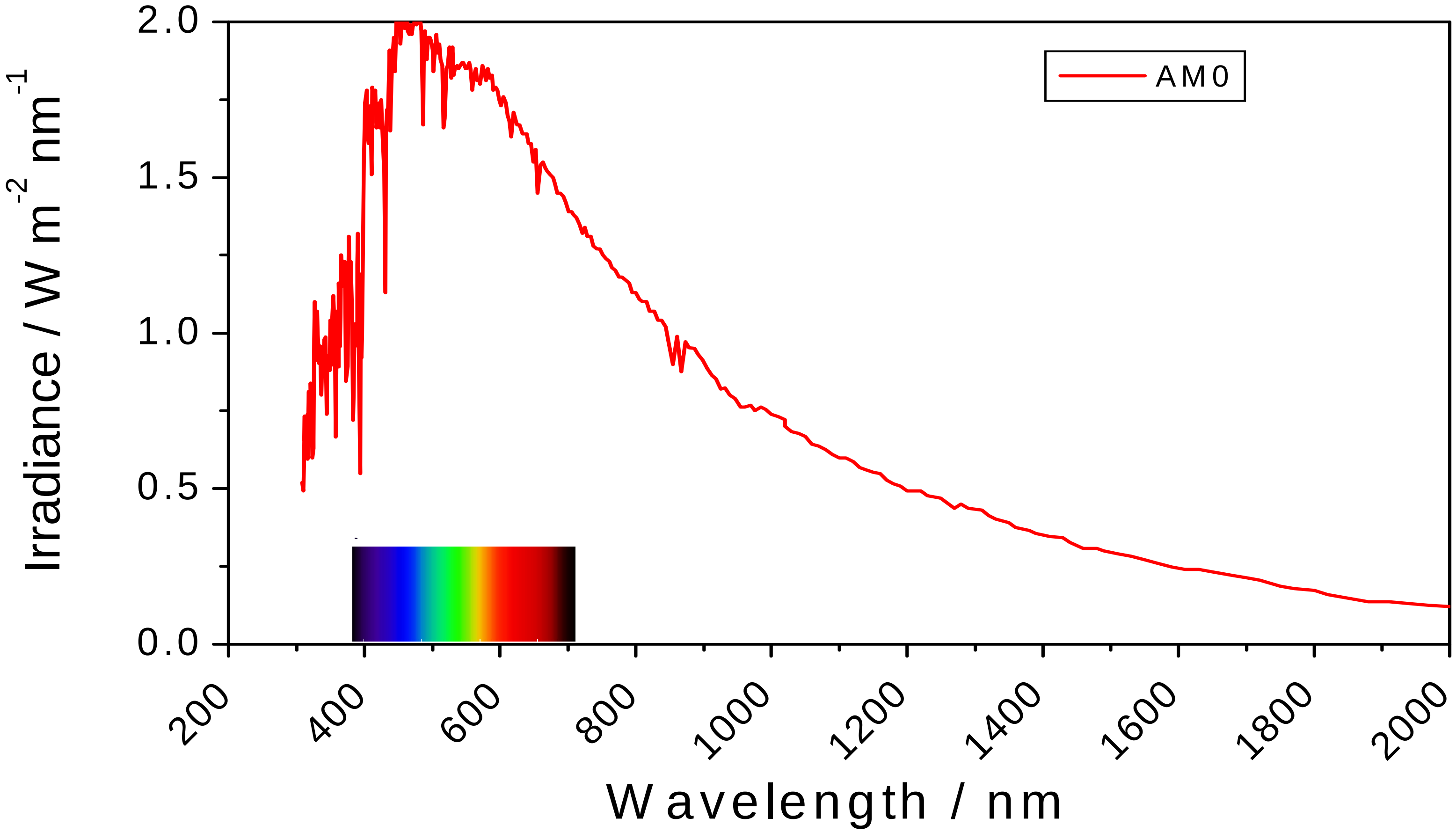
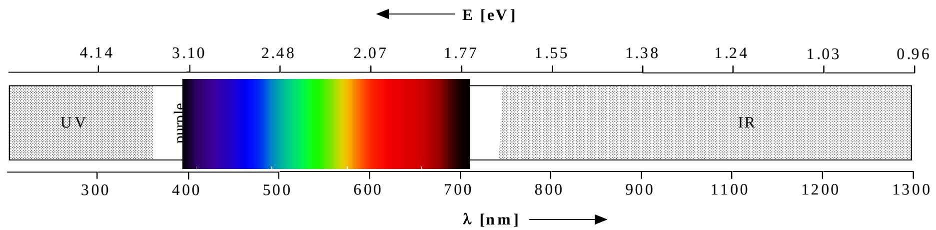
SCHEIDEGGER

1.2. THE SOLAR RESOURCE



Solar power spectrum





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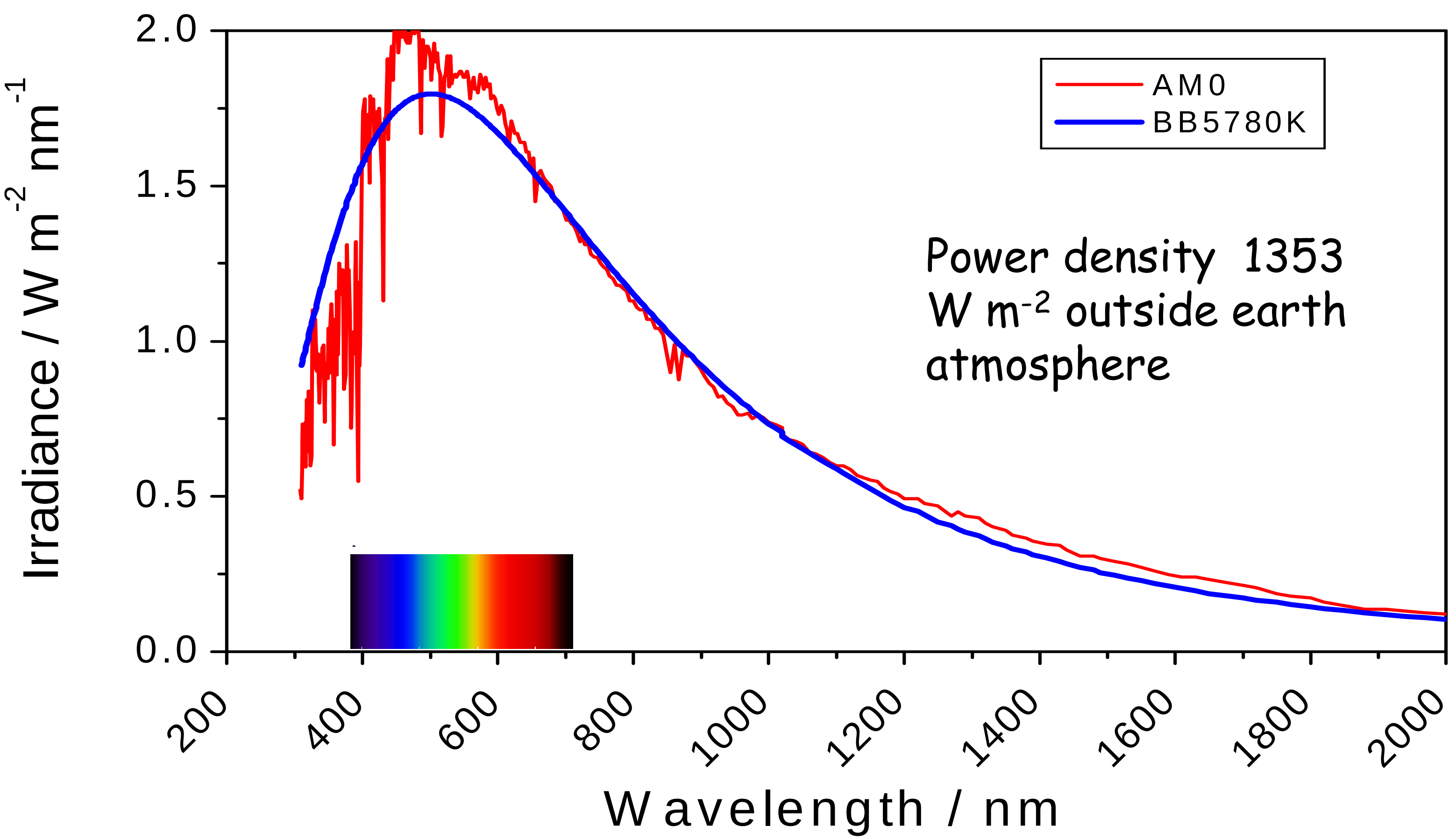
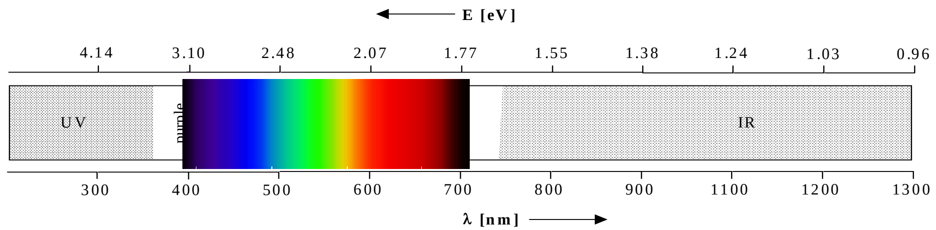
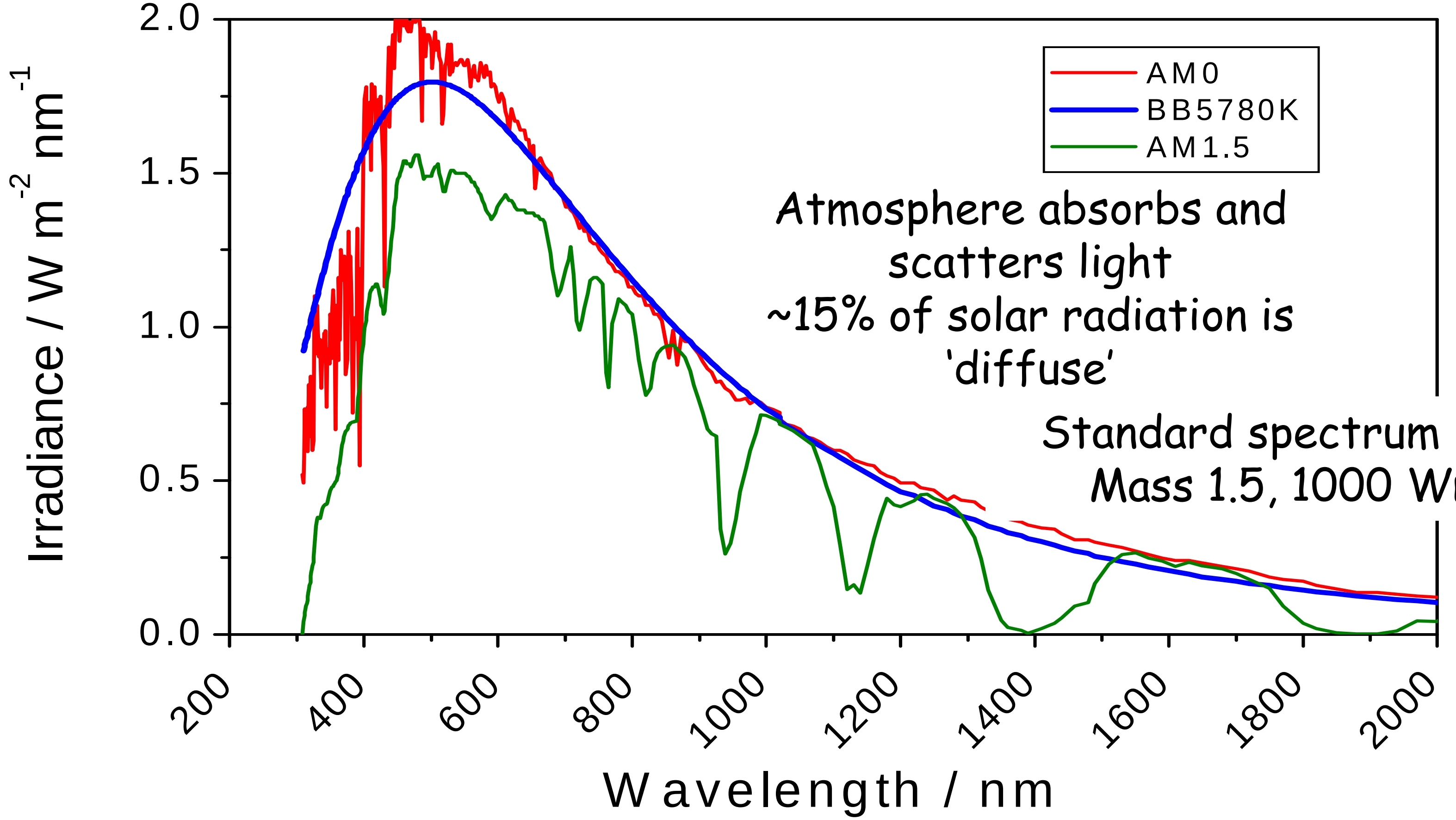
Solar power spectrum





Solar power spectrum

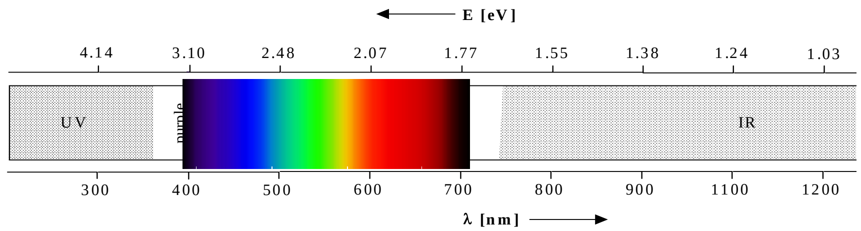


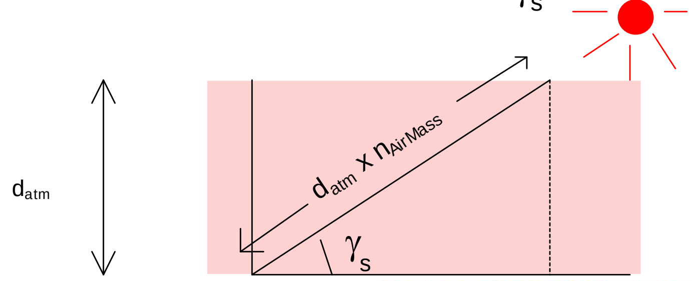
Atmosphere absorbs and scatters light

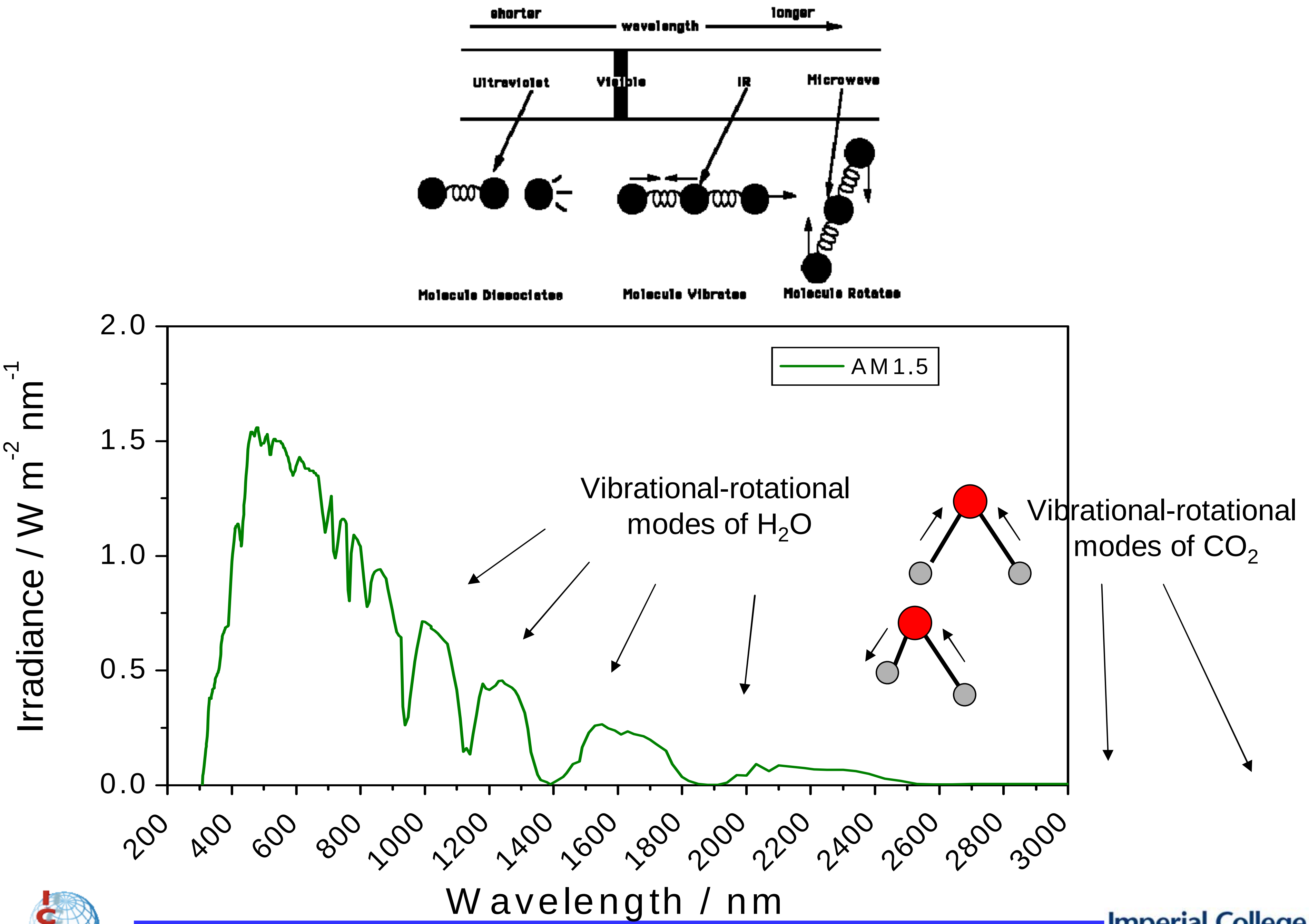
~15% of solar radiation is 'diffuse'

