Renewable Energy
Lecture 13: Photovoltaic technology

Grade: 4th Class

Dr. Eng. Azher M.Abed

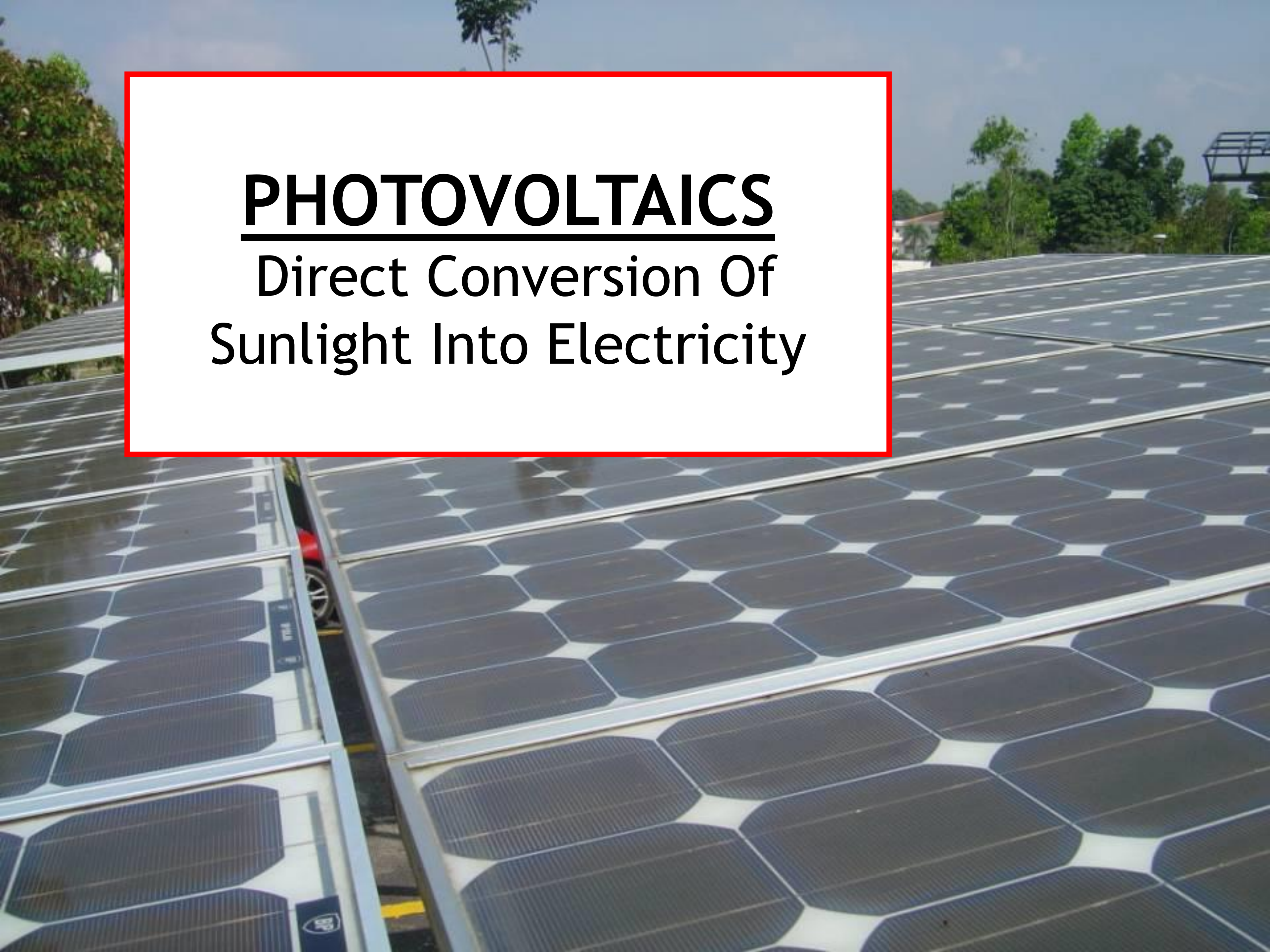
E-email : azhermuhson@gmail.c

CONTENTS

- INTRODUCTION
- FUNDAMENTALS OF PV
- PV SYSTEMS
- BUILDING INTEGRATED PHOTOVOLTAIC (BIPV)
- DESIGN AND INSTALLATION ISSUES
- EXAMPLE-SIZING OF PV SYSTEMS

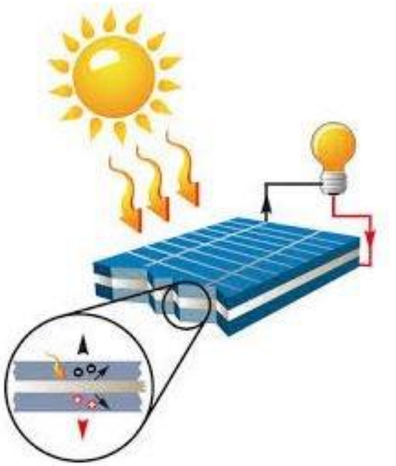
PHOTOVOLTAICS

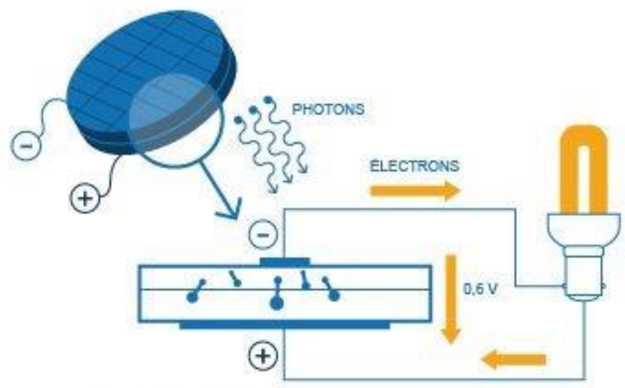
Direct Conversion Of Sunlight Into Electricity



تعريف الفوتوفلتية

تعرف ظاهرة الفوتوفلتية بأنها عملية لتحويل الضوء ضوء الشمس إلى طاقة كهربائية مباشرة باستخدام الخواص االلكترونية لبعض المواد والتى تصنف ضمن أشباه الموصالت Semiconductors مثل السليكون





