

Learning objectives in this chapter

- Explain the operating principle of a solar cell
- Know the efficiency and power density of PV
- Know different PV technologies
- Know to apply basic useful formulas

Principle of operation

The operating principle of a solar cell relies on the **direct** conversion :

1) of incident energy of photons (=solar irradiation spectrum, see 'Solar basics' chapter) on a semiconductor (s.c.)

2) into electricity, by the creation of pairs of charge carriers (electrons (n⁻) and holes (p⁺)) in the s.c.

3) and the separation of these thanks to a p-n junction

Reminder of semiconductor physics



- in atoms, electrons (= *particle* + *wave*) are found on precise and confined energy levels (= *s*, *p*, *d*, *f* orbitals => quantum mechanics)
- when closely arranging many identical atoms in a solid (=a crystal), these energy levels combine to form continuous energy bands between 2 energy values; these bands are one of the following:



- *partially filled* (valence electrons, far from the nucleus)
- *empty* (allowed energy levels, but without electrons)



Fermi distribution:

 \rightarrow all these electrons in the solid crystal <u>interact</u>

(i) with each other,

(ii) with the nuclei,

and due to the Pauli exclusion principle

(= no 'free' occupation on the available energy levels, and maximum 2 electrons (of opposite spin) on each level),
the density of authorised energy levels for the electrons in
the confined crystal volume is given by the Fermi distribution
(different from that of 'free' molecules in a gas, which is given by the Maxwell-Boltzmann energy (speed) distribution)

 \rightarrow number dN of electrons in the energy level interval E+dE :



Electrical conduction in a solid

When an electric field acts on a solid, only electrons close to the Fermi level (= weakly bonded) acquire energy (kinetic, translational), and can hence conduct electricity, but only when they are in a partially filled energy band, and if the Fermi level is located in this band (which is the typical case for a **metal**; which is why metals conduct electricity)

Semiconductor

- for a semiconductor (f.ex. Silicium, Si), the Fermi level E_F is located between 2 bands
- above $E_F =$ **conduction** band *bc* (*empty*), $3sp^{3*}$
- below E_F = valence band bv (full) (filled with the 4 valence (=outer) electrons of each Si atom) 1s² 2s² 2p⁶ 3s² 3p²



- \rightarrow electrical conductivity of semiconductors
 - = 10^{5} - 10^{10} times lower than metals (the *bv* is already full)
 - = increases with temperature (contrary to metals)

(since some electrons will populate the free *bc* when they acquire thermal energy)

Fermi level : *intrinsic* semiconductor vs. *doped* semiconductor





Example of silicon doping of p-type and n-type

Both p- and n-layers are <u>electrically</u> <u>neutral</u>, yet n-type silicon has excess **mobile** electrons and p-type silicon has excess **mobile** holes



Sandwiching the two layers together creates a **p-n junction** at their interface, which creates an internal electrical field, necessary to keep electrons and holes separated => P.V.

Let
$$n_c$$
 be the number of **mobile electrons**,
 p_v the number of **mobile holes**,
 N_c the number of levels for electrons e⁺,
 P_v the number of levels for holes p^+
 $n_c = \int_{k_c}^{\infty} 2g_c(E) \frac{1}{1 + exp\left[\frac{E - E_F}{kT}\right]} dE$ et $p_v = \int_{-\infty}^{\mu_c} 2g_v(E) \frac{1}{1 + exp\left[\frac{E_F - E}{kT}\right]} dE$
 $n_c = \int_{k_c}^{\infty} 2g_c(E) exp\left[\frac{-(E - E_F)}{kT}\right] dE = \int_{k_c}^{\infty} 2g_v(E) exp\left[\frac{-(E - E_C)}{kT}\right] dE exp\left[\frac{-(E_C - E_F)}{kT}\right]$
 $n_c = N_c \cdot exp\left[\frac{-(E_C - E_F)}{kT}\right]$ et analog ue $p_v = P_v \cdot exp\left[\frac{-(E_F - E_V)}{kT}\right]$
 $n_c p_v = N_c P_v exp\left[\frac{-Egap}{kT}\right] = const = n_{intrinsèque}^2$
 $\frac{n_c}{p_v} = \frac{N_c}{P_v} exp\left[\frac{-(E_C - E_F)}{kT} + \frac{-(E_F - E_V)}{kT}\right] = \frac{N_c}{P_v} exp\left[\frac{2E_F - E_C - E_V}{kT}\right]$
 $E_F = \frac{E_C + E_V}{2} + \frac{kT}{2} ln\left(\frac{n_c}{p_v}\right) + \frac{kT}{2} ln\left(\frac{P_V}{N_c}\right)$
for s.c. intrinsic: 1 1