Standard spectrum is Air Mass 1.5, 1000 Wm^{-2}

Air Mass = Cosec γ_s

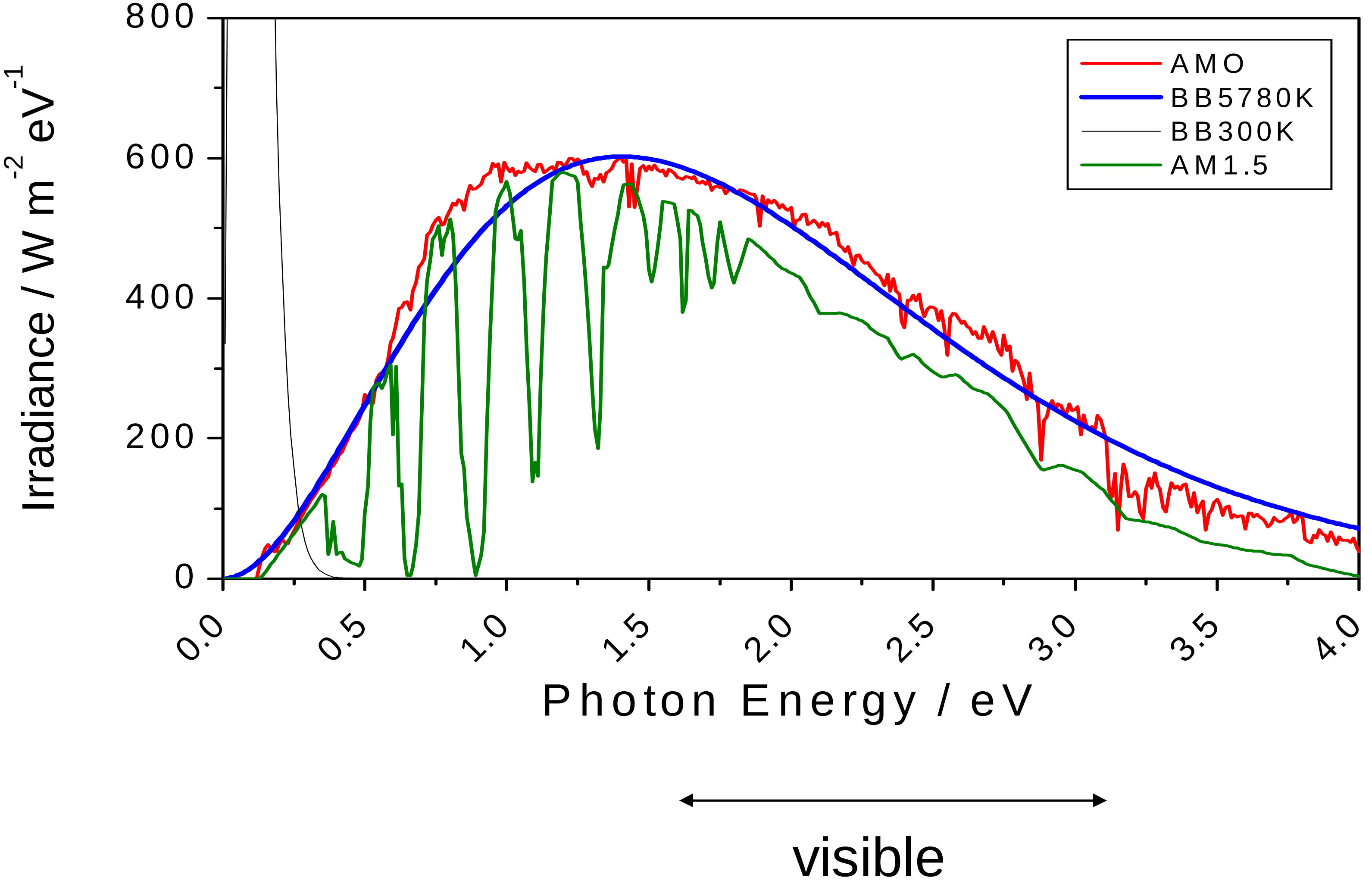





shorter
wavelength
longer
Ultraviolet
Visible
IR
Microwave
Molecule Dissociates
Molecule Vibrates
Molecule Rotates
AM1.5
Vibrational-rotational modes of H_2O
Vibrational-rotational modes of CO_2
Irradiance / W m^{-2} nm^{-1}
Wavelength / nm
2.0
1.5
1.0
0.5
0.0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000

Solar power spectrum

$$E/\mathrm{eV} = 1240/(\lambda/\mathrm{nm})$$



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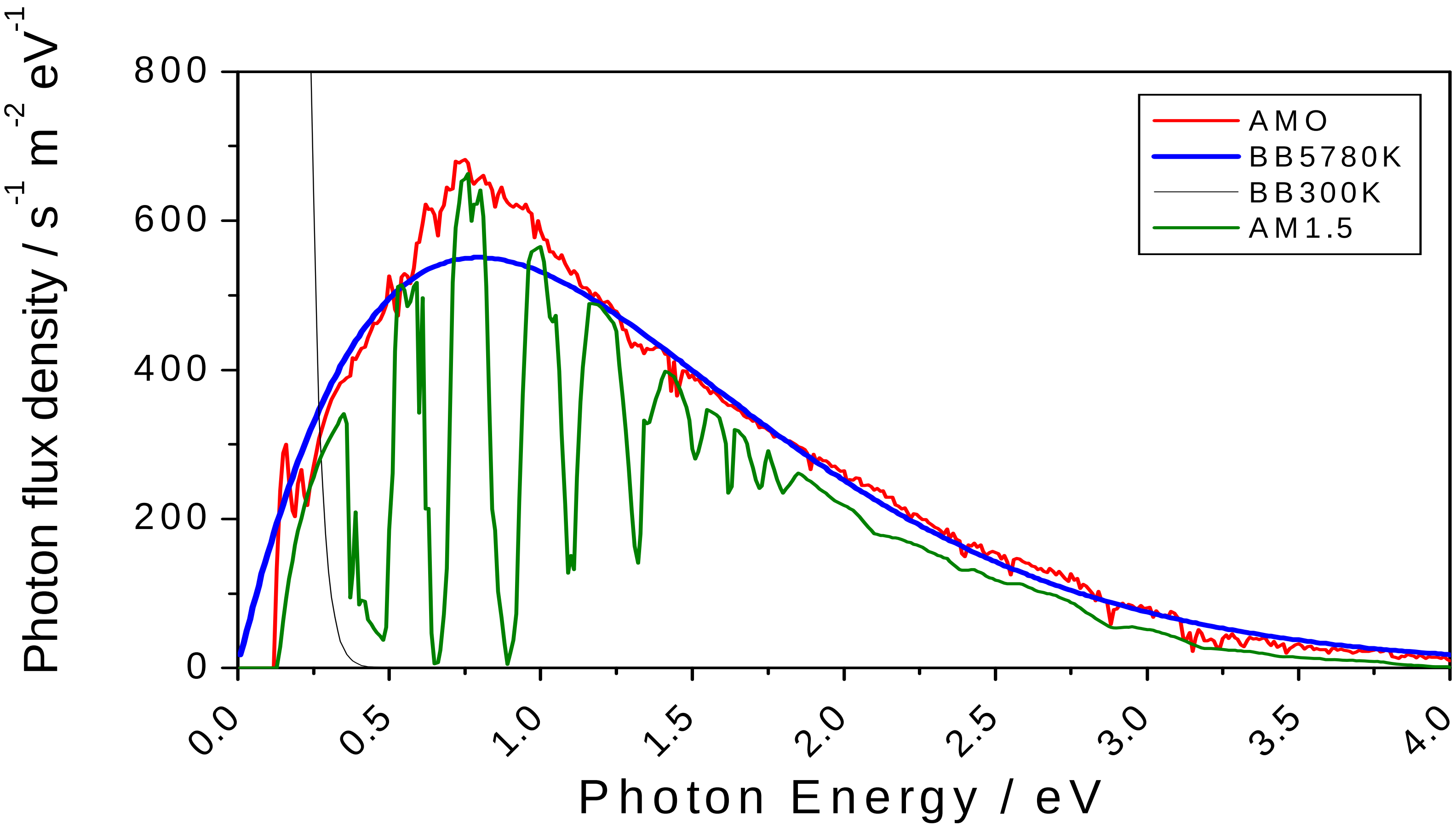
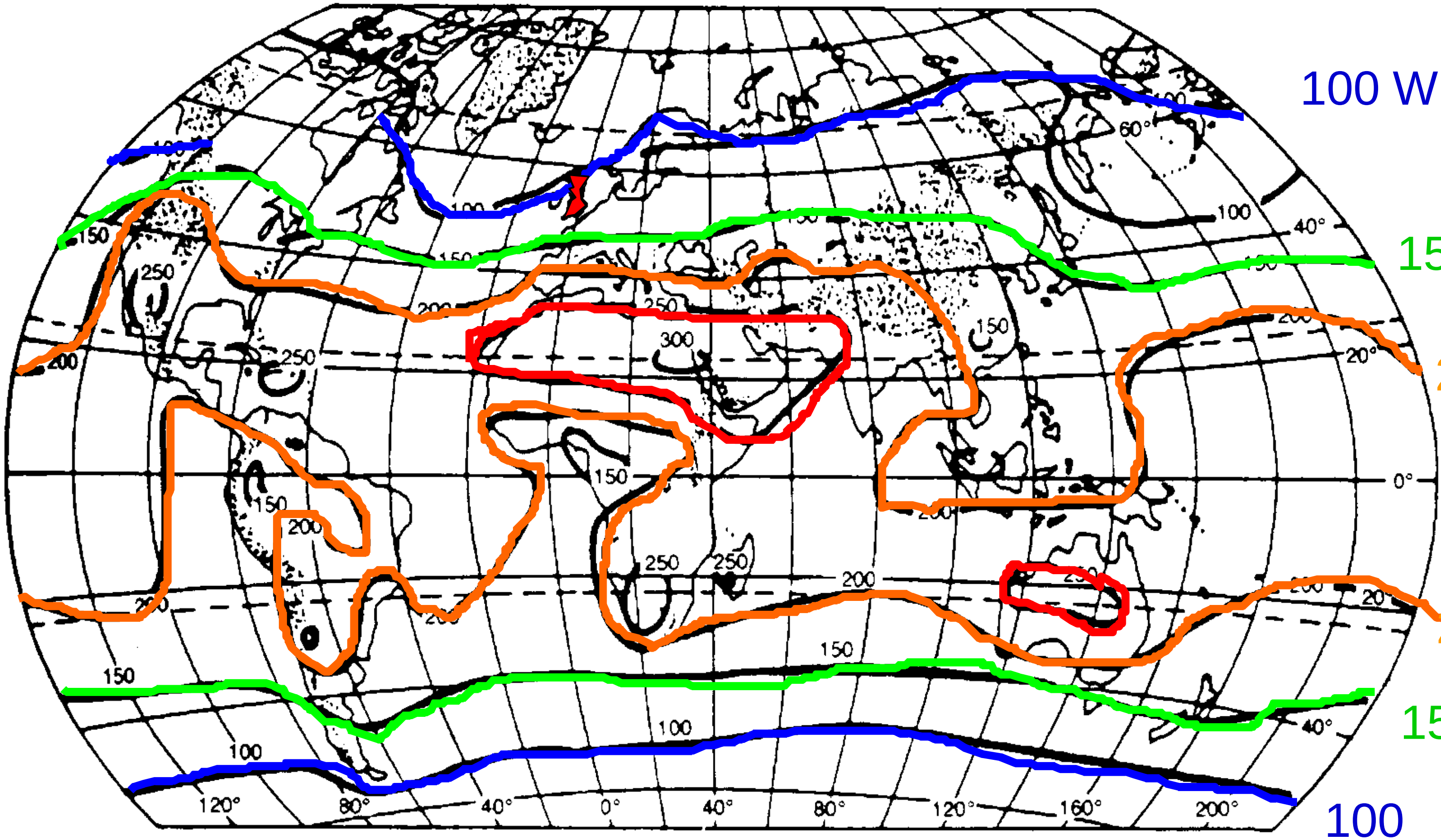
Solar photon flux spectrum



Important quantity for PV is solar photon *flux* density (not power density)

Average ~ 200 Wm^{-2} (5 peak sun hours)



Southern Britain ~ 125 Wm^{-2} (~3 peak sun hours)

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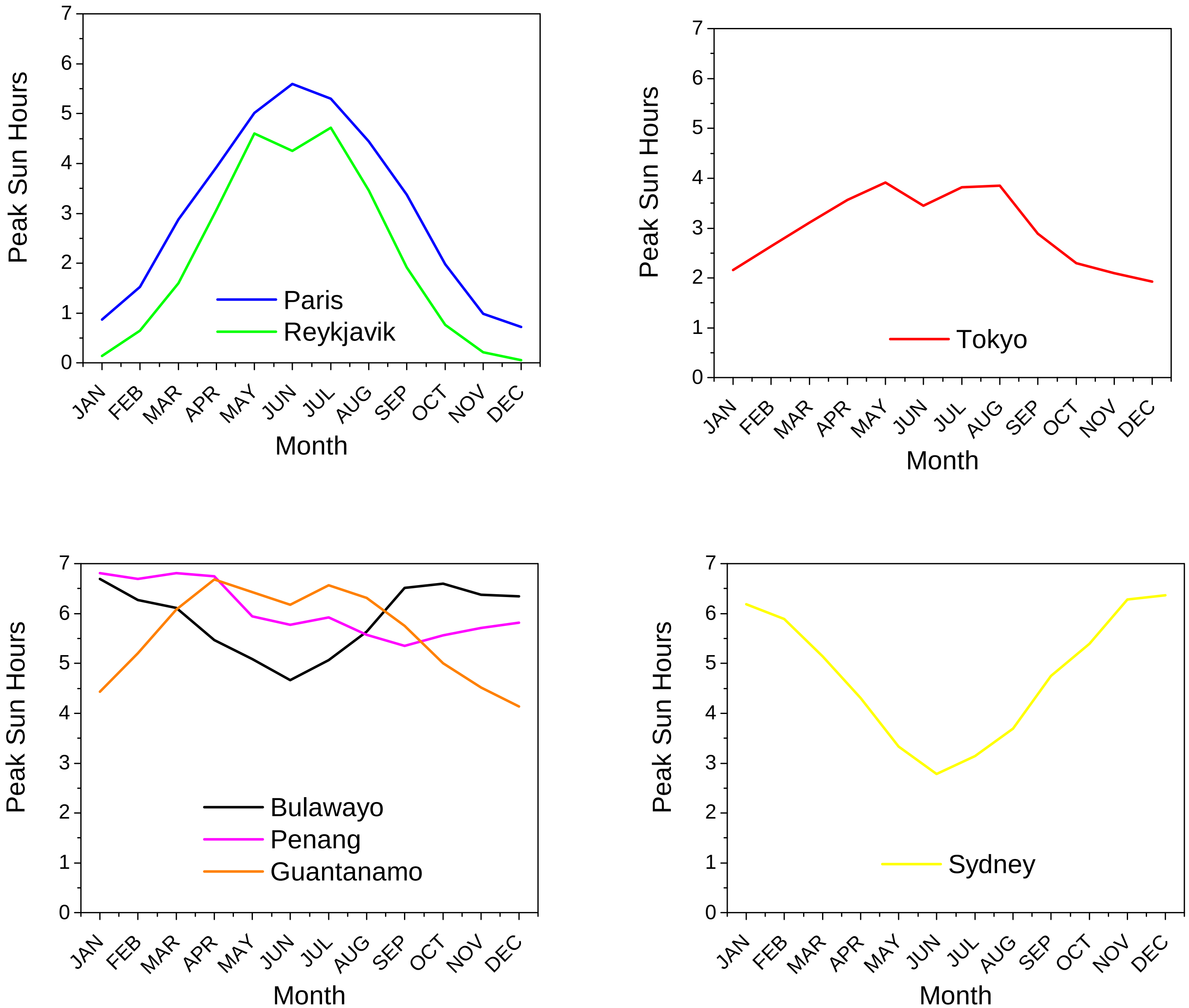
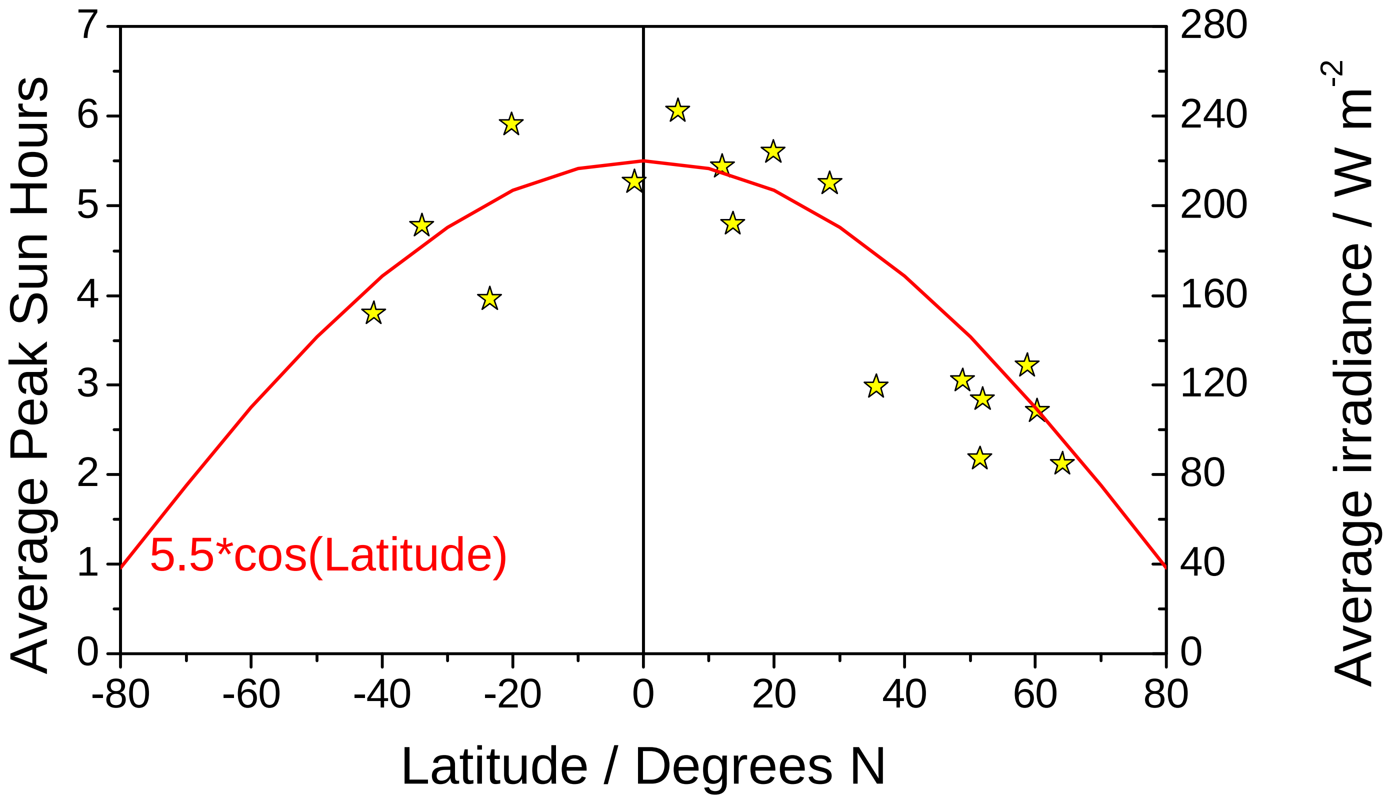

Peak Sun Hours
Month
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
0 1 2 3 4 5 6 7
Paris
Reykjavik
Tokyo
Bulawayo
Penang
Guantanamo
Sydney



What will be the consequences of latitude on off-grid power generation?