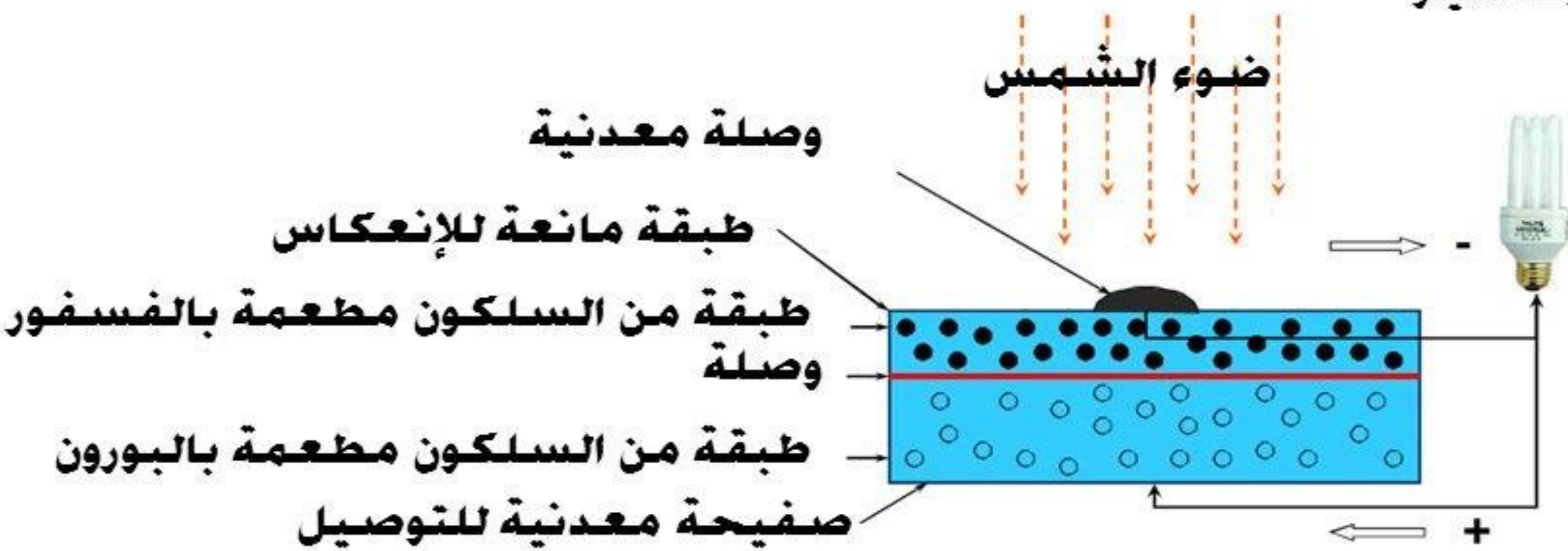
PRINCIPE D'UNE CELLULE PHOTOVOLTAÏQUE.

يتركب مصطلح الفوتوفلتية photovoltaic من جزئين هما:

من ا كلمة photoوالتى تعني الضوء ومن اسم فولتا Volta العالم الفيزيائي اليطالى

طريقة عمل الخلية الشمسية

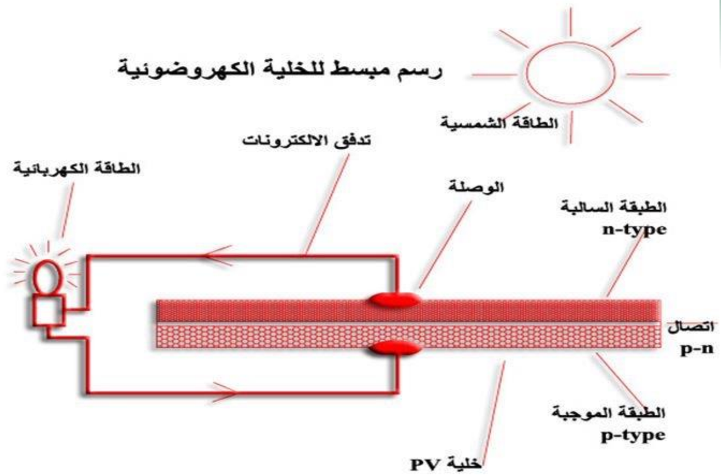
عند تعرض الخلية للإشعاع الشمسي فإن الألكترونات الحرة تمتص " طاقة الفوتونات المكونة للإشعاع الشمسي و إذا كانت هذه طاقة كافية فإنها تعمل على تحفيز الإلكترونات للسريان خلال الموصل المتصل في أطراف الخلية ، بزيادة كثافة الضوء الساقط على الخلية تزداد حركة الإلكترونات ويتولد التيار

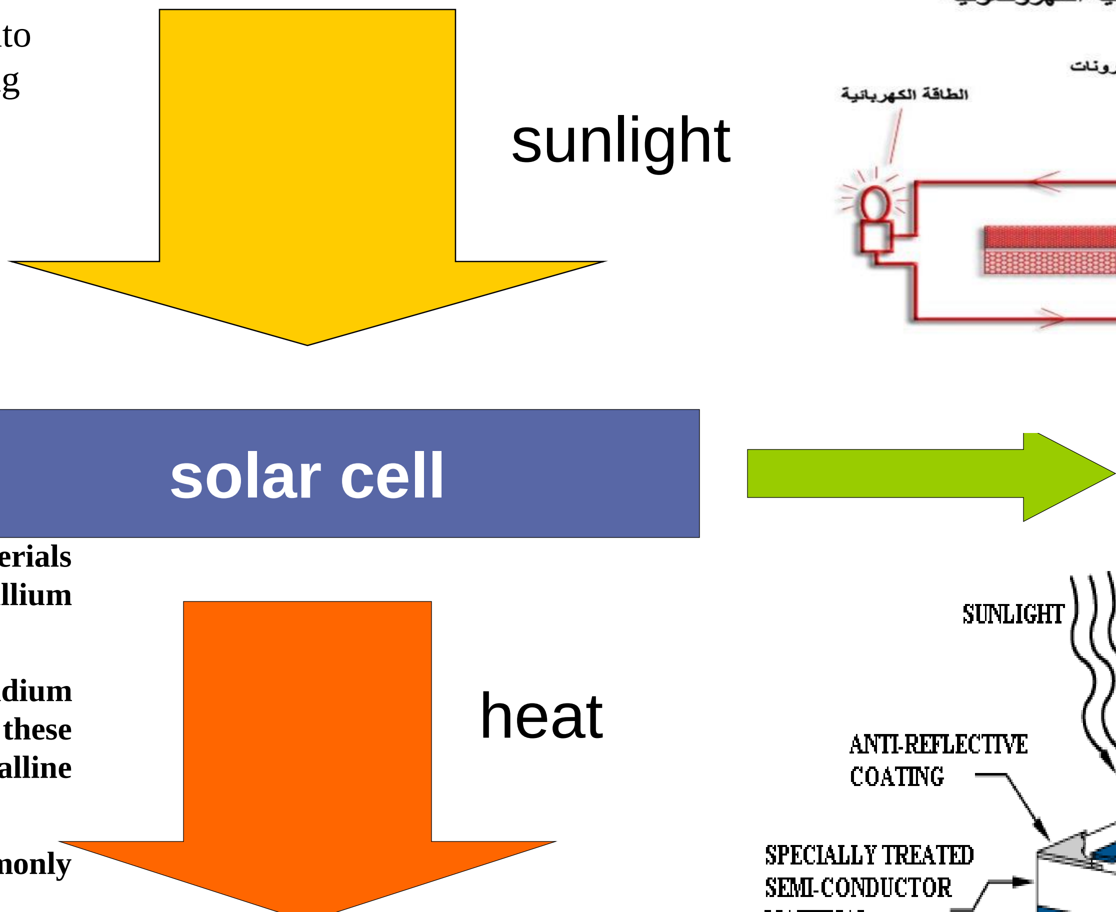


SOLAR CELLS

The term **photovoltaic** means the direct conversion of light into electrical energy using