The Fermi level is located exactly midway between by and bc

 \Rightarrow an intrinsic semiconductor is a poor electrical conductor f.ex. Silicon : $n_{intrinsic} = 10^{10} e^{-1}/cm^{3}$, but 5.10²² atoms/cm³, hence 2.10⁻¹³ mol e⁻¹⁰ => $\rho = 10 k\Omega cm$

Doping of a semiconductor

Doping
$$\mathbf{n} : \mathbf{n}_{c} \gg \mathbf{p}_{v}$$
 $\mathbf{n}_{c} = \mathbf{N}_{c} . \exp\left[\frac{-(\mathbf{E}_{C} - \mathbf{E}_{F})}{kT}\right] \text{ donc } \mathbf{E}_{F} = \mathbf{E}_{C} + kT \ln\left(\frac{\mathbf{n}_{c}}{\mathbf{N}_{c}}\right)$

The Fermi level is very close to the **<u>conduction</u>** band *bc*

Doping
$$\mathbf{p} : \mathbf{p}_{v} >> \mathbf{n}_{c}$$
 $p_{v} = P_{v} . exp\left[\frac{-(E_{F} - E_{V})}{kT}\right]$ donc $E_{F} = E_{V} - kT \ln\left(\frac{p_{v}}{P_{V}}\right)$

The Fermi level is very close to the valence band bv

f.ex. <u>2 ppm</u> P⁵⁺ or B³⁺ = 10¹⁷ atoms/cm³ = 10¹⁷ e⁻/cm³ $p = 0.3 \Omega cm$

→ ... which is why we need clean rooms in s.c. manufacturing!

Solar spectrum - see 'Solar basics' chapter

 Energy of photons is given by the Planck equation : E_{photon} = h_V = hc/λ h = Planck' s constant = 6.6262 10⁻³⁴ Js c = speed of light = 3.10⁸ m/s λ = wavelength (m) and v = frequency (s⁻¹)



- From this irradiance, 29% is reflected, the rest absorbed (39% by oceans, 22% by atmosphere, 10% by continents) => 1 kW/m² at the zenith
- depends on latitude + season: for Lausanne: 750 W/m² in summer, 360 W/m² in winter
- solar energy is *direct* (=sunny weather) and *diffuse* (=cloudy weather)
- Swiss year average : 140 W/m² (day and night)

Band-gap

- When irradiating a semiconductor, photons with energy E_{photon} ≥ E_{bandgap} excite electrons from *bv* to *bc*, thereby creating a charge carrier pair (e⁻, p⁺)
- The following relation applies : λ (nm) * E_{bandgap} (eV) = 1240 $h\nu$



Different PV materials have different energy band gaps (E_{gap})

Material	E _{gap} [eV]
Silicon	1.11
Gallium arsenide	1.43
Aluminium- Gallium arsenide	1.70



Photons with energy > the band gap energy are absorbed to create Photons with less free electrons and energy pass through holes the material without PV effect Electron-+ Hole

Band *bending*: (1) junction between s.c. and metal



Explanation:

- charge exchange between **Me** and **s.c.** until equilibrium
- compensated by an internal electrical field
- a single Fermi level exists at equilibrium
- a charged 'double layer' develops, with potential difference $\Delta \phi$ = $\phi_{Me} \phi_{sc}$
- from Poisson's equation, we know that:

 $\nabla \phi = d\phi^2/dx^2 = -4\pi q(x)/\epsilon_0$ (ϵ_0 = dielectric constant), i.e.

a charge distribution q(x) is associated with this potential difference, which extends solely into the s.c. (=space charge layer)

(since the metal conductivity is much higher)

=> band-'bending'