Energy consumption per capita in Western Europe ~ 5 kW

Mean solar irradiance in Southern Britain ~ 125 W m^{-2}

What land area is needed to supply the energy needs of a city of 10 million people using solar irradiation:

(a) with conversion efficiency of 50%?

(b) with conversion efficiency of 5%

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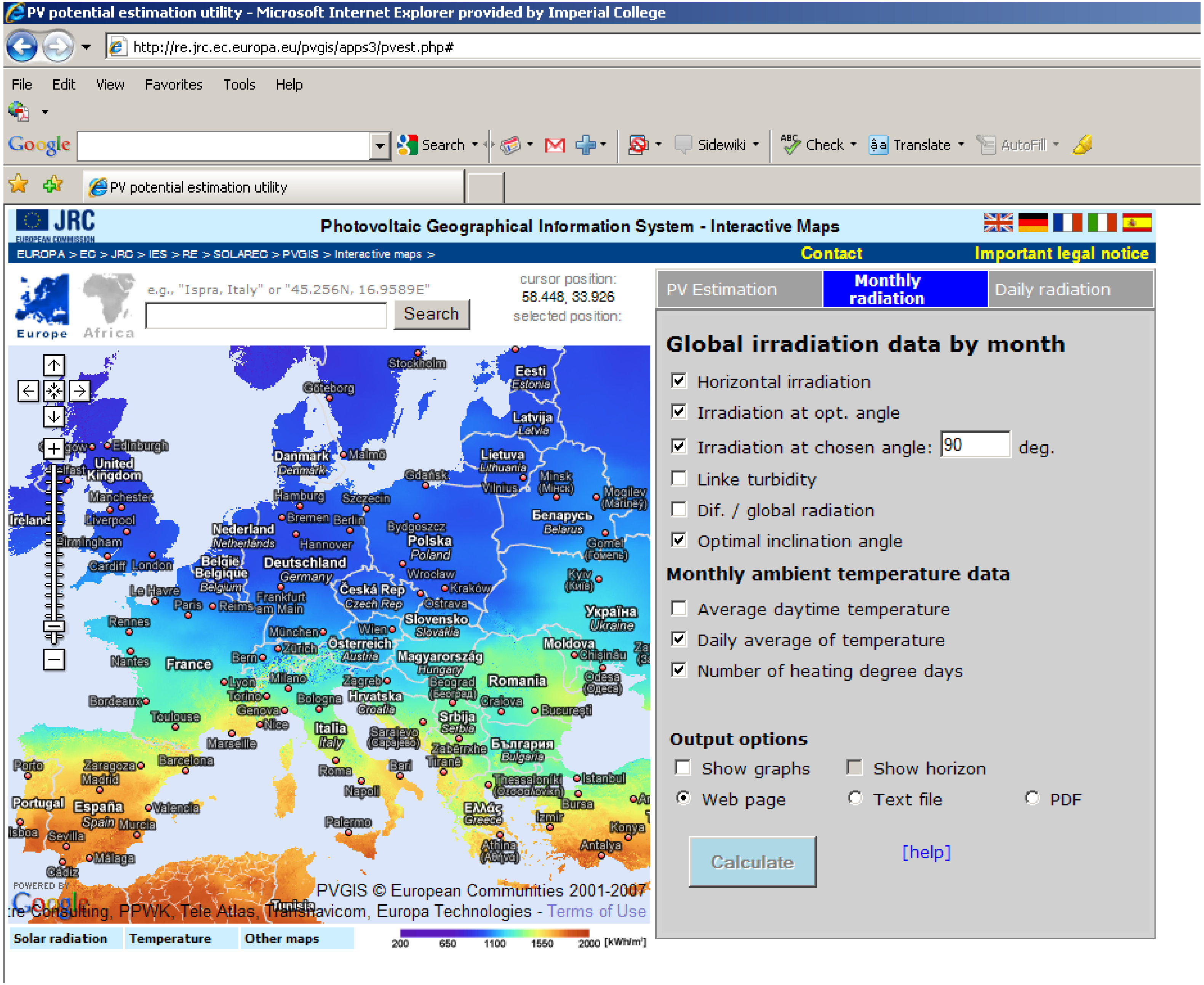
PVGIS home - Microsoft Internet Explorer provided by Imperial College
http://re.jrc.ec.europa.eu/pvgis/
File Edit View Favorites Tools Help
Google
Search
Sidewiki
Check
Translate
AutoFill
PVGIS home
JRC
EUROPEAN COMMISSION
You are here: EC / JRC / IE / RE / SOLAREC / PVGIS / Home
Important legal notice
PVGIS Home
Interactive maps
Country maps
FAQ
Solar radiation
Temperature
About PVGIS
Publications
Download
Site map
Joint Research Centre
Institute for Energy
Photovoltaic Geographical Information System (PVGIS)
Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology
Interactive access to solar resource and photovoltaic potential:
Europe
Africa
See also aggregated data of solar and PV potential for European countries and regions.
The old system with French, German Italian, Spanish, and Slovak language interface still works.
Posters and maps of solar resource and photovoltaic electricity potential
(Europe NEW, Africa)
old version maps for Europe
Topics
About PVGIS
How database for Europe was created
Solar radiation data worldwide (update)
Air temperature in Europe
News
You can now calculate performance for Cadmium Telluride (CdTe) modules here
Versione italiana finalmente pronta. Provala qui
New version of European country maps


PV potential estimation utility - Microsoft Internet Explorer provided by Imperial College
http://re.jrc.ec.europa.eu/pvgis/apps3/pvest.php#
File Edit View Favorites Tools Help
JRC
Photovoltaic Geographical Information System - Interactive Maps
EUROPA > EC > JRC > IES > RE > SOLAREC > PVGIS > Interactive maps >
Contact
Important legal notice
Europe
Africa
e.g., "Ispra, Italy" or "45.256N, 16.9589E"
Search
cursor position:
58.448, 33.926
selected position:
PV Estimation
Monthly radiation
Daily radiation
Global irradiation data by month
Horizontal irradiation
Irradiation at opt. angle
Irradiation at chosen angle: 90 deg.
Linke turbidity
Dif. / global radiation
Optimal inclination angle
Monthly ambient temperature data
Average daytime temperature
Daily average of temperature
Number of heating degree days
Output options
Show graphs
Show horizon
Web page
Text file
PDF
Calculate
[help]
PVGIS © European Communities 2001-2007
Solar radiation
Temperature
Other maps
200
650
1100
1550
2000 [kWh/m²]

http://re.jrc.ec.europa.eu/pvgis/apps3/MRcalc.php - Microsoft Internet Explorer provided by Imperial College

http://re.jrc.ec.europa.eu/pvgis/apps3/MRcalc.php

Monthly Solar Irradiation

PVGIS Estimates of long-term monthly averages

Location: 40°42'50" North, 3°36'12" West, Elevation: 827 m a.s.l.,

Optimal inclination angle is: 34 degrees
Annual irradiation deficit due to shadowing (horizontal): 0.0 %

Month	H_h	H_{opt}	$H(90)$	I_{opt}	T_{24h}	N_{DD}
Jan	1930	3200	3240	63	5.4	359
Feb	2680	3860	3440	55	6.6	292
Mar	4370	5570	4150	44	9.8	204
Apr	5080	5470	3150	27	11.5	149
May	6420	6240	2820	16	15.5	26
Jun	7170	6650	2580	7	21.3	4
Jul	7330	6950	2790	11	23.6	2
Aug	6400	6700	3420	23	23.3	3
Sep	4940	5960	4030	38	19.0	38
Oct	3340	4640	3920	51	14.4	154
Nov	2100	3310	3220	60	8.5	336
Dec	1560	2570	2640	64	5.7	378
Year	4450	5100	3280	34	13.7	1945

H_h: Irradiation on horizontal plane (Wh/m^2)

H_{opt}: Irradiation on optimally inclined plane (Wh/m^2)

$H(90)$: Irradiation on plane at angle: 90deg. (Wh/m^2)

I_{opt}: Optimal inclination (deg.)

T_{24h}: 24 hour average of temperature (°C)

N_{DD}: Number of heating degree-days (-)

1.3. PHOTOVOLTAIC ENERGY CONVERSION

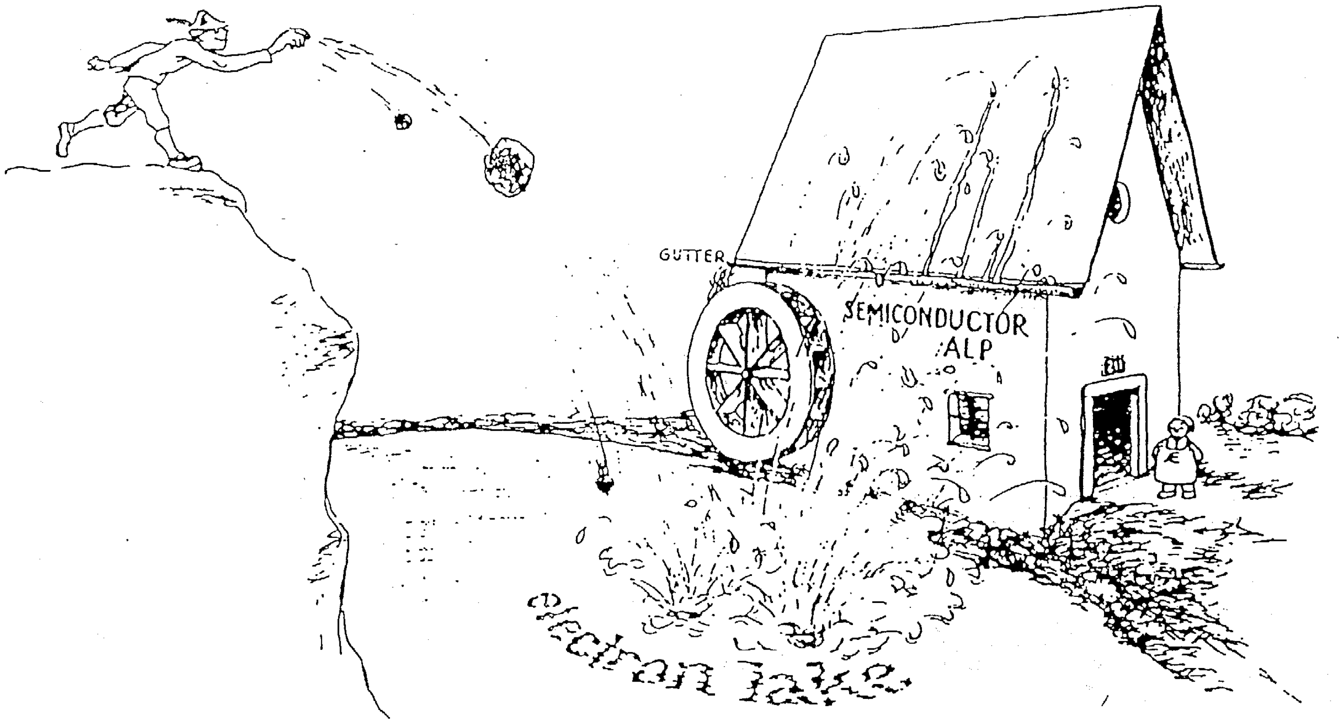
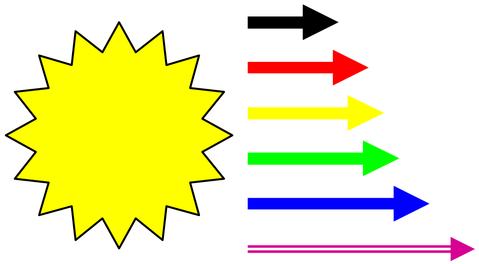
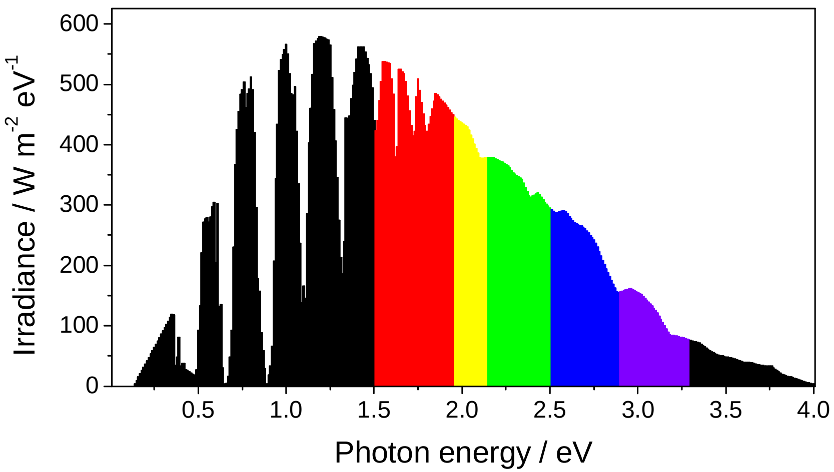


Fig. 7: "Semiconductor Alp", a mechanical analogon of the photoelectric effect

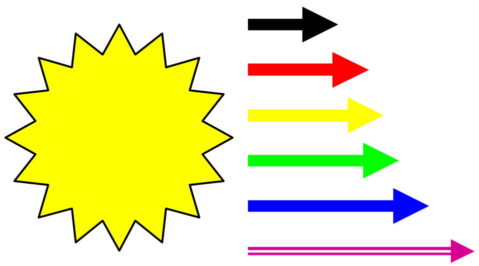
Light energy conversion

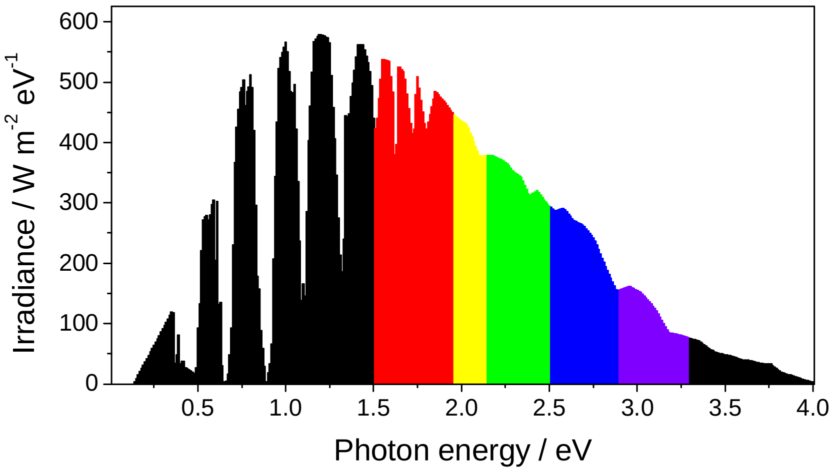
- Packets of light energy (photons) defined by the wavelength of light
- May be absorbed in matter to promote electrons to higher energy