solar cells

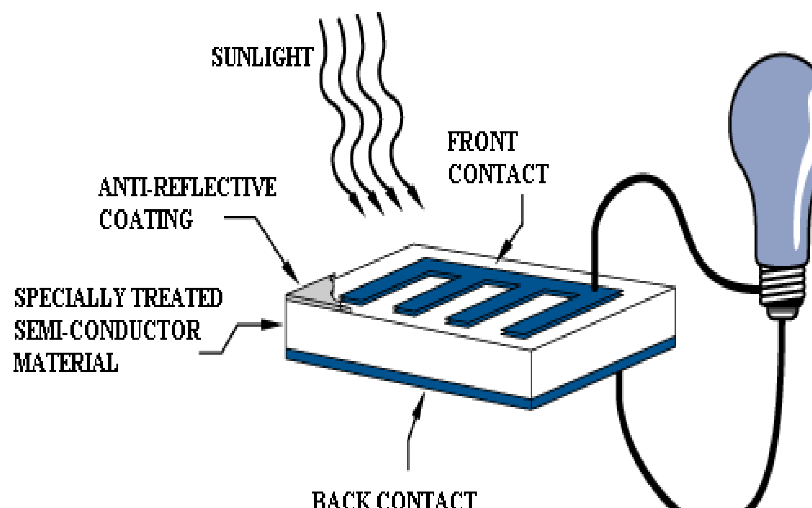




Semiconductor materials such as silicon, gallium arsenide, cadmium

telluride or copper indium diselenide are used in these solar cells. The crystalline solar

cell is the most commonly used variety.



FEATURES OF PV

- **Renewable / sustainable**
- **direct conversion**
  - **quiet**
  - **reliable**
- **Modular**
  - **mW ~ multiMW**

PV EFFECT: BASIC PROCESS AND LOSSES

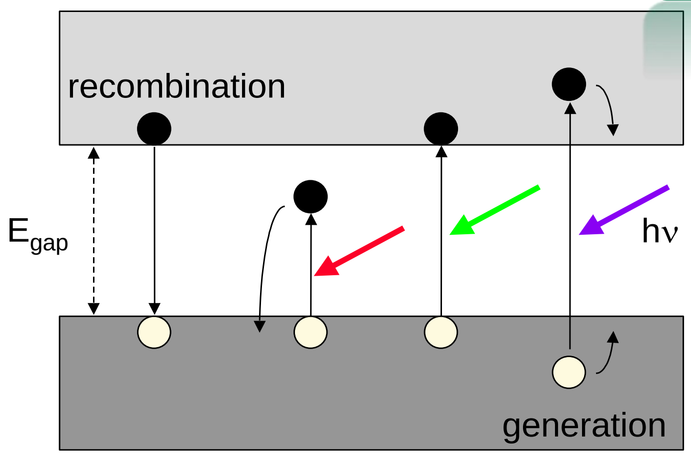
light absorption

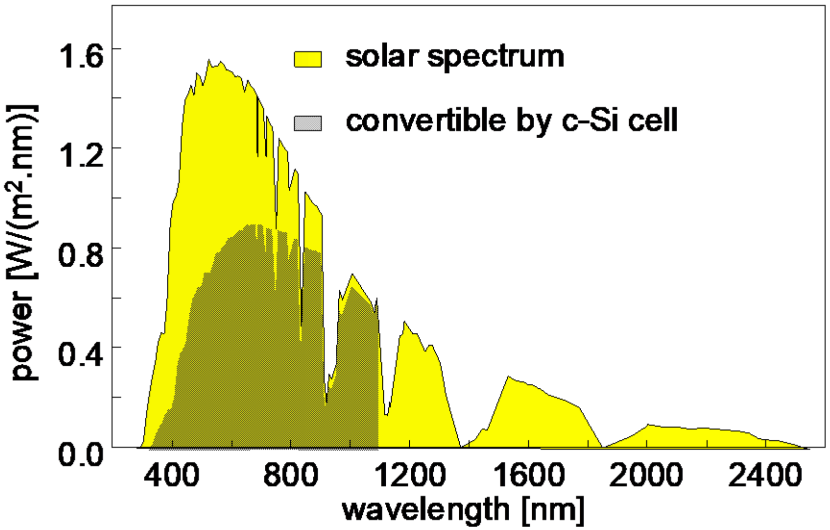
transport of charge carriers

charge separation & collection

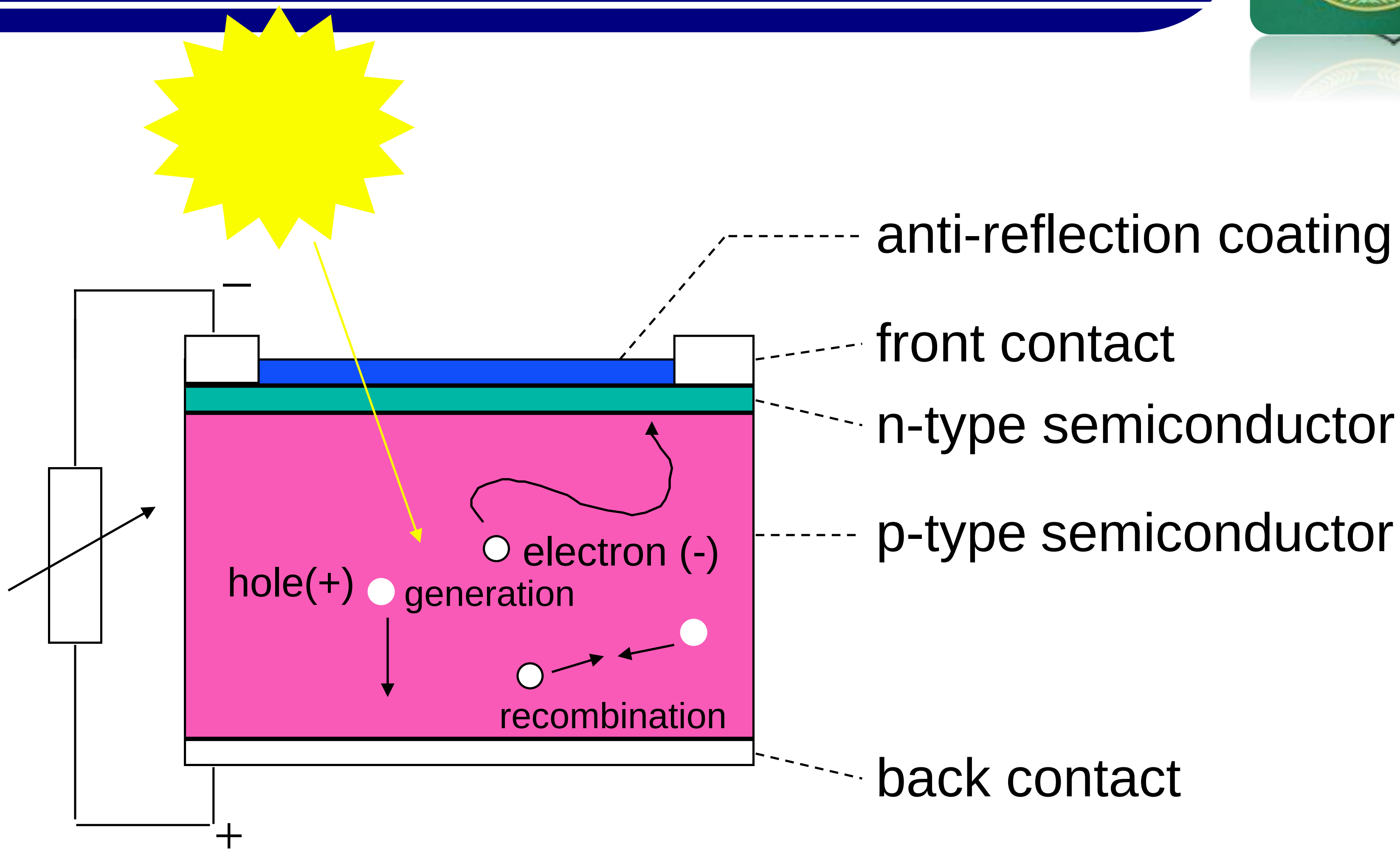
power generation (energy dissipation)