Band *bending*: (2) junction s.c / s.c (p-n, diode)



before junction



potential

further

barrier for

charge flow

 \mathbf{p}^+

E_F

(-)

n⁻

- charge exchange (e-,p+) occurs across both bands *bc, bv* until equilibrium is reached (=the Fermi levels equalize)
- an internal field exists (=a voltage barrier) which opposes the natural charge flows of e⁻ (←) and p⁺ (→)

With an applied voltage V, it follows:



Forward bias (direct bias)

- V_{applied} = positive between p and n (=anodic)
 (= counteracting the band bending, reducing the internal electric potential)
- electrons from s.c. (n) are drawn into s.c. (p) (= the natural charge flow)



Reverse bias (indirect bias)

- V_{applied} negative between p and n (= cathodic)
 (= amplifying the band bending, increasing the internal electric potential)
- electrons from s.c. (**p**) are forced into s.c. (**n**) (= counternatural charge flow)



Side note : Principle of a LED



LED: Light (=photon) Emitting Diode

Εv

CHARACTERISTIC i-V (current-voltage curve) OF A DIODE



Illumination of a p-n diode (= PV solar cell)

- The photon energy $h_{\rm V}$ promotes electrons from bv to bc across the band gap.
- generation of charge carrier pairs

 (e⁻, p⁺) in the *bv* and *bc* bands,
 and separation of these by the
 internal voltage barrier (band
 bending) at the p-n-junction
- electrical current created by light, $h\nu(i_{photo}')$, is thus opposite to the natural charge flow of the pn diode (i_{dark}') $i_{tot} = i_{dark} - O_{photo}$





Animation:













Equivalent electrical circuit, with a consumer (=load)



Diode characteristic: $i_{dark} = i_0 \cdot [exp(e_0 V/kT) - 1]$

short-circuit current ($V_{user} = 0 \Rightarrow V_{diode} = R_s \cdot i_{load} \Rightarrow i_{load} = i_{photo} - i_{dark} - (R_s / R_p) \cdot i_{load} \Rightarrow i_{load} (1 + (R_s / R_p)) = i_{photo} - i_{dark}$

Power from a solar cell ('fill-factor')



Solar cell efficiency



in research: η = 29% (Si), in practice: η = 20-24%

Effect of temperature :

- dV/dT = -2 mV/K
- only small effect on i_{cc} (IRR is more important)
- good location for solar panels = high mountain area (cold; snow albedo (IRR_{effective} = IRR_{incident}*1.3))

i-V characteristic under variable irradiation



Real operation with consumer (=load R)



=> MPP : maximum power point tracking

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Summary of useful formulas

$$V_{OCV} = \underbrace{\frac{kT}{e_0}} \bullet \ln\left[\frac{i_{photo}}{i_0} + 1\right] = V_T \bullet \ln\left[\frac{i_{cc}}{i_0}\right]$$

$$V_{max} = V_{OCV} + V_T \ln\left(\frac{V_T}{V_{max}}\right)$$
 $i_{max} = i_{cc} \left(1\right)$

$$FF = \frac{P_{max}}{V_{OCV} \cdot I_{cc}}$$
$$\eta = \frac{P_{max}}{irradiance \left[\frac{W}{cm^2}\right] * surface}$$

 $-\frac{V_T}{V_{OCV}}$

Solar panels

- series + parallel connection of cells (each cell = 100 cm²),
 f.ex. 30 in series (30 mA/cm² @ 0.5 V) → 15 V x 3 A
- cells are *classified* according to their i_{cc} value
- MPP : maximum power point tracking
- to avoid "hot spots" (= a cell in reverse bias), shunt diodes are used to deviate excess current

f.ex. a tree leaf falls on a cell and blocks the sunlight

PV module assembly









Solar PV power plants

- should be >100 kW_p, to benefit from an economy of scale and an efficient DC/AC inverter
- connection at 400 V
- with batteries, disjunctors, fuses
- existing installations from 100 kW_p to 10 MW_p
 e.g. 10 MW_p (800 x 800 m), load factor 18%, needs IRR of ≥ 1800 kWh/m².yr

Market

- 2 TW_p installed late 2024
- 2000 TWh produced (7% of world electricity)
- consistent growth of >20% / yr
- monopolised by silicon technology

https://www.pv-tech.org/iea-solar-pv-made-up-7-electricity-generation-2024/



Recombinations

=mechanisms of **destruction of charge** carriers (e⁻,p⁺) (=**losses**)