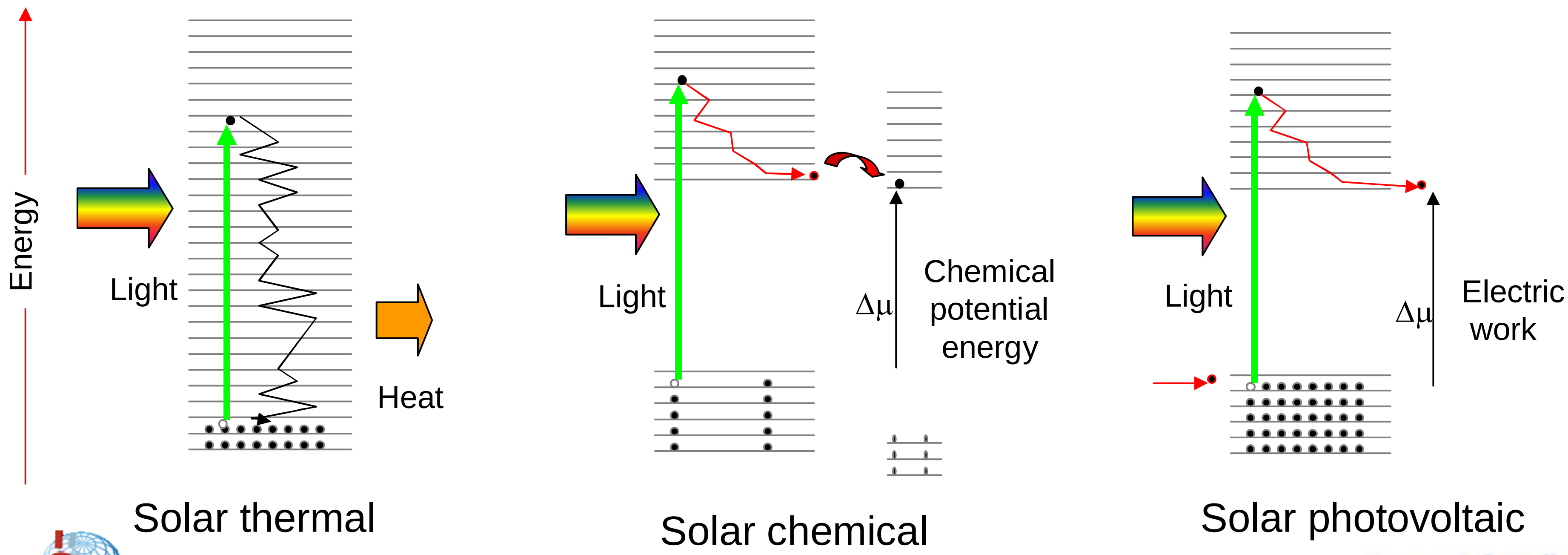




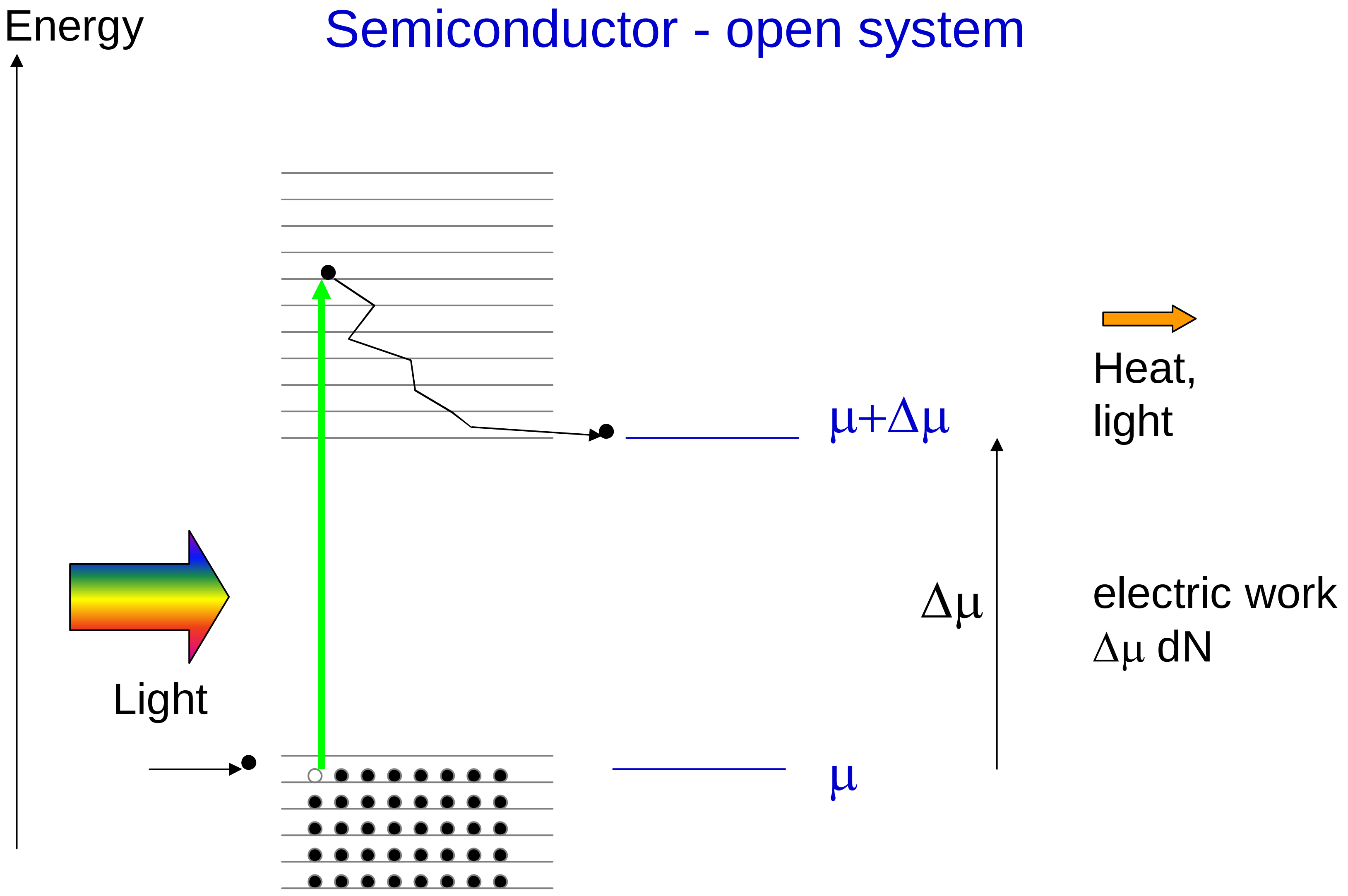
What happens next depends on the system …



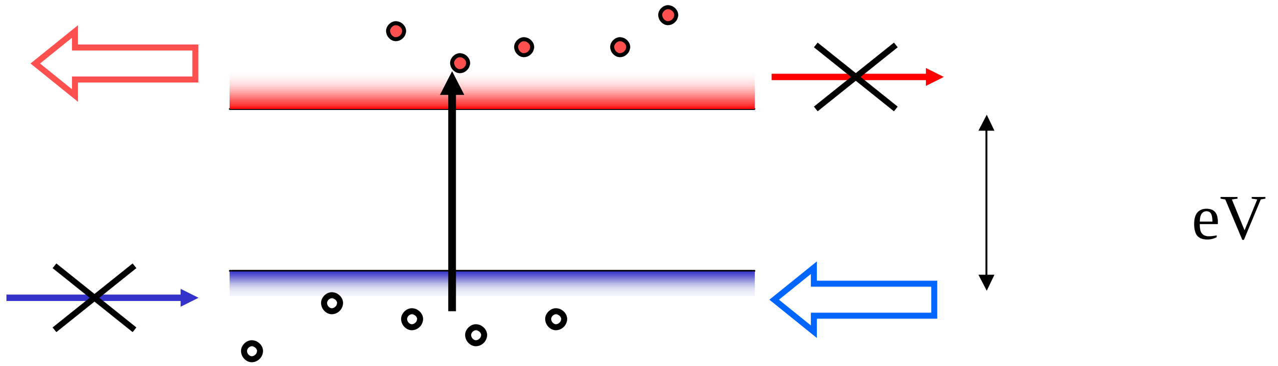

Irradiance / W m^{-2} eV^{-1}
600
500
400
300
200
100
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Photon energy / eV


Energy
Light
Heat
Solar thermal
Light
Δμ
Chemical potential energy
Solar chemical
Light
Δμ
Electric work
Solar photovoltaic

Semiconductor - open system

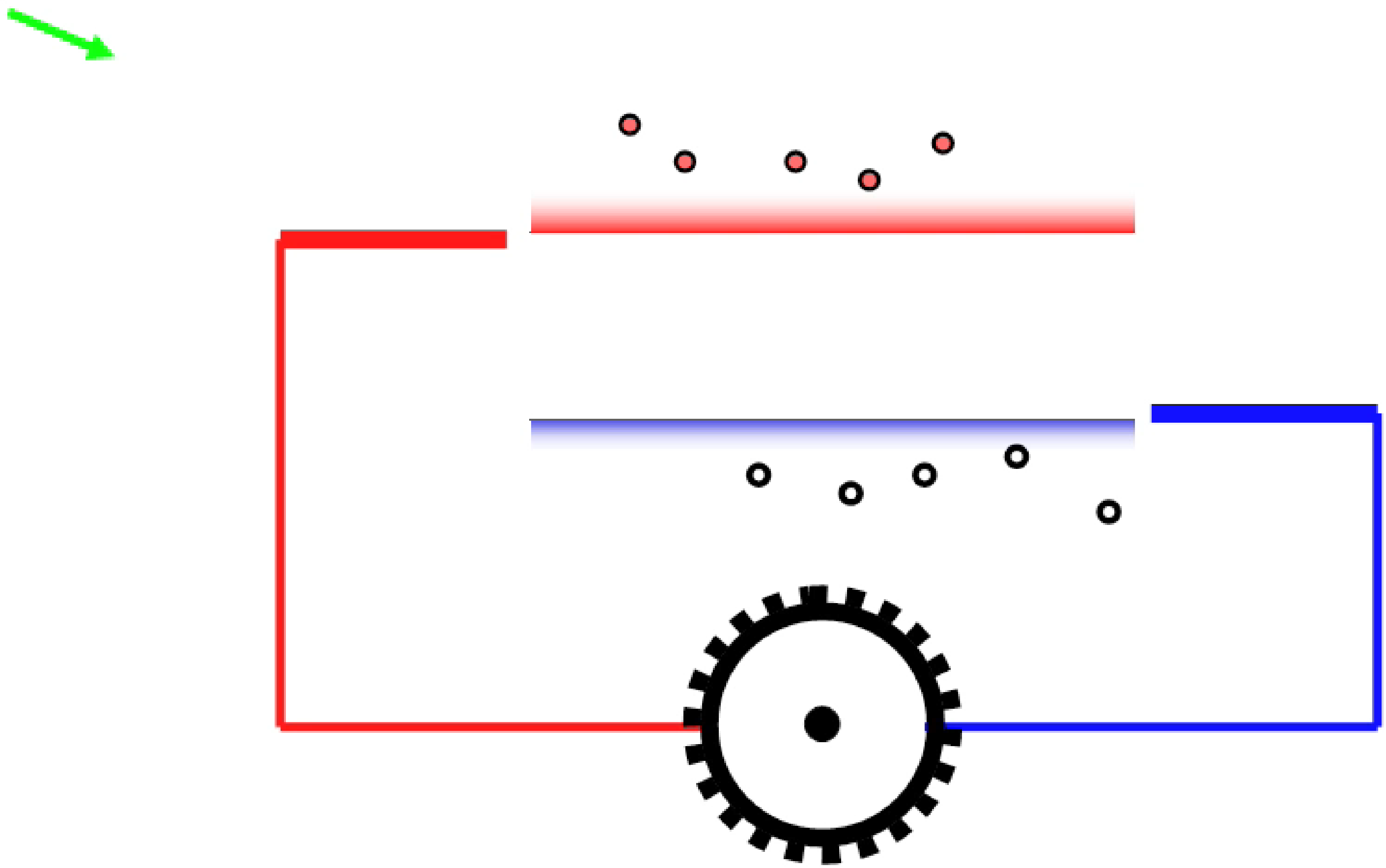


Photons in, electrons out



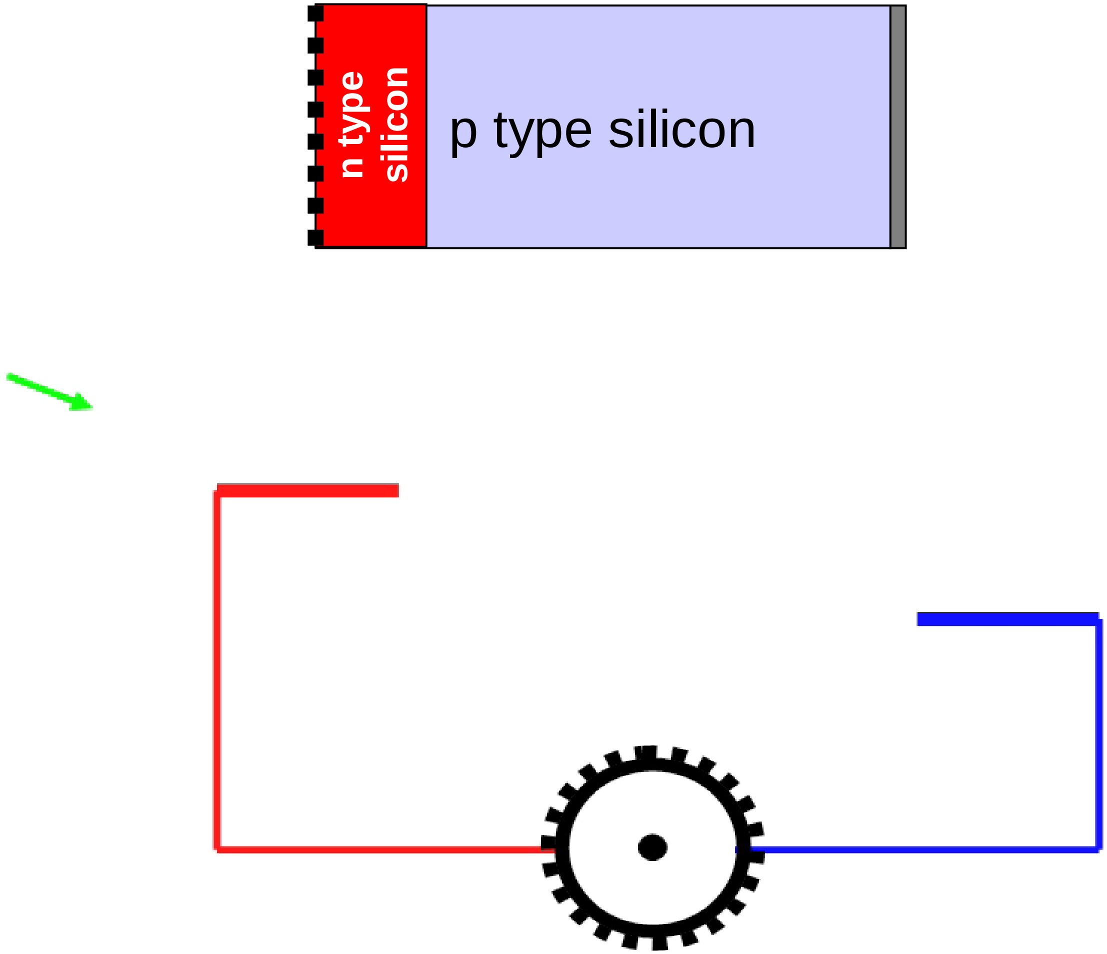
- Photovoltaic energy conversion requires:
  - photon absorption across an energy gap
  - separation of photogenerated charges
  - asymmetric contacts to an external circuit

Photons in, electrons out

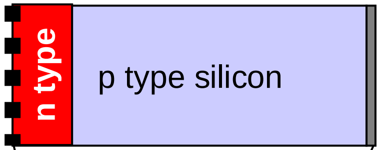


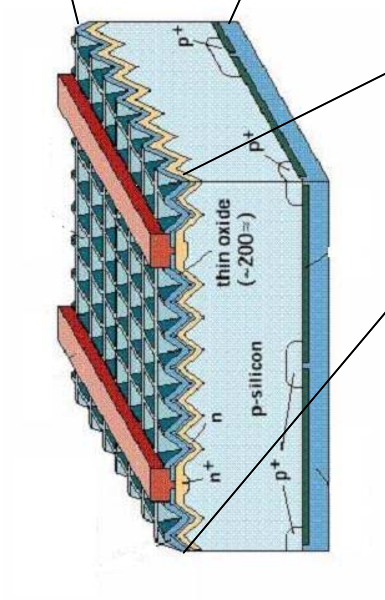
movie

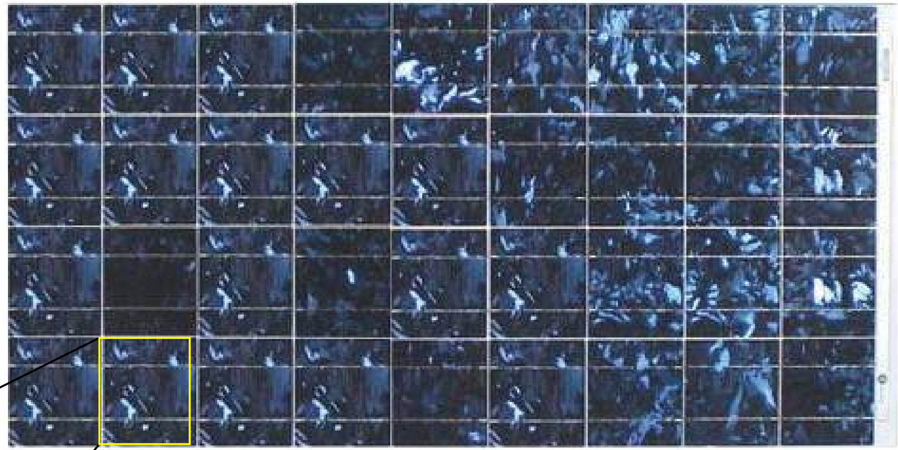
Photons in, electrons out



movie





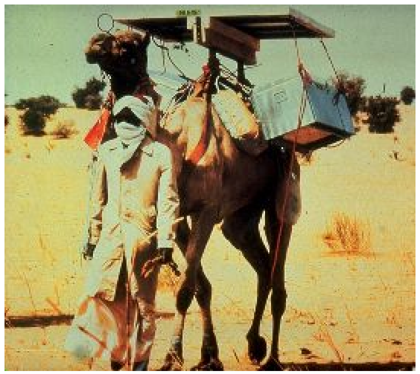


efficiency
~ 14%

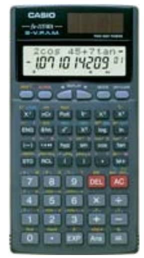
power rating
~ 80 W_p

CIS Tower, Manchester
0.4 MW_p
(Solar Century)