final recombination

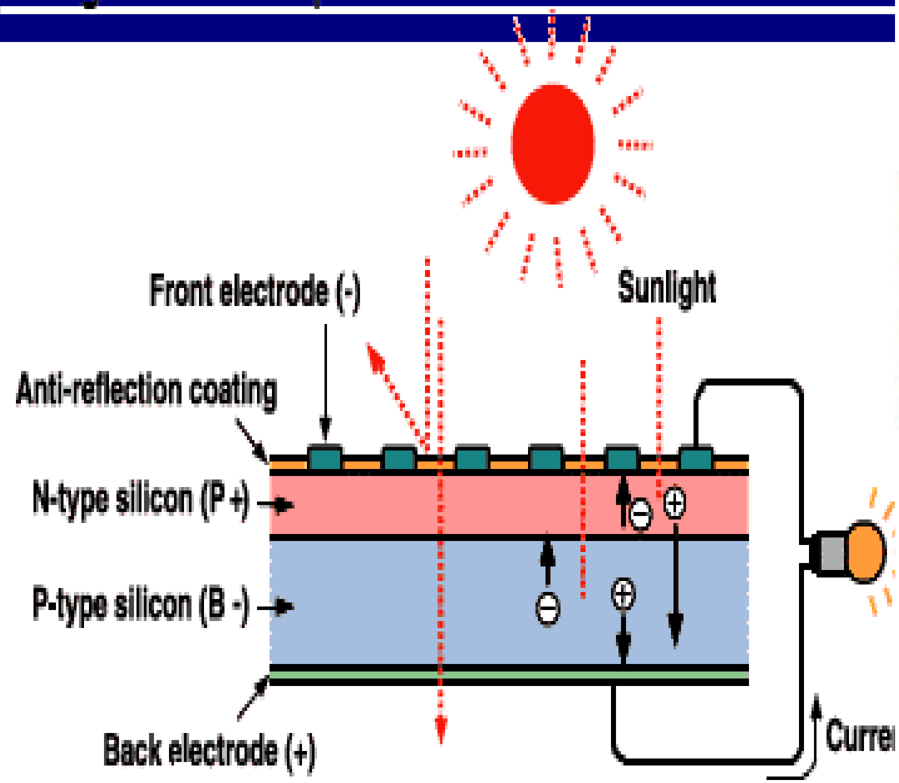




OPERATING PRINCIPLE SOLAR CELL



Solar Cells Absorb the Energy in Photons

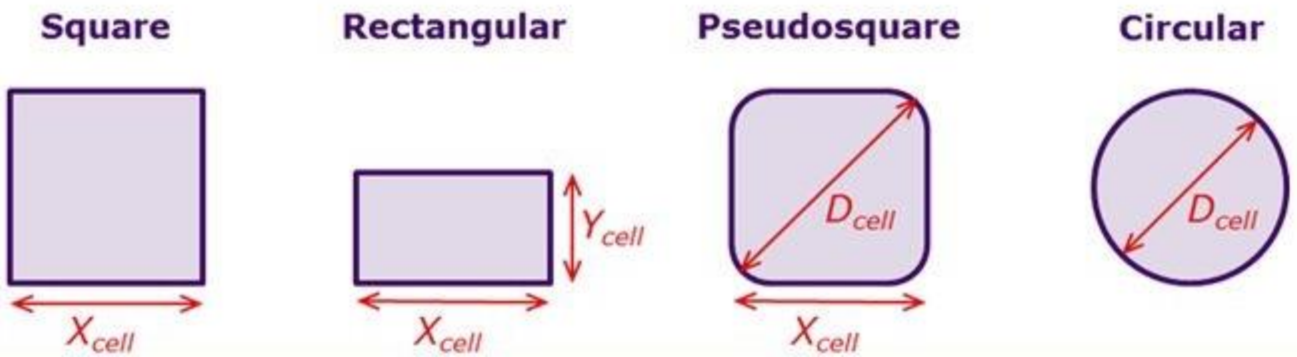


تصنيع الخلايا الشمسية الرقيقة

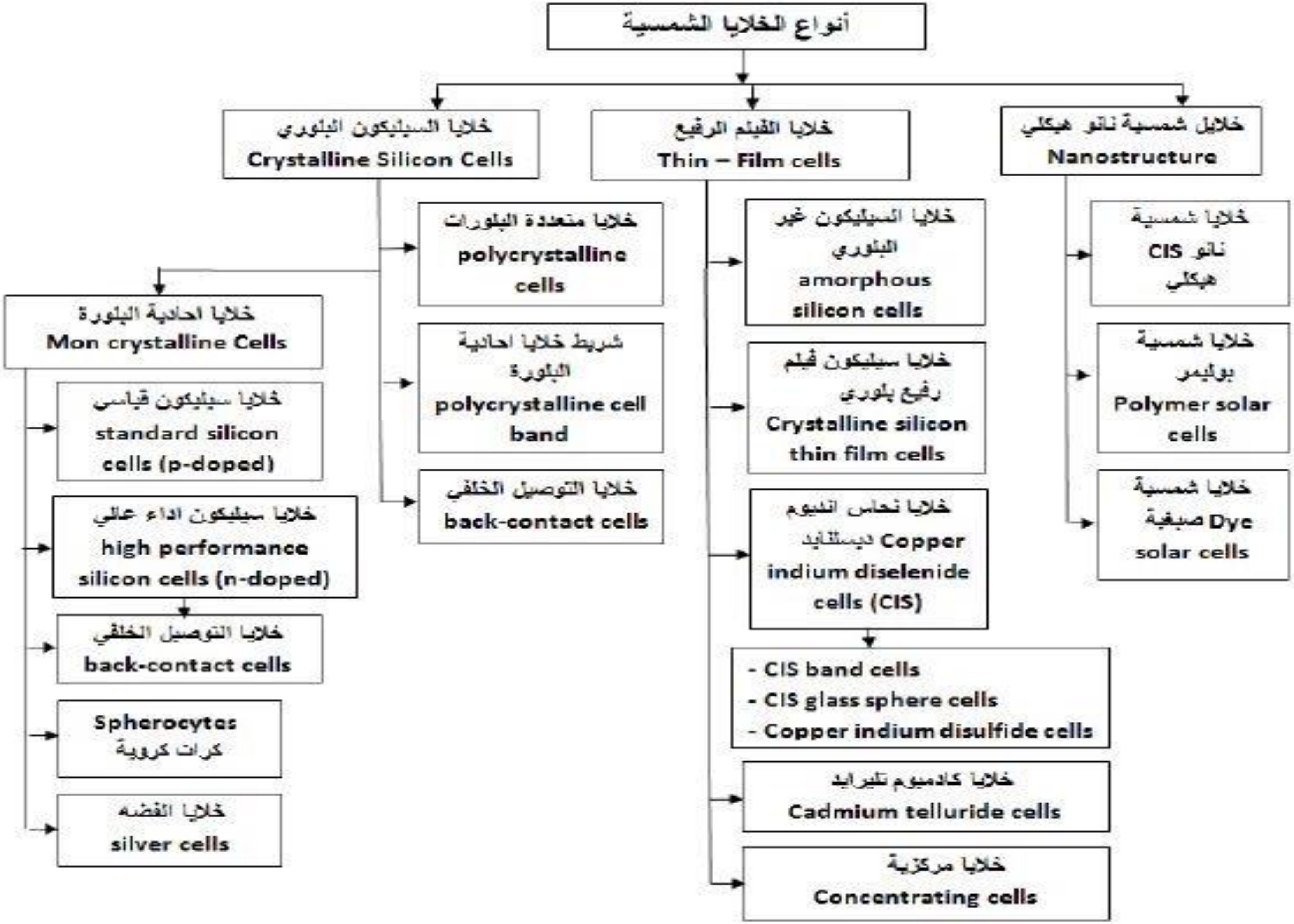
- تصنف الخلايا الشمسية إلى عدة أنواع تبعاً للمادة المستخدمة في التصنيع:
- السليكون البلوري Crystalline silicon
  تعتبر بمثابة مكوناً رئيسياً في منظومات انتاج الكهرباء من الطاقة الشمسية
- تتراوح كفاءة تحويل أشعة الشمس إلى تيار كهربي من 18- 25 %
  وتصل الكفاءة النظرية الى 29%.
- الخلايا الشمسية متعددة الوصل Multijunctions
- وهي غالباً ما تصنع من مادة كاليوم أرسينايد GaAs
- خلايا ذات اتصالين أو ثلاثة وصلات
  تقوم كل طبقة فيها بامتصاص عدة الون من ألوان الطيف الما
- الهدف من الخلايا الشمسية متعددة الوصل هو امتصاص في مجموعها أكبر قدر من الضوء وتحويله إلى كهرباء.
- تتراوح كفاءتها من 30%-35. ويمكن الحصول على كفاءة تزيد عن 42 %