- 1. return of electrons from *bc* band to *bv* band, emitting a photon (luminescense) : this effect is very small in Si
- SRH (Shockley-Read-Hall) : impurities and structural defects capture e⁻ and p⁺ (= recombination centers, occurring in cascade between the *bc* and *bv* energy levels);

 \rightarrow to reduce this effect : <u>ultrapure</u> material is needed (\rightarrow up to **monocrystals**)

 effect Auger (in heavily doped s.c.): the recombination energy is transferred to a third particle (e⁻ or p⁺) as kinetic energy

global recombination rate: ~ $1/\tau_p$ (n-type) or ~ $1/\tau_n$ (p-type) with τ = lifetime of (e- ,p+) : nano- to milliseconds

Solar cell layers, in more detail



Incident photons in Si(p) create the pairs (e⁻, p+), with e⁻ migrating to n and via the external circuit to the anode p⁺ migrating to p⁺ and via the external circuit to the cathode

$$e_{out} = i_n = -e_0 \int_{volume V} (g - r) dV$$
 g : pair generation rate (e,p)
r : recombination rate

$$p_{out} = i_p = e_0 \int_{volumeV} (g - r) dV$$

Theoretical efficiency

In theory : photons are generated at 5760 K (Sun surface temperature) \rightarrow Carnot efficiency with 293K cold source would then be 95% A detailed treatment shows that in practice we find :



Remark :

a high energy photon can create several pairs (e⁻,p⁺) !

A stack of cells with decreasing E_{gap} can increase the efficiency (record = 44%).

PV technology

- Fabrication of high purity Si
- Fabrication of crystalline Si (3 methods)
- Cutting to wafers and cells
- Costs
- Other technologies
 - thin layers (amorphous Si, other s.c.)
 - concentration cells (reflected light multiplication)

PV technologies: an overview



Crystalline silicon (c-Si) modules represent 85-90% of the global annual market today. C-Si modules are subdivided in two main categories: *i*) single crystalline (sc-Si) and *ii*) multi-crystalline (mc-Si).

Thin films currently account for 10% to 15% of global PV module sales. They are subdivided into three main families: *i*) amorphous (a-Si) and micromorph silicon (a-Si/µc-Si), *ii*) Cadmium-Telluride (CdTe), and *iii*) Copper-Indium-Diselenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS).

Emerging technologies encompass advanced thin films and organic cells. The latter are about to enter the market via niche applications.

Concentrator technologies (CPV) use an optical concentrator system which focuses solar radiation onto a small high-efficiency cell. CPV technology is currently being tested in pilot applications.

Novel PV concepts aim at achieving ultra-high efficiency solar cells via advanced materials and photo-chemical processes. They are currently the subject of basic research.

Detailed information on technologies can also be found in the IEA PVPS Implementing Agreement website www.iea-pvps.org

Solar PV value chain



Silicon PV technology

- Silicon : > 85% of the market
- for Si :
 - 40% monocrystalline
 - 25% polycristalline
 - 35% amorphous
- $E_{bandgap} = 1.12 \text{ eV}$ (= close to the optimum of the solar spectrum)
- poor infrared absorption \rightarrow wafer must be thick : 0.3 mm \rightarrow disadvantage: long current path for (e⁻,p⁺)
- must then be ultrapure to avoid recombinations : costly
 - diamond saw: 0.35 mm thick (14 wafers/cm)
 - \rightarrow 50% per wafer high purity Si is lost by sawing!
 - multi-wire saw : 0.15 mm thick (30 wafers/cm)

Ultrapure Si fabrication

- 1) reduction of sand, SiO₂, by carbon : SiO₂ + C → Si + CO₂ 98.7% pure, 1-3 \in /kg
- 2) chlorination: Si + 3 HCl \rightarrow SiHCl₃ (liq.) + H₂ then purification (until 2 ppb) by distillation
- reduction of SiHCl₃ by H₂ (= the reverse of reaction 2) at 1100C: impurities down to 0.1 ppb, powder of 50 €/kg

Crystalline Si (3 methods)