Applications



Solar powered refrigeration
~100 W_p



~1 mW_p

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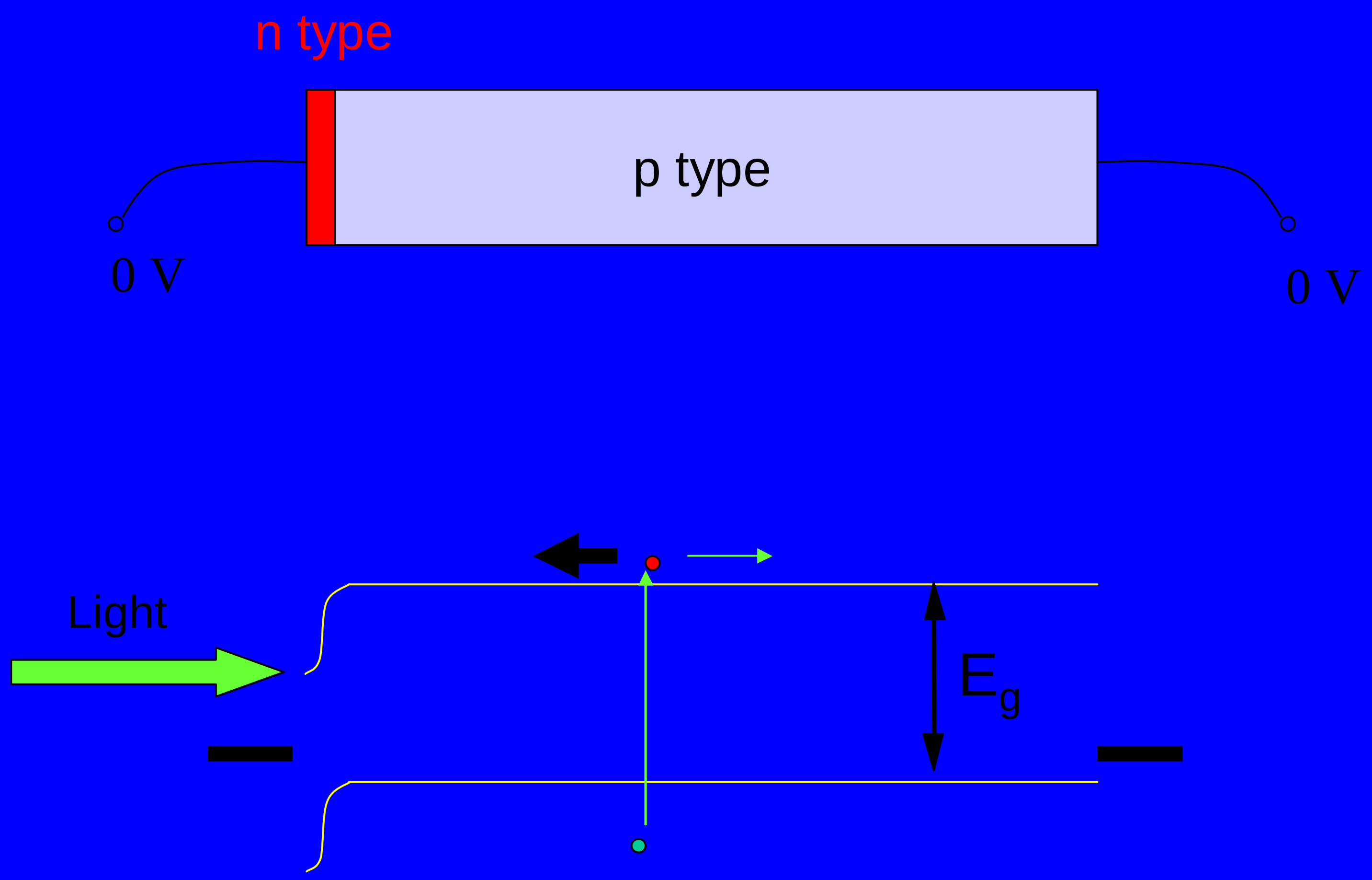
1.4. THE P-N JUNCTION



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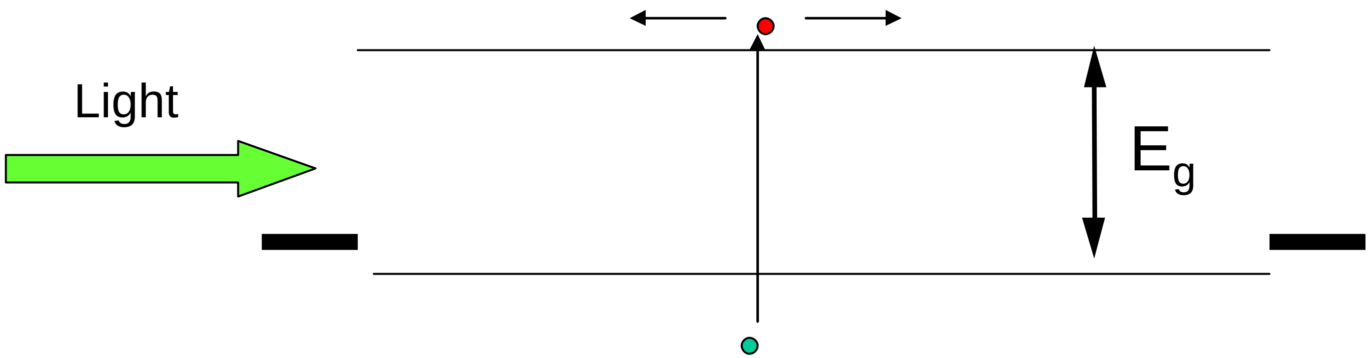
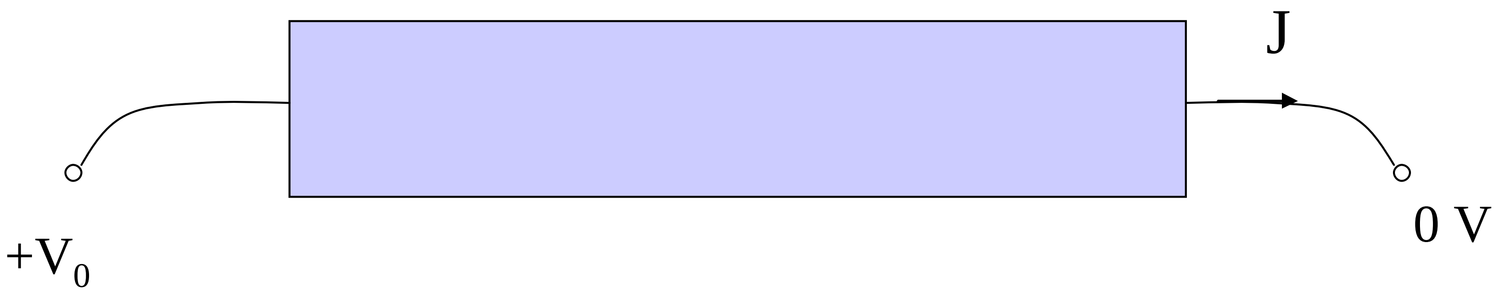
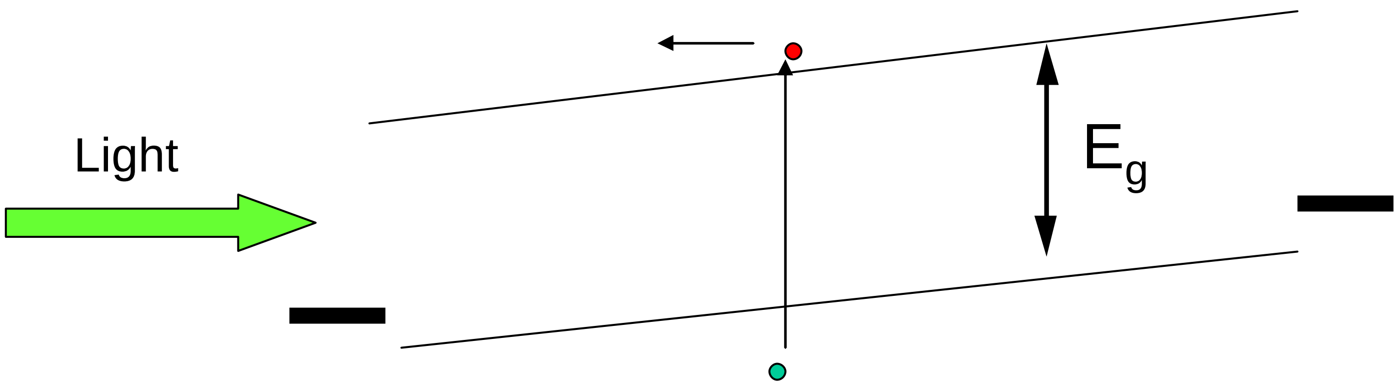
How do the electrons know which way to go??



No driving force to direct photocurrent





Applied voltage drives photocurrent, but power consumed

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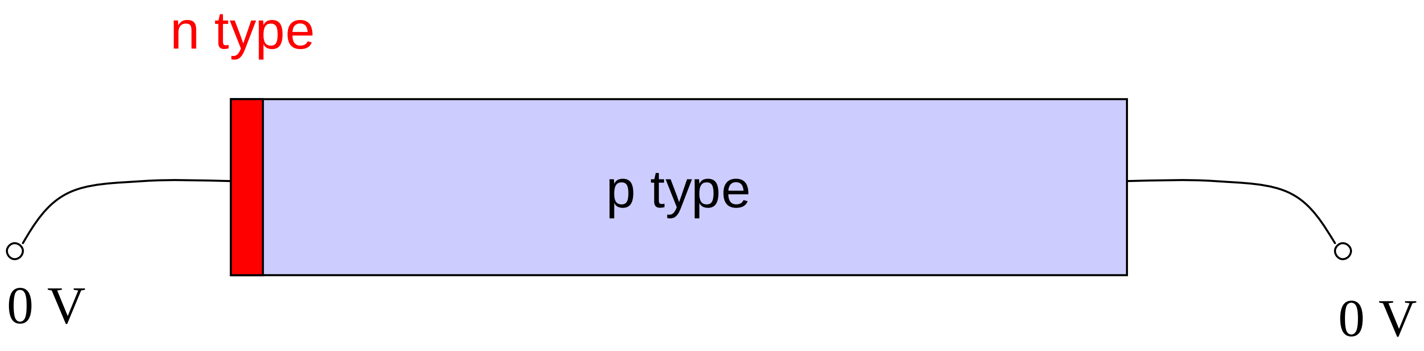
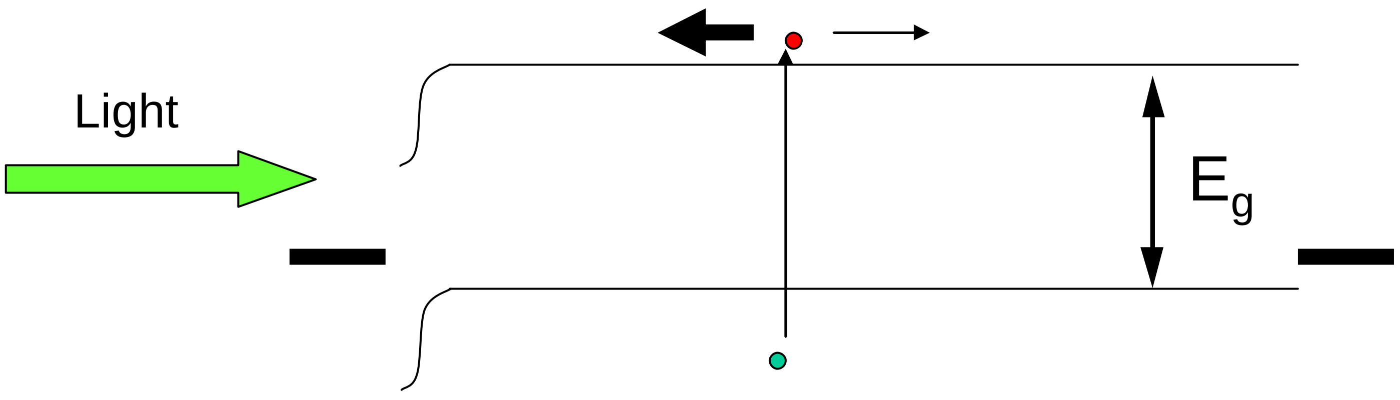
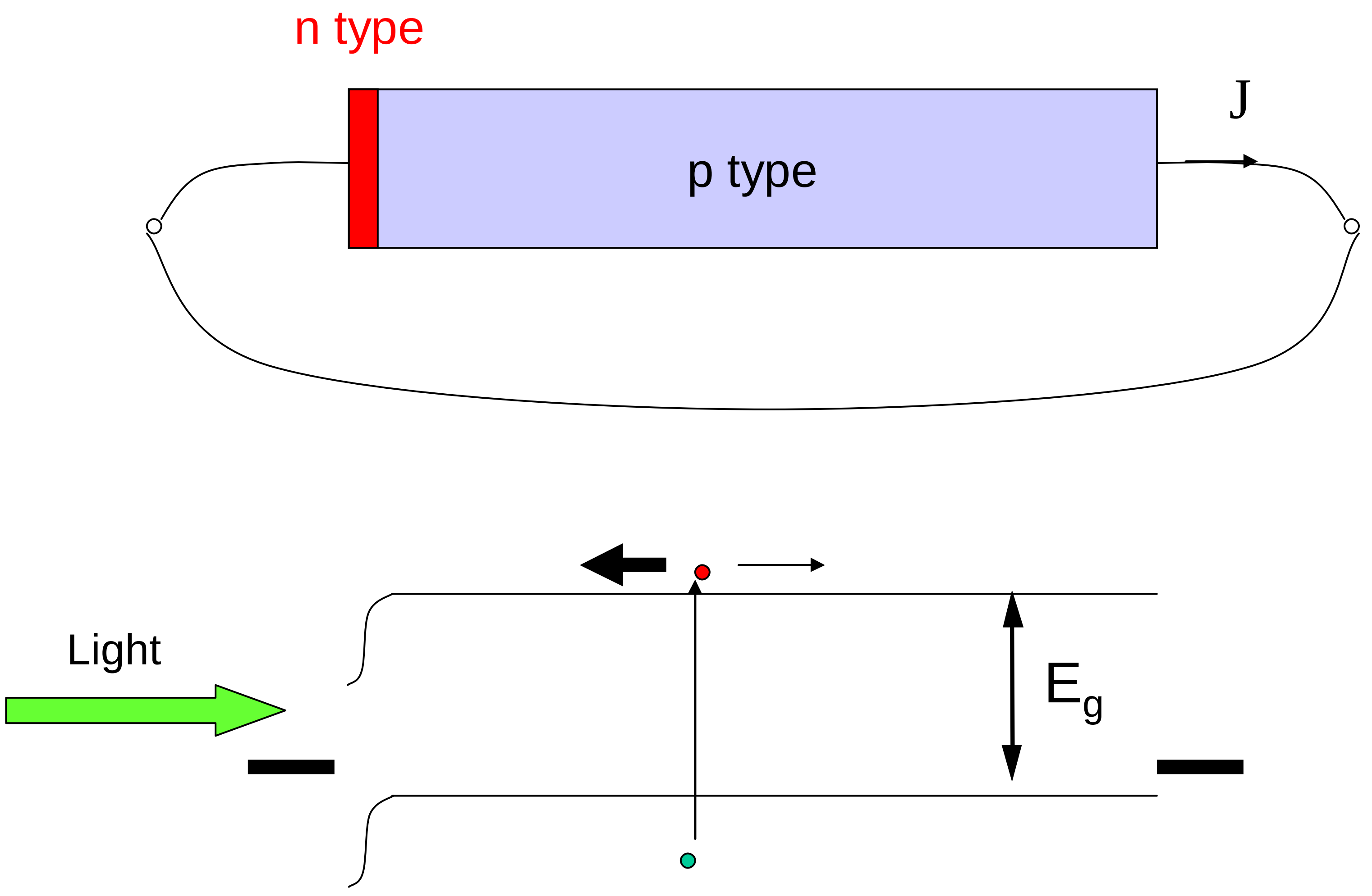