- وتتميز هذه الخلايا بصعوبة صناعتها وكلفتها العالية.
  At $\$200/\text{m}^2$ the capital cost would be $\$1.50/\text{Wp}$
- استخدمت لإمداد الأقمار الصناعية بالطاقة

الخلية الفوتوفلتية cell PV

تم تطوير شرائح السيليكون في بداية الخمسينات وضعها بأشكال
وأبعاد هندسية معينة قادرة على تحويل الطاقة الشمسية إلى طاقة
كهربائية . تعطي من 0,5ـ0,6 فولت و تختلف
شدة التيار حسب مساحة الخلية و شدة الإشعاع وتصنع باشكال
مختلفة وبمقسات مختلفة اشهرها المربعة(125×125)

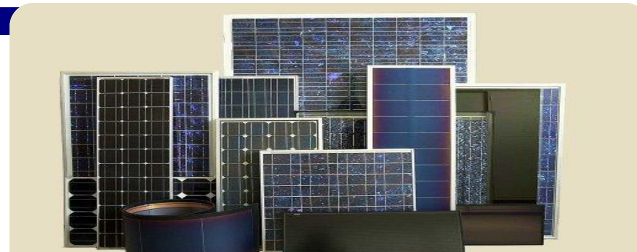


Solar Cell Types



Solar Cell Types

One silicon solar cell produces 0.5 volt



Thin-film technology has always been cheaper but less efficient than conventional c-Si technology.

SILICON BASED SOLAR CELL (90 %)

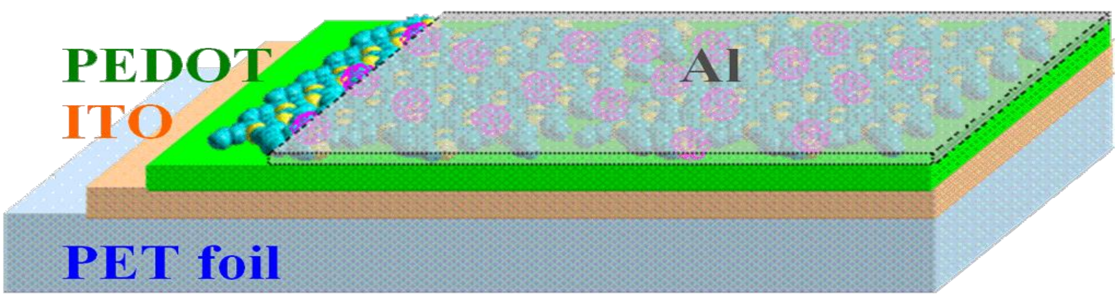
THIN FILM

Cadmium telluride (CdTe), copper indium gallium diselenide (CIGS)

(10 %)