- 1) Czochralski method (costly) : fusion at 1440C, growth of a tube (L=1 m, ϕ =30 cm) for 24 h, Si utilisation of 70%
- 2) floating-zone method (very costly): polycrystalline Si is remolten against a monocrystal (no contamination, no loss), tubes of ϕ 10 cm
- 3) Siemens method (cheapest): molten block of 40x40x40 cm³ is cooled to 1 cm grains (*polycrystalline*)

Cell fabrication, step-by-step

- 1) chemical surface attack by hot NaOH or HF \rightarrow texturisation (20 μ m) to reduce the surface light reflexion from 40% to 15%
- 2) diffusion of phosphorous in the surface (+oxidation at 900C): (n⁻)
- 3) screenprinting of aluminium on the back + fusion (700C) : creation of the p⁺ layer
- 4) deposition of silver-glass on the front (cathode collector) by screen printing
- 5) deposit of silver on the back (aluminium) by screen printing (anode)
- 6) titanium vapor treatment (400C) on the front \rightarrow TiO₂ layer for antireflection (reduced to 1-5%)
- 7) plasma attack to remove n⁻ edges (phosphorous)

Alternative Technologies

- Objectives
 - reduce the cost per module/m² amorphous Si as thin layers
 - increase the efficiency _____

concentration cells

Thin film technology

- lower quality and efficiency, but lower cost Si (6 \$/kg vs. 53 \$/kg)
- short current paths : charge carrier lifetime τ can be short
- **non-saturated Si bonds** (α -Si, Si:H), containing 10% H₂ (1.75 eV) : deposited from SiH₄ plasma at 250C
- 40 μ m thick
- continuous fabrication of the module simultaneously to the cells

Thin film technology

Challenges:

- Iower efficiency (10% in research, 5% in modules)
 - improved by tandem concept (successive layers of < 1 μ m of SiC:H (2eV), Si:H (1.7 eV), SiGe:H (1.3 eV)) : 10% possible)
- intrinsic instability issue (rapid impurification)

Other thin film cells :

- CIS (CuInSe₂, 2 μm, 1.1 eV)
- CdTe (1.5 eV, low cost by screen printing, stable)

Thin film energy generation



Amorphous Si thin film device structure

- pin diode consists of three separate thin a-Si films
- a thin conductive oxide on the glass serves as a window



Amorphous Si vs. Crystalline Si module



Amorphous Si vs. crystalline Si I-V characteristic

Earthscan

Concentrated PV

- small cells of high efficiency
- only direct solar irradiation is used (30-50 "suns" by concentration)
- MPP (track the sun trajectory)
- point cell (Stanford, USA) : 26.5% @ 300 suns
- GaAs (OCV 1 V) : 28% @ 1000 suns
- tandem cells GaAs/GaSb : 33% (Boeing)
- triple junction: 44% efficiency
- secure and inexpensive to develop, high potential for low cost PV

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Concentrator systems



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PV technology overview

Crystalline silicon Mono and multicrystalline

Status: main market share

Thin films CIGS, CdTe, Thin film silicon

Status: increasing market share

Market

Concentrator technologies Mostly III-V based

Status: entering the market, many start-ups Emerging technologies Nano inorganic Organic / Dye sensitized

Status: niche application

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

Best Research-Cell Efficiencies



CINREL



Current performance and price of different PV module technologies*

^{*} percentage share of 2008 market





Source: IEA PVPS.

KEY POINT: Current technologies will co-exist with emerging technologies and novel concepts.

Table 1: Current efficiencies of different PV technology commercial modules

Wafer-based c-Si		Thin films		
sc-Si	mc-Si	a-Si; a-Si/µc-Si	CdTe	CIS/CIGS
14-20%	13-15%	6-9%	9-11%	10-12%



Technologies

- Efficiencies of various technologies:
 - Crystalline (Si: mono and poly):
 - Efficiency: 14-21%
 - Potential: 20-25%



- Thin film (CdTe, CIGS a-Si / μ c-Si):
 - Efficiency: 14-16%
 - Potential: 16-20%
 - Concentrated (III-V-based):
 - Efficiency: 25-30%
 - Potential: 30-50%





Technologies

• Market shares:







Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018

World PV growth

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



Residential application



PV building integration



PV power plant



Mont-Solei (in operation since 1992)