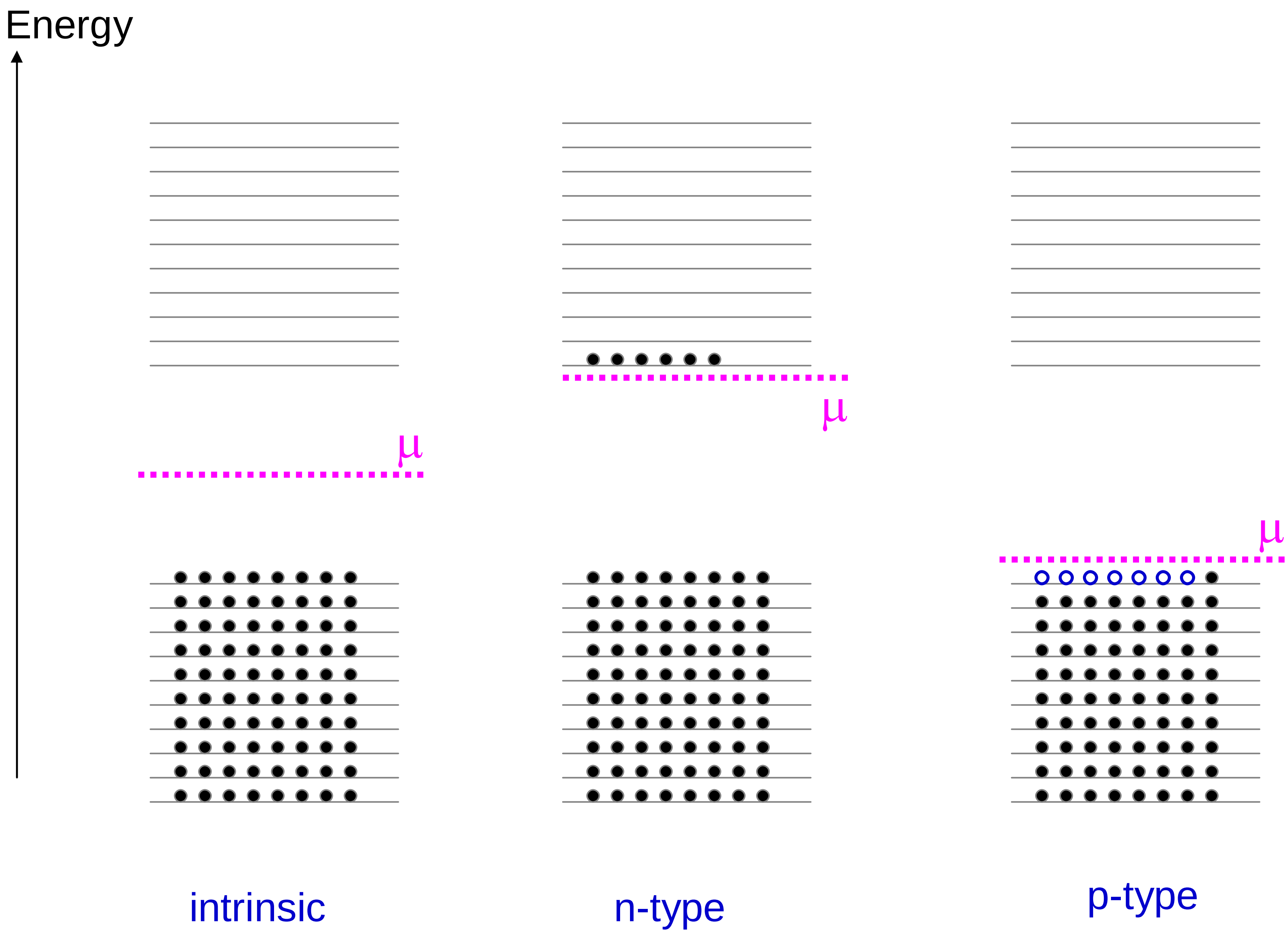
Compositional change drives photocurrent



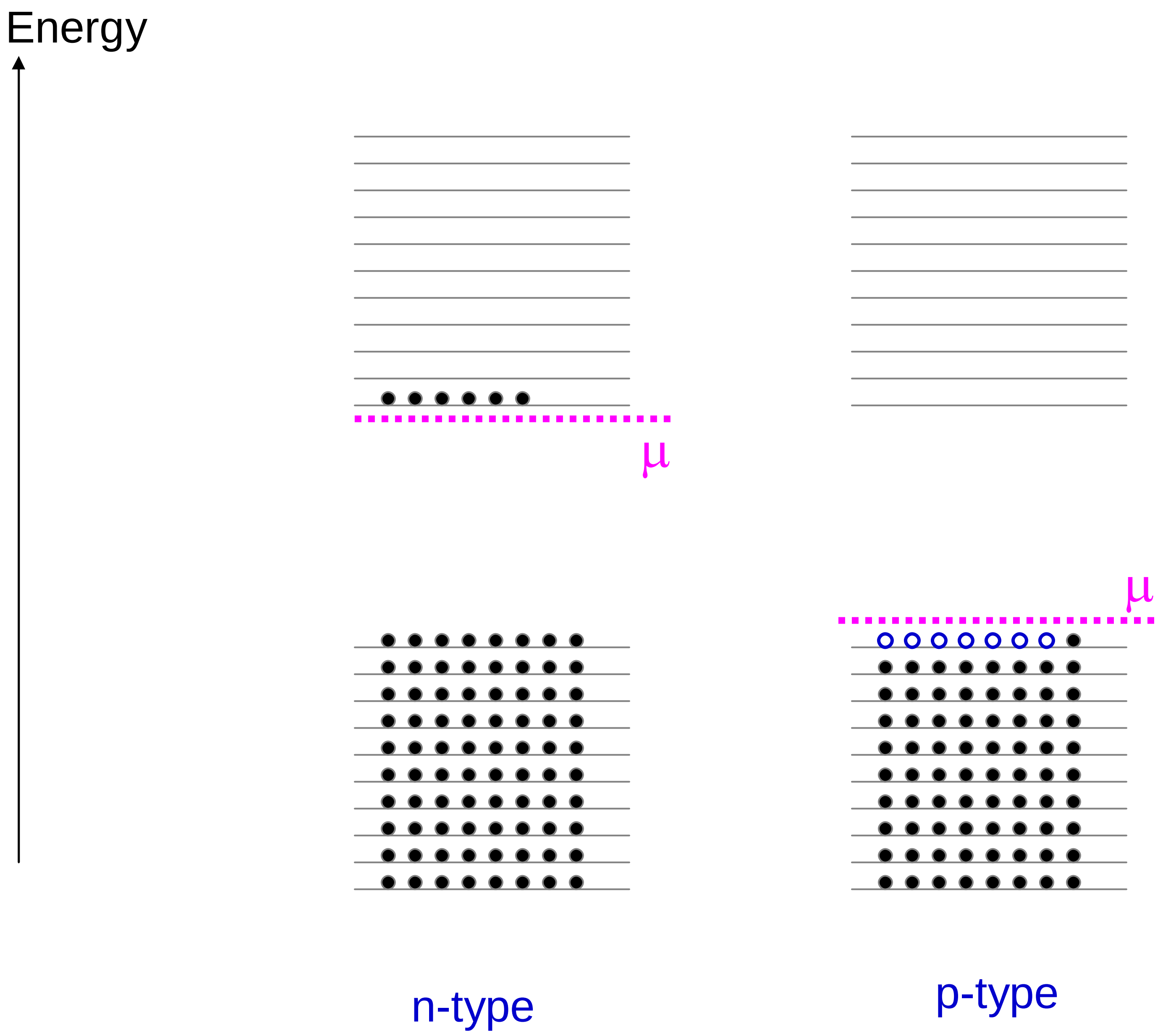
Compositional change drives photocurrent

- To generate electric power from solar radiation we need
  - An energy gap (to keep photo-generated electrons at high $\Delta\mu$)
  - A preferred direction for electron extraction

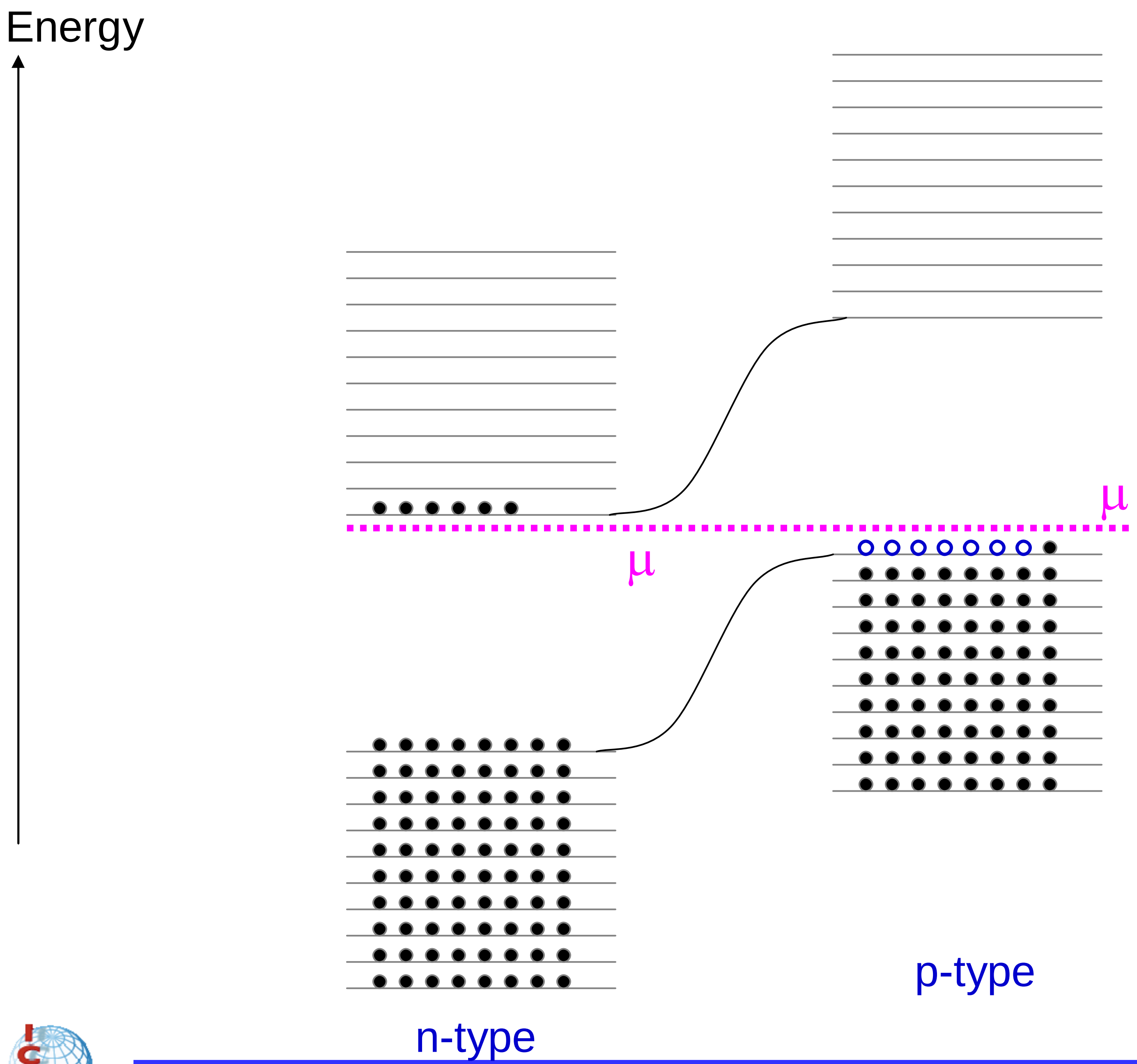
- A semiconductor provides the energy gap
- Asymmetric contacts (for directed charge extraction) can be provided by a p-n or n-p junction

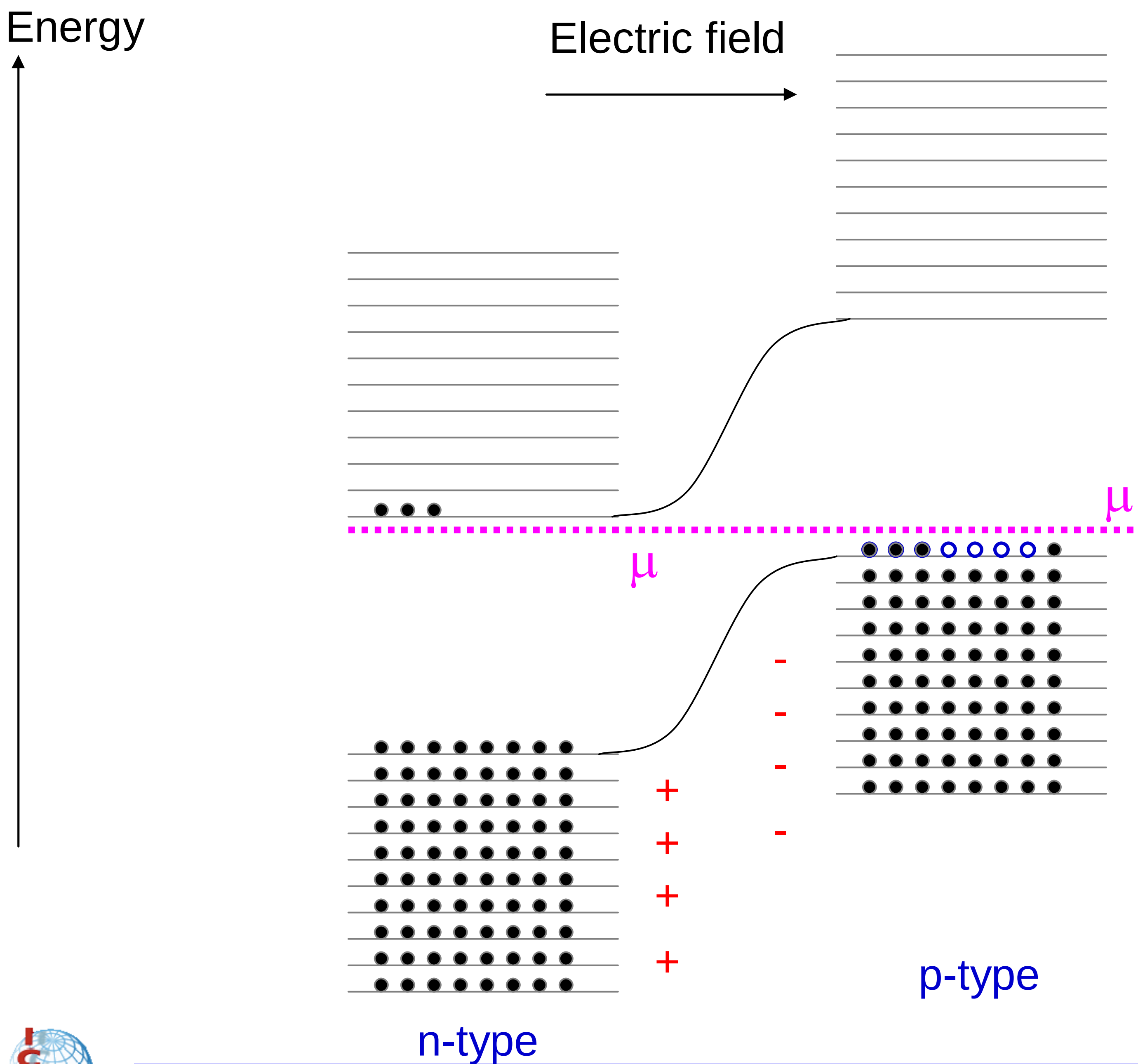


Energy
μ
μ
μ
intrinsic
n-type
p-type



Energy
μ
μ
n-type
p-type


Energy
μ
μ
p-type
n-type



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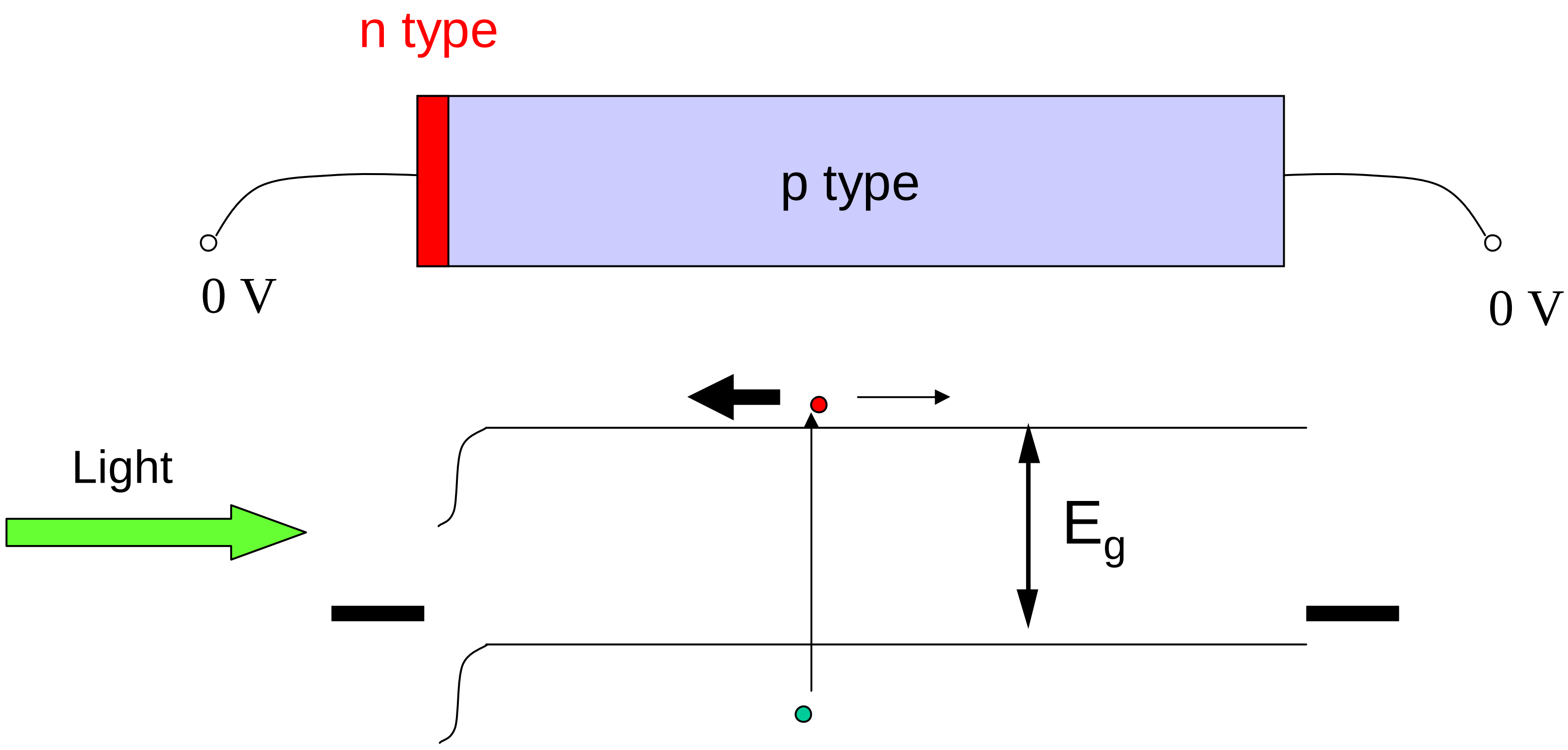
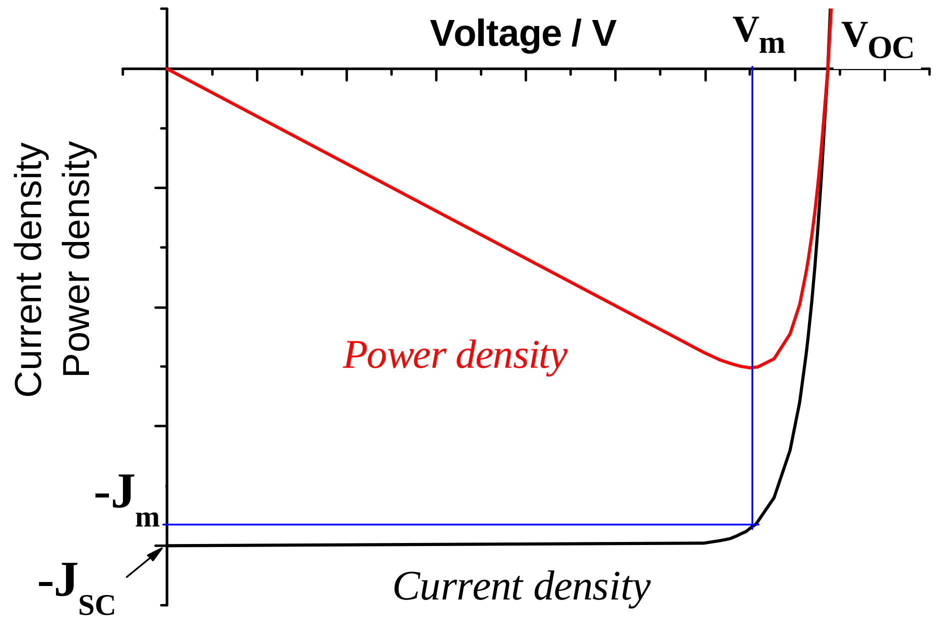
Semiconductor p-n junction