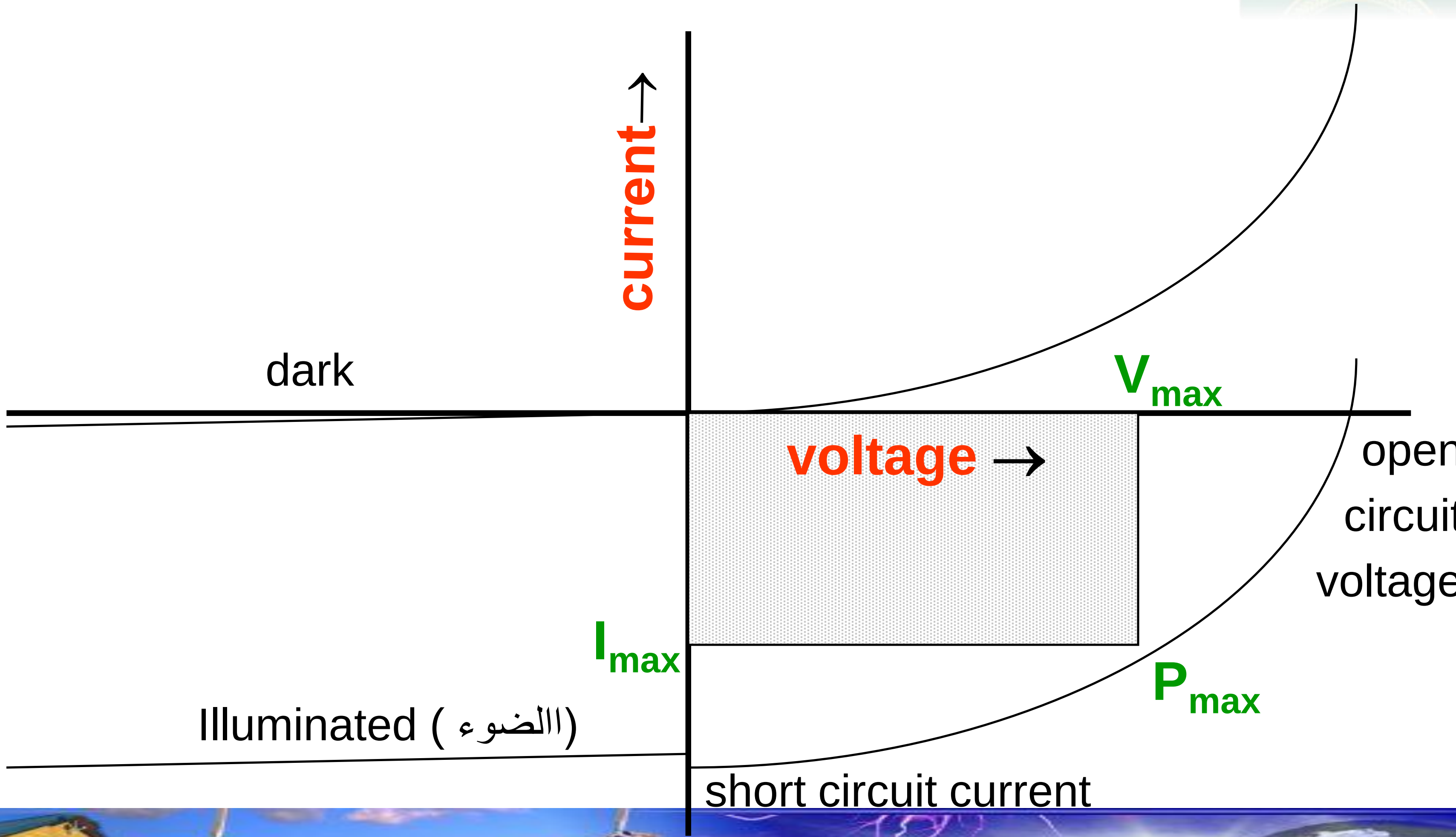
ORGANIC SOLAR CELL

or **plastic solar cell** is a type o photovoltaic that uses organic electronics, a branch of electronics that deals with conductive organic polymers o small organic molecules



Schematic of plastic solar cells. PET – polyethylene terephthalate, ITO – indium tin oxide, PEDOT:PSS – poly(3,4-ethylenedioxythiophene), active layer (usually a polymer:fullerene blend), Al – aluminium.

CURRENT – VOLTAGE CHARACTERISTIC OF A SOLAR CELL



EFFICIENCY AND YIELD

$$\text{efficiency} = \frac{\text{maximum electric power}}{\text{incident illumination power}}$$

at Standard Test Conditions (STC)

$$\text{energy yield} = \frac{\text{electric energy}}{\text{incident solar energy}}$$

under practical conditions

STC: 25 ^{o}C, air mass (AM) 1.5, 1000 W/m^2, $\perp$

EFFICIENCY IDEAL AND PRACTICAL CELLS

- **<u>ideal</u> cells**

loss factor ______________________________ **remedy**

- spectral mismatch
- recombination

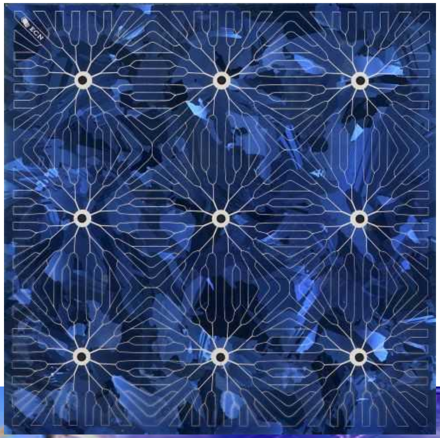
$\left.\right\} \eta \leq 30\%$

- multicolour (tandem) cells
- concentration

$\left.\right\} \eta \leq 85\%$

- **<u>practical</u> cells and modules: add**

- excess recombination
- shadowing & reflection
- transmission
- resistance
- non-optimal band gap(s)



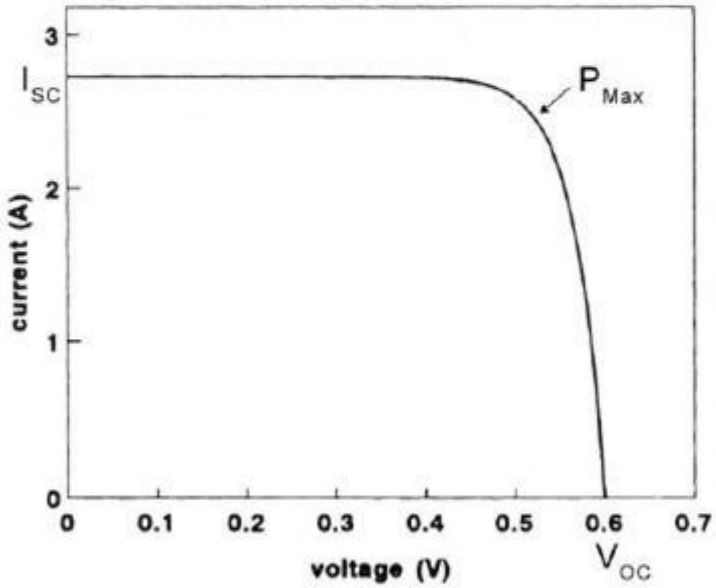
example: multicrystalline silicon cell (15%)

Effect of the Temperature and the Solar Radiation on PV Efficiency

العلاقة بين الجهد والتيار للخلية الفوتوفلتية

توصف الخلية الفوتوفلتية بفرق جهد دائرتها المفتوحة وتيار دائرتها المغلقة ،

فرق جهد الدائرة المفتوحة Voc هو قيمة الفولت الذى تعطية الخلية الفوتوفلتية عندما لا يمر أى تيار بالدائرة ، وهو أقصى فولت تعطية الخلية من الإشعاع الشمسى