Biggest PV installation in CH till 2005

4500 m² Si cells 720'000 kWhe/yr rated power: 500 kWe around 200 households Cell efficiency: 12-17 % Efficiency of the inverter: 96 % Global efficiency: ~ 11.5 %

real land use * 5

Total occupied surface: 20'000 m²



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Football stadium Power Plant

7'000 panels (12'000 m²) of polycrystalline Si (efficiency : 15%) 1'200'000 kWh / yr (rated power: 1'300 kW) around 400 households



Romande Energie – EPFL Solar Power Plant

(in operation since August 2010)

2 MWe 15 MCHF



In 2012 biggest PV installation in Switzerland, with 20'000 m² of PV and annual production of 2 GWh (~ 3% of EPFL consumption)
Solar shuttle boat





First regular shuttle service of electro-solar tourist boat in Europe; the autonomy of the boat is ensured by batteries that can receive or deliver electricity from/to the grid

Solar ship



World 's largest solarpowered catamaran

102 feet long, 50 feet wide multi-hull vessel

500 m² black PV panels, containing 38 '000 SunPower next generation cells

top speed 27 km/h, seating capacity 50 passengers

Cost: 18 million €

Solar flight



Solar-powered, remotely piloted aircraft (USA, 1988)

7'200 W 6 electric engines (2 h autonomy on battery)

Successful record flight - 80'000 feet, in 1998 - a significant milestone on the way to commercial solar-powered aircraft acting as low-cost complements to satellites (operational flying altitude: more than 20 km)



"Zephyr-6" Solar-Powered Plane, the "eternal flight" plane

UK-built solar-powered plane that has set an unofficial world endurance record for a flight by an unmanned aircraft (14 days and 24 minutes, mid-July 2010)

Extremely thin and light solar panels cover its wings; Zephyr has a lot of surface for solar panels and a lot of lift relative to its 50 kg weight (thanks to a carbon-fiber body)



Solar Impulse

Proposed by Bertrand Piccard, this aircraft achieved the first round-theworld manned solar airplane flight



With 200 m² of PV and 12 % total efficiency of the propulsion chain, the plane 's motors achieve 8 horsepower or 6 kW

= the amount of power of the Wright brothers plane in 1903 Solar Impulse's wings (nearly the wingspan of an Airbus 340) are multifunctional:

they carry load, produce energy, and house an electrical network; they are to be ultra-strong, efficient and light structures



PV in Switzerland

M ²	Туре	Production	Remark
60 mio m ² estimate (assumption: 100 W _p / m ²)	Silicon modules	4.6 TWhe (7%) 6.4 GW installed peak power	
Potential	138 mio m ² on roofs 52 mio m ² on façades	7 TWh (50% roof use) 2.6 TWh (cos∳ factor)	calculated assuming 200 kWh/m ² .yr (20% efficiency)
	island installations	several TWh	
		20% of electricity	

Some estimates go from 30 TWhe to 60 TWhe / yr for Swiss PV potential

Compared to solar thermal installations (CH)

m²	Туре	Thermal prod. in PJ	Remark	
1.55 mio	glazed collectors on house roofs	2.5	space + hot water heating	
160'000	unglazed collectors not always on roofs	0.19	private/public pool heating	
876'000	agricultural collectors on roofs	0.4	for hay drying	
Total : 2.6 mio		3 PJ		
Potential:	138 mio m ² roofs	100 PJ if 50% roof space used	Assumption : 30% eff. 400 kWh/m².yr	
= 30% of space + HW heat				

Potential of PV electricity generation

With 10% efficiency PV panels



Ch. Baillif PV Lab EPFL NE

Market end-use sectors:

- **Residential** (typically <20 kW on individual homes)
- Commercial (typically <1 MW for commercial office buildings, schools, hospitals, and retail)
- Utility scale (starting >1 MW, mounted on buildings or directly on the ground)
- **Off-grid** applications (varying sizes)

These different applications have different system costs and compete at different price levels.

Evolution of photovoltaic electricity generation by end-use sector



Summary

- Solar PV power is commercially available and reliable technology with a **significant potential** for long-term growth in nearly all world regions.
- It is estimated that PV will continue to grow (now 7% of electricity)
- PV achieved competitive parity with the power grid by 2020 in many regions.