- Band gap enables photogeneration
- Compositional change drives photocurrent

1.5. SOLAR CELL PERFORMANCE CHARACTERISTICS



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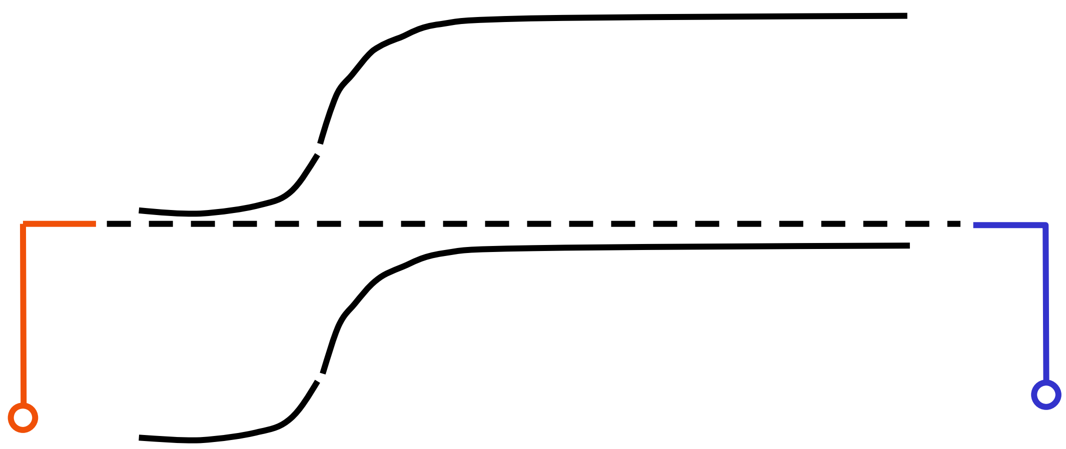
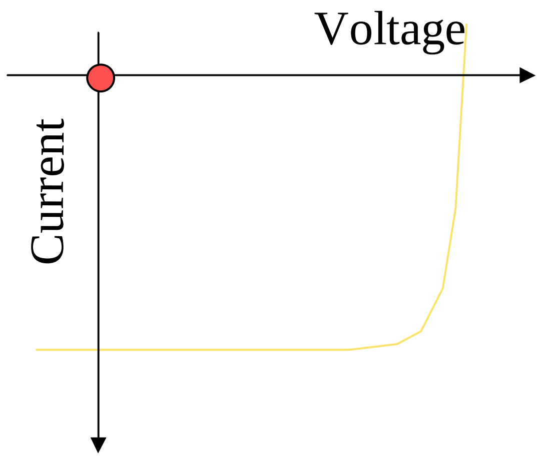
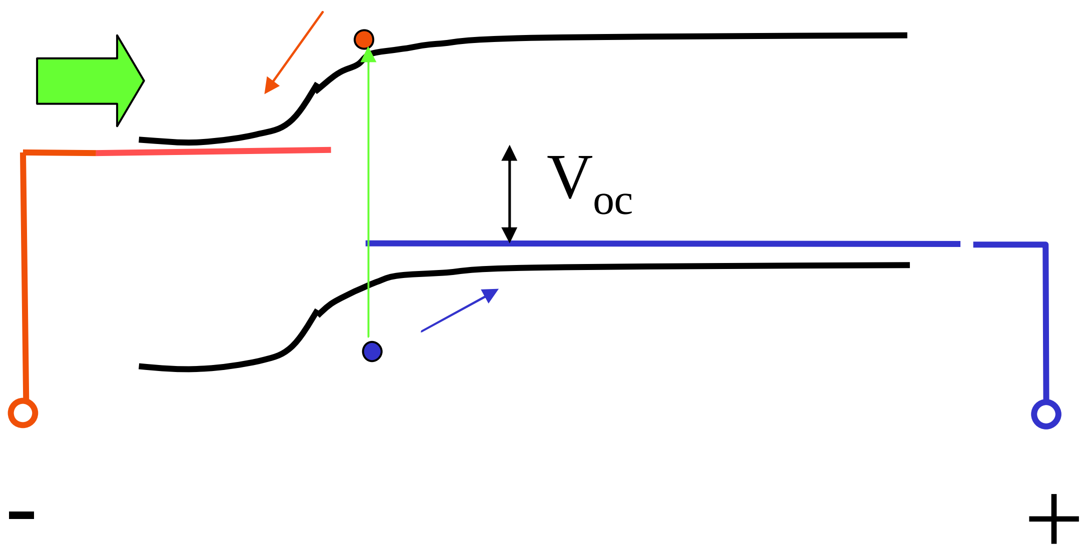
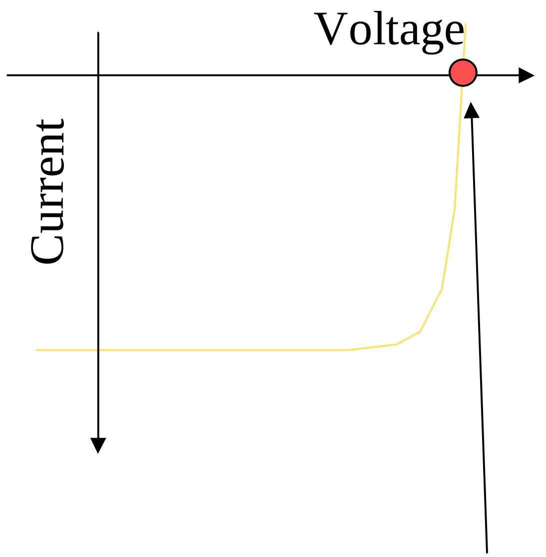
In the dark





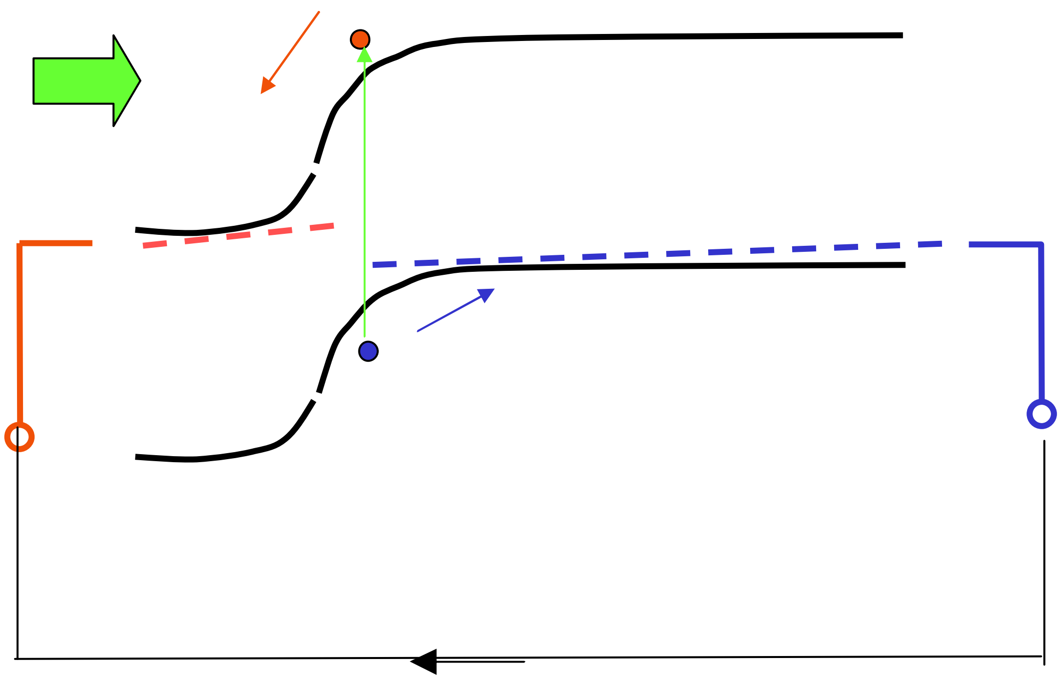
Open circuit

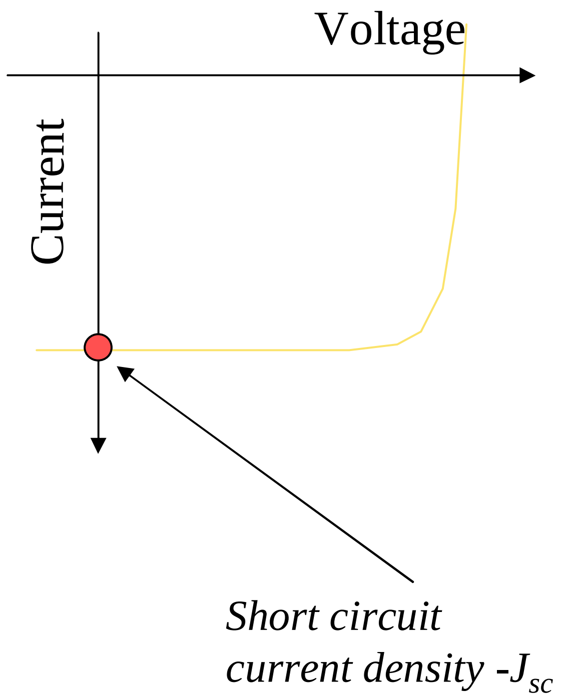




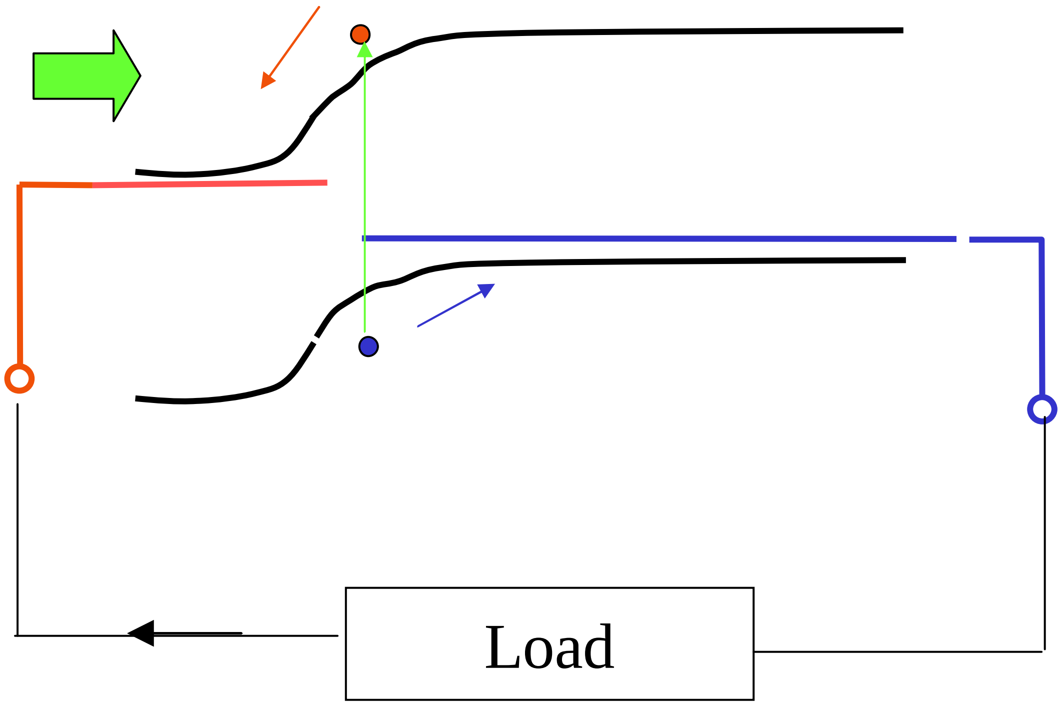
Open circuit voltage V_{oc}

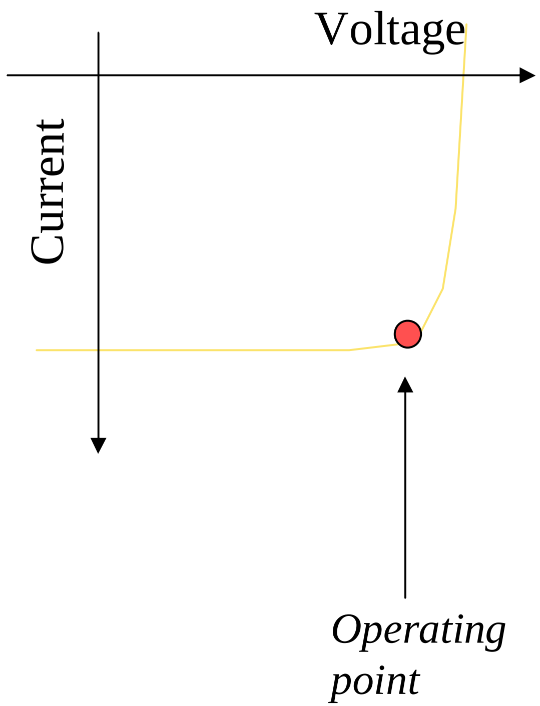
Short circuit





Operating: photovoltage x photocurrent = electric power





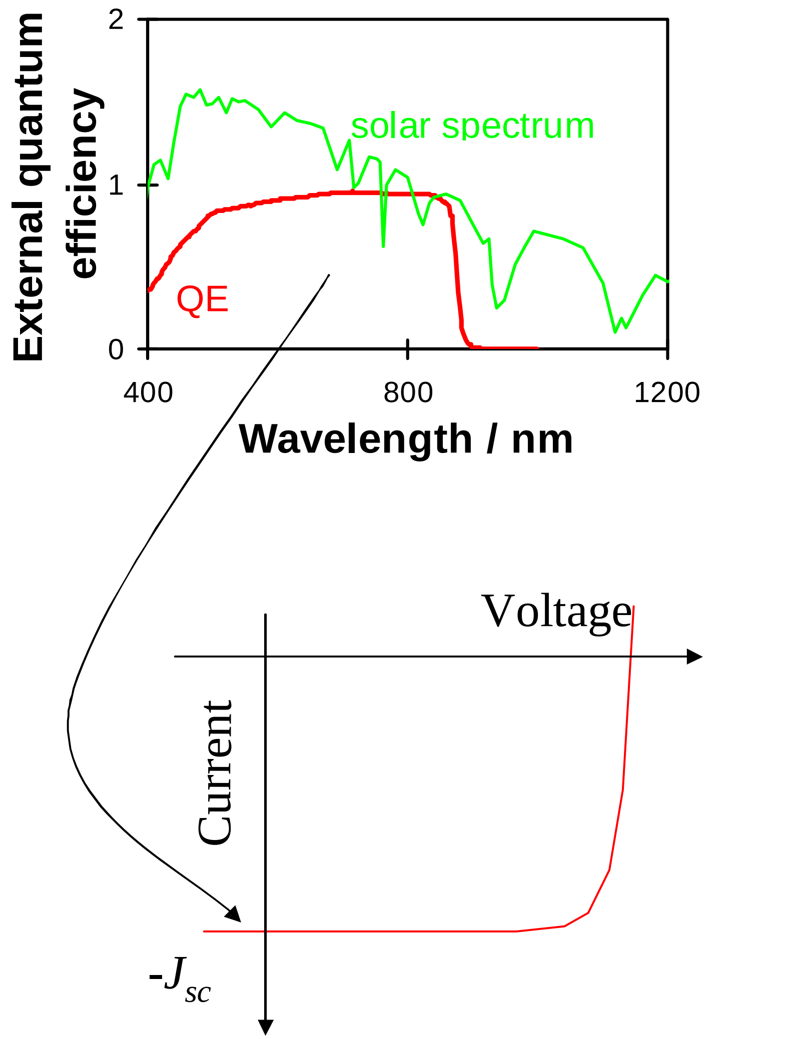
Solar cell characteristics

- Quantum efficiency

$$QE = \frac{\text{electrons out}}{\text{photons in}} = \frac{J_{sc}(E)}{q b_{sun}(E)}$$