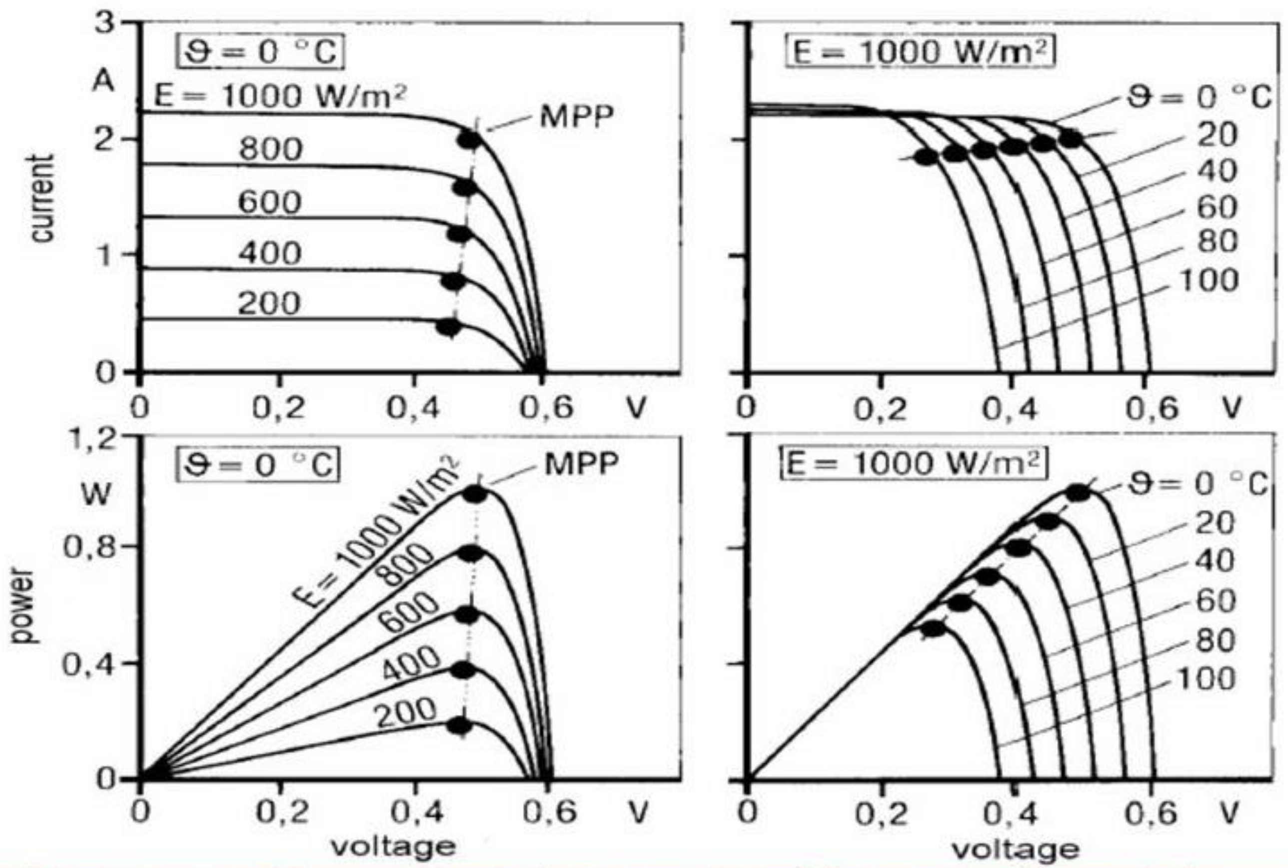


تيار الدائرة المغلقة أو تيار دائرة القصر Isc

هو التيار المار فى الخلية الفوتوفلتية بدون حمل أو مقاومة . وهو أقصى تيار تستطيع الخلية الفوتوفلتية إنتاجة من الإشعاع الشمسى .

Effect of the Temperature and the Solar Radiation on PV Efficiency

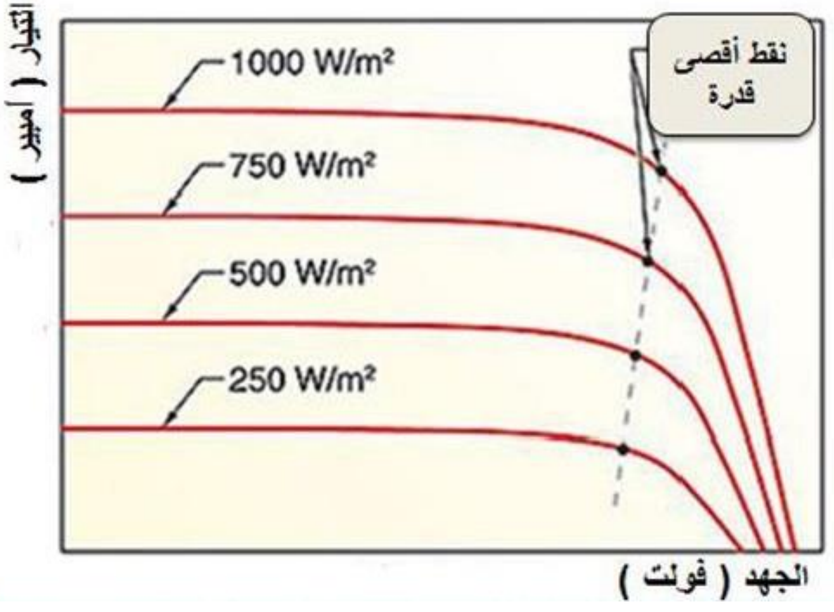
تأثيردرجة حرارة و شدة الإشعاع على منحنيات التشغيل