- Short circuit current density

$$J_{sc} = q \int \text{photon flux density}(E) \times \text{QE}(E)\, dE$$

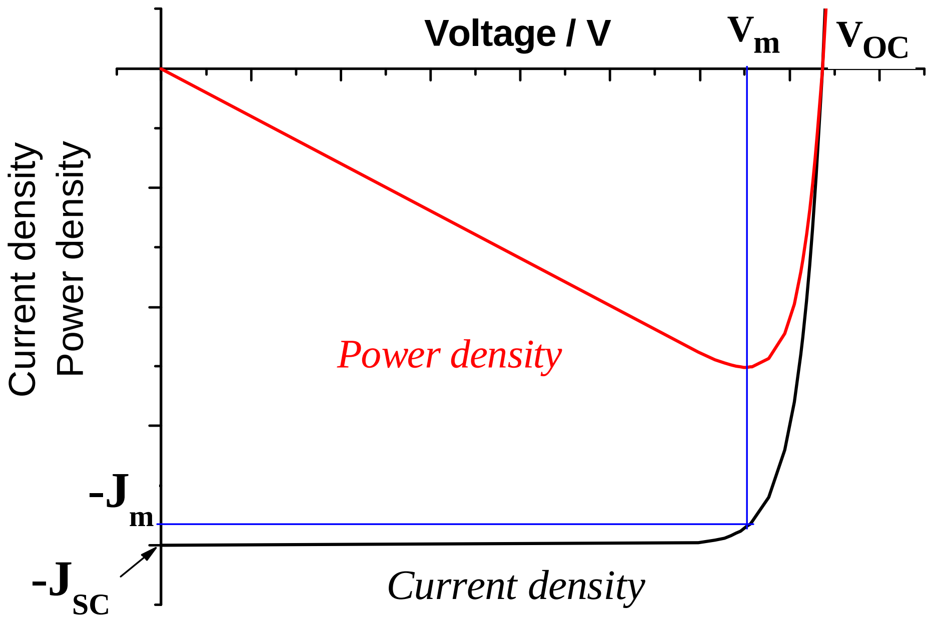


Solar cell characteristics

- Short circuit current density J_{sc},
- Open circuit voltage V_{oc}
- Fill factor FF $$FF = \frac{J_m V_m}{J_{sc} V_{oc}}$$
- Power conversion efficiency

$$PCE = \frac{J_{sc} V_{oc} FF}{P_{in}}$$

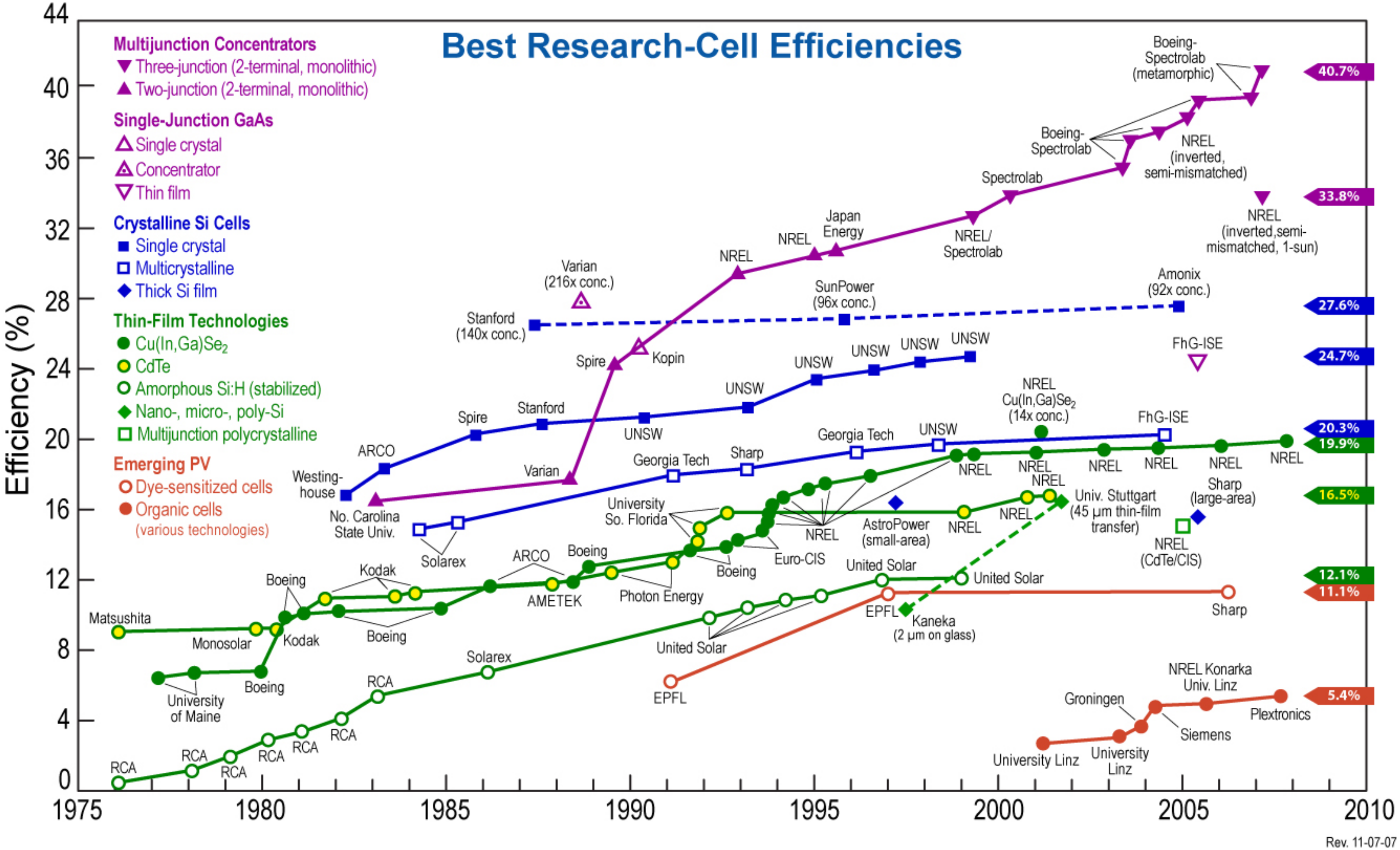
$$P_{in} = \int b_{in}(E) E \, dE$$



- Measured under Standard Test Conditions (AM1.5, 1000 Wm^{-2}, 25°C)

Solar cell performance

Cell Type		Area (cm^2)	V_{oc} (V)	J_{sc} (mA /cm^2)	FF (%)	Efficiency (%)
c-Si	UNSW PERL	4.0	0.696	42.0	83.6	24.9
c-GaAs	Kopin	3.91	1.022	28.2	87.1	25.1
poly-Si	UNSW/ Eurosolare	1.0	0.628	36.2	78.5	19.8
a-Si	Sanyo	1.0	0.887	19.4	74.1	12.7
$CuInGaSe_2$	NREL	1.04	0.669	35.7	77.0	18.4
Cd Te	NREL	1.131	0.848	25.9	74.5	16.4
polymer / fullerene	various	0.1	~0.6-0.8	~12-15	~60	5 - 6



More on this in next Monday’s lectures

Summary

- Installed photovoltaic capacity reached 13 GWp in 2008, mainly in grid connected applications
- Overhead sun provides ~ 1 kW m^{-2} of radiant power at the Earth's surface, annually averaged irradiance ~ 100 – 200 W m^{-2} depending on latitude
- In photovoltaic energy conversion,
  - absorbed photons promote electrons to higher energy levels within a semiconductor
  - opposite charges are driven towards opposite contact by electrode selectivity
  - charges are extracted (⇨current) with some electrochemical potential energy (⇨voltage)
- Power conversion efficiency is about 25% for the best single junction solar cells.

Energy consumption per capita in Western Europe ~ 5 kW
Mean solar irradiance in Southern Britain ~ 125 W m^{-2}
What land area is needed to supply the energy needs of a city of 10 million people using solar irradiation:

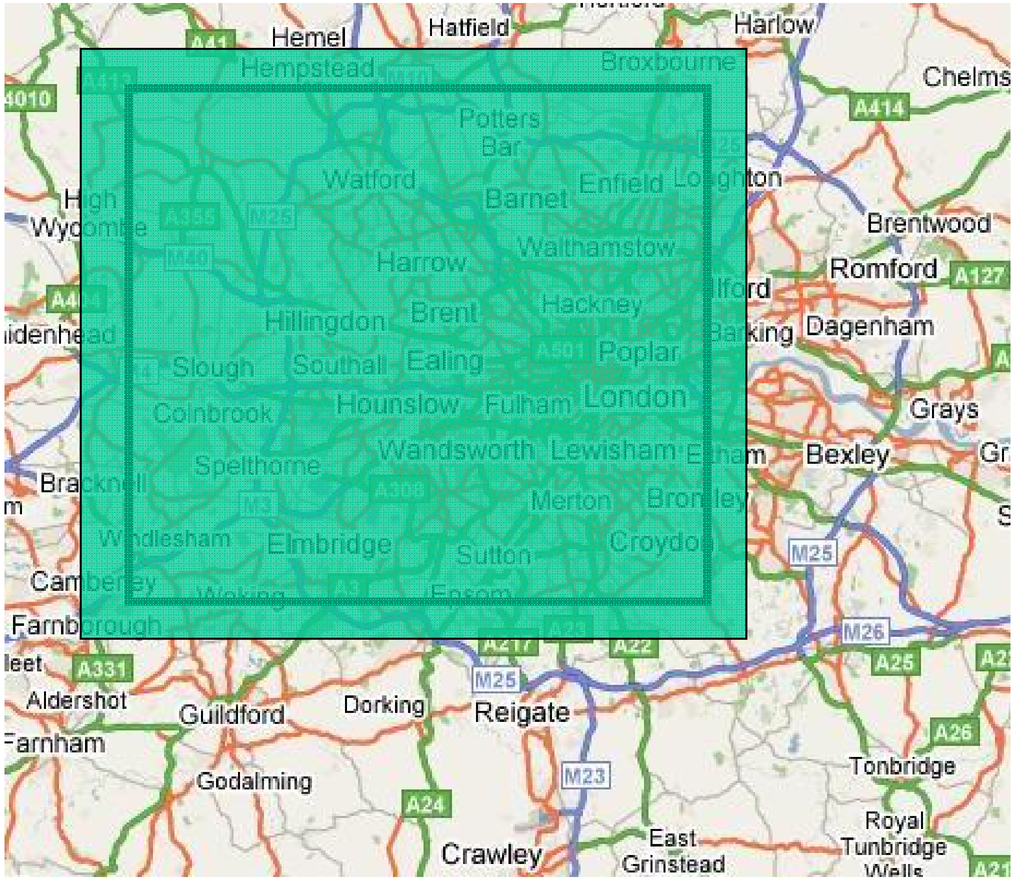
(a) with conversion efficiency of 50%?

$10^7 \times 5000/(125 \times 0.5)\ m^2$
$= 8 \times 10^8 = 800\ km^2$

Energy consumption per capita in Western Europe ~ 5 kW
Mean solar irradiance in Southern Britain ~ 125 W m^{-2}
What land area is needed to supply the energy needs of a city of 10 million people using solar irradiation:

(b) with conversion efficiency of 5%?

$10^7 \times 5000/(125 \times 0.05)\ m^2$
$= 8 \times 10^8 = 8000\ km^2$



Imperial College London

Device physics of solar cells

- Physics governed by charge continuity

$$\frac{1}{e}\frac{dJ}{dx}+G-R=0$$

- Generation G = light absorption rate

$$G=\alpha b_{sun}e^{-\alpha x}$$

- Recombination R usually linear

$$R=Bnp\approx\frac{n}{\tau}$$

- Current density J Dominated by minority carrier diffusion.

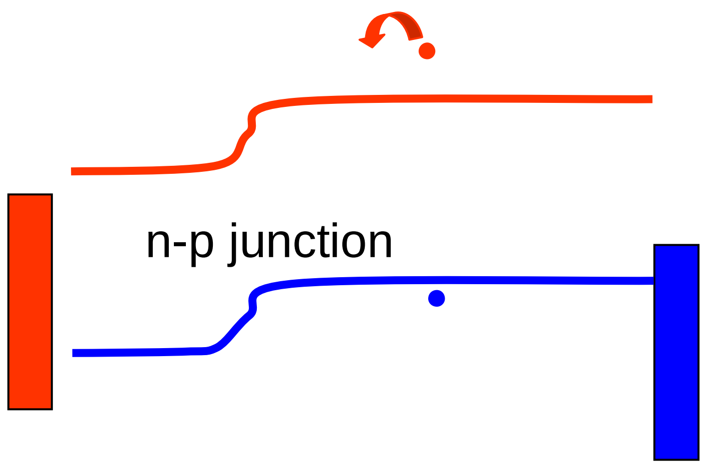
$$J=qD\frac{dn}{dx}+qn\mu\varepsilon$$

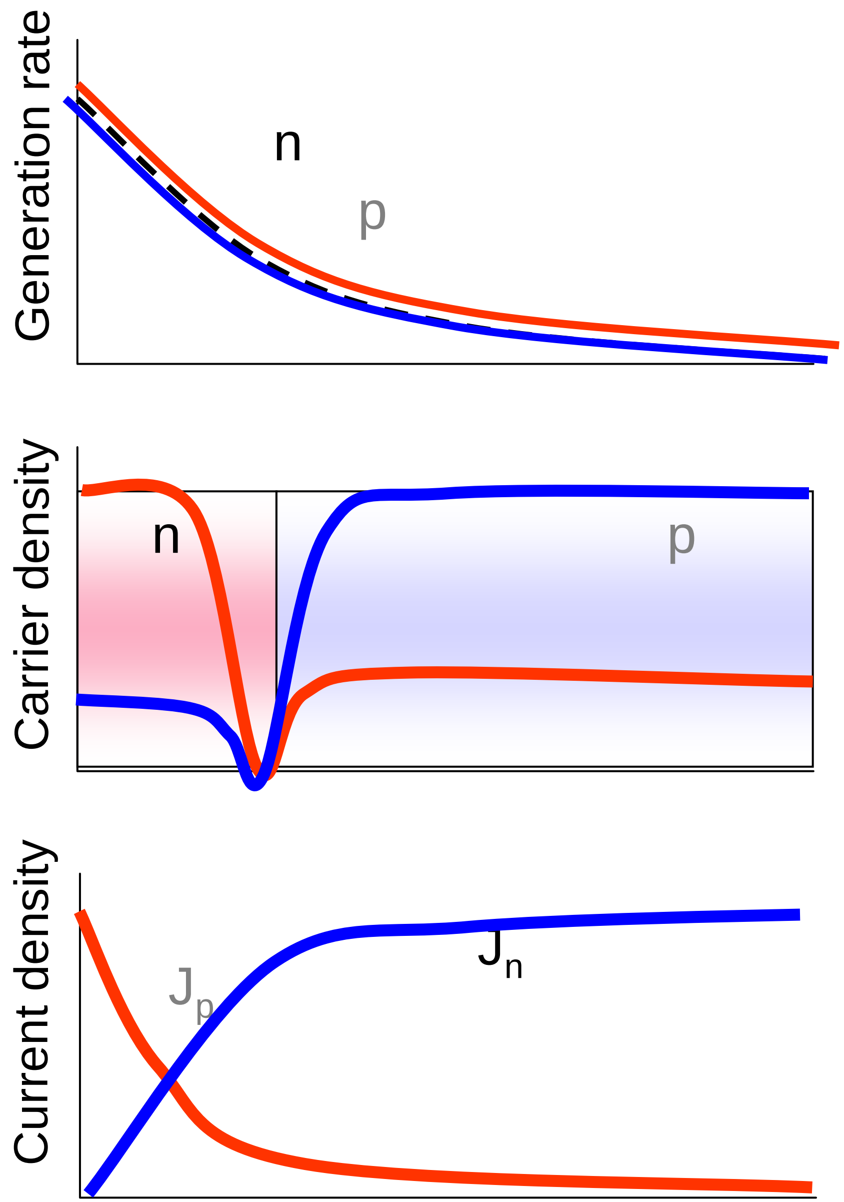
- Differential equation for carrier density

$$D_n\frac{d^2n}{dx}-\frac{n}{t_n}=-G$$

- Boundary conditions

$$n(0)=n_0e^{V/kT} \qquad J_n(d)=0$$


n-p junction


Generation rate
n
p
Carrier density
n
p
Current density
Jp
Jn

Device physics of solar cells

- Result: diode equation for J-V

$$J = -J_{sc} + J_0\left(e^{qV/mkT} - 1\right)$$

- Important parameters:
  - absorption coefficient α, optical depth αd, reflectivity
  - charge diffusion length $L = (D\tau)^{1/2}$
  - type of recombination (e.g. linear, bimolecular, via defect states)
  - parasitic resistances: series R and shunt R (leakage)

Solar cell design

- good optical absorption:
  - Increase thickness
  - Anti-reflection coating, texturing
  - Fine contacts
- efficient charge separation:
  - Increase junction built-in bias, junction area
  - Suppress recombination
- efficient transport
  - Improve material quality
- low electrical losses
  - reduce series resistance

24.4% efficient PERL cell