Effect of the Temperature and the Solar Radiation on PV Efficiency

تغير قيم الجهد والتيار تبعا لتغير الإشعاع الشمسي عند درجة حرارة ثابتة

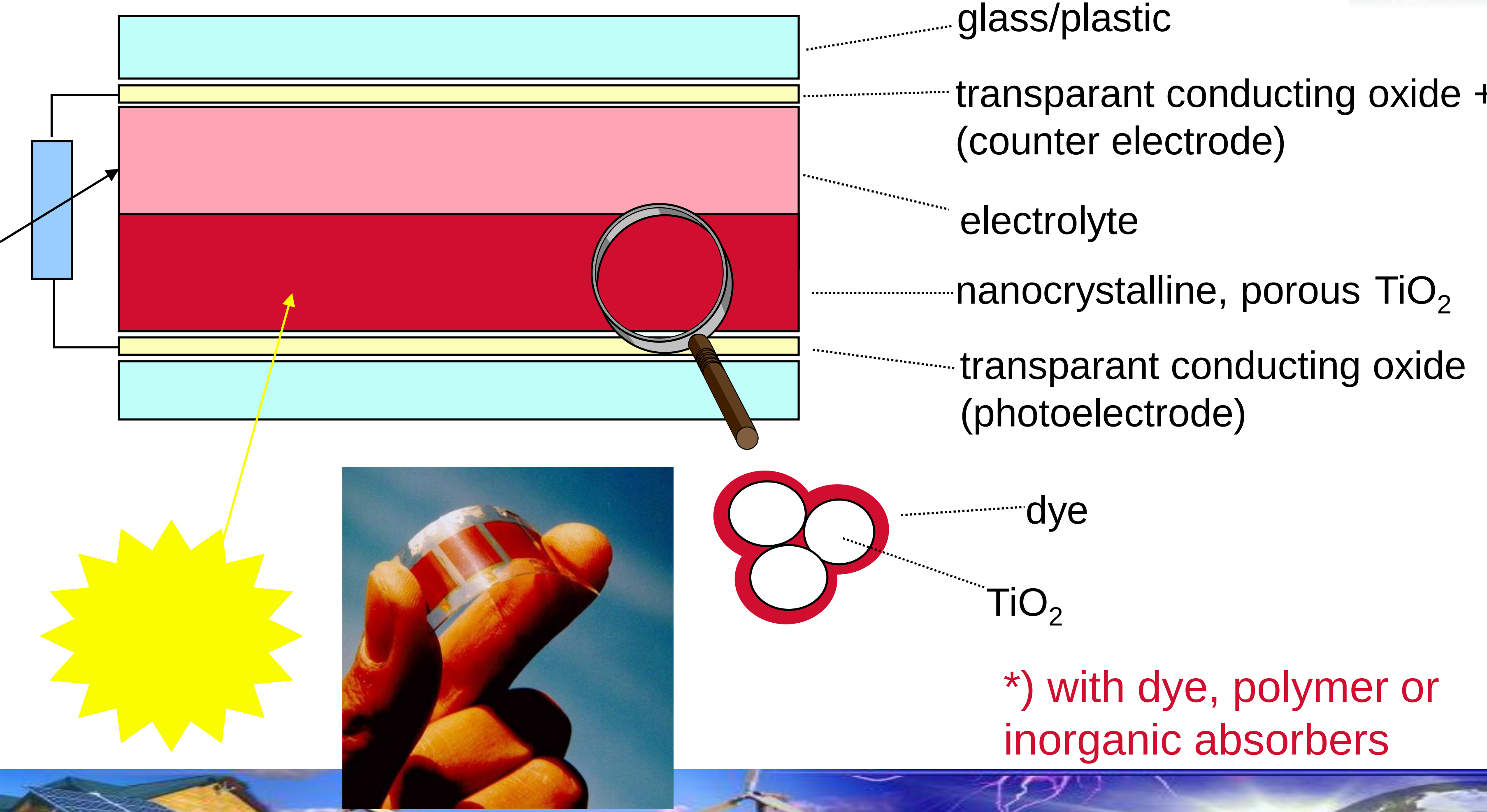
من خلال المنحنيات التالية نلاحظ أن فرق الجهد الناتج من الخلية الفوتوفلتية يظل ثابتا عند كل مستويات الإشعاع الشمسي الساقط لكن التيار الناتج يتغير بشكل مباشر تبعا لقيم الإشعاع الشمسي الساقط عند كل لحظة زمنية .



PV TECHNOLOGIES

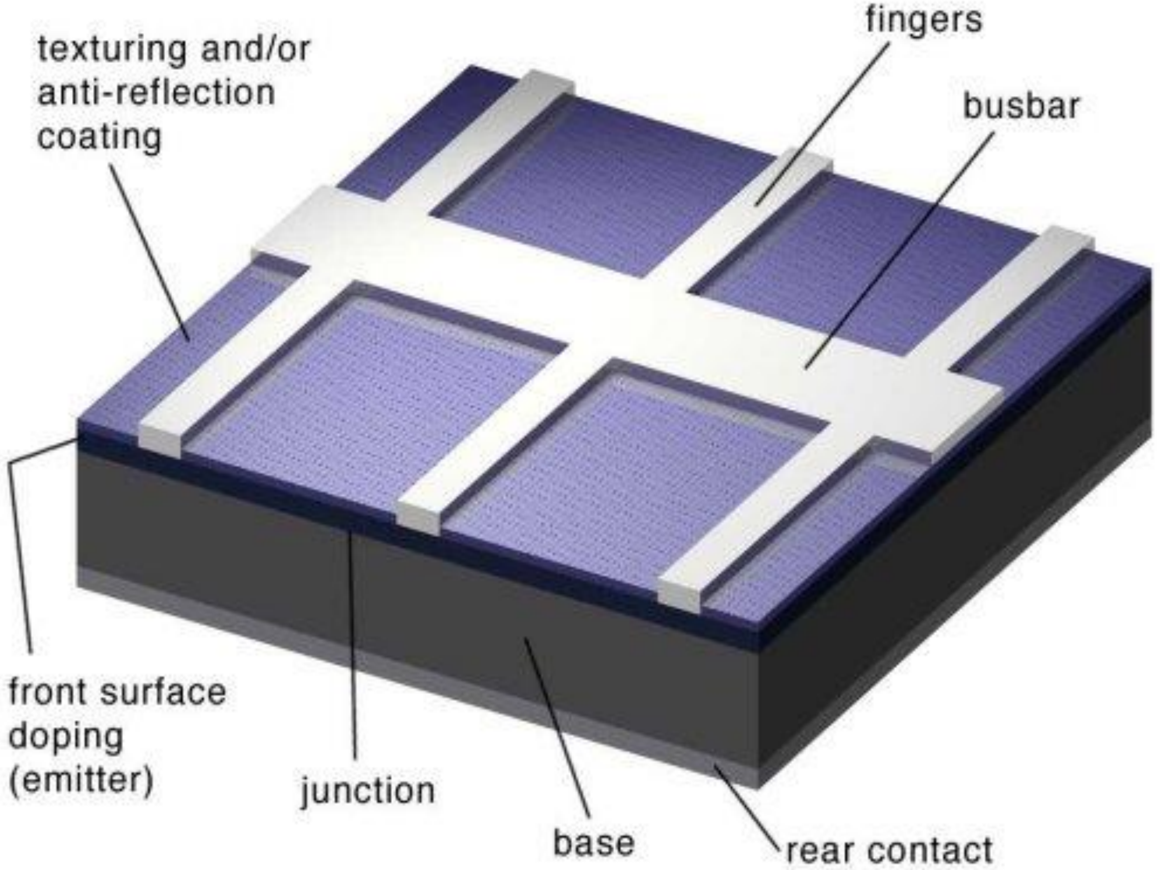
- **commercial**
  - wafer-type crystalline silicon (c-Si; mono & multi)
  - thin-film amorphous silicon (a-Si;
    incl. silicon-germanium and microcrystalline silicon)
- **pre-commercial / pilot production**
  - thin-film cadmium telluride (CdTe)
  - thin-film copper-indium/gallium-diselenide (CIGS)
- **laboratory**
  - sensitized oxides (a.o. dye cells)
  - organic cells (o.a. polymer cells)

PV TECHNOLOGIES
example sensitized*) oxide cell (not to scale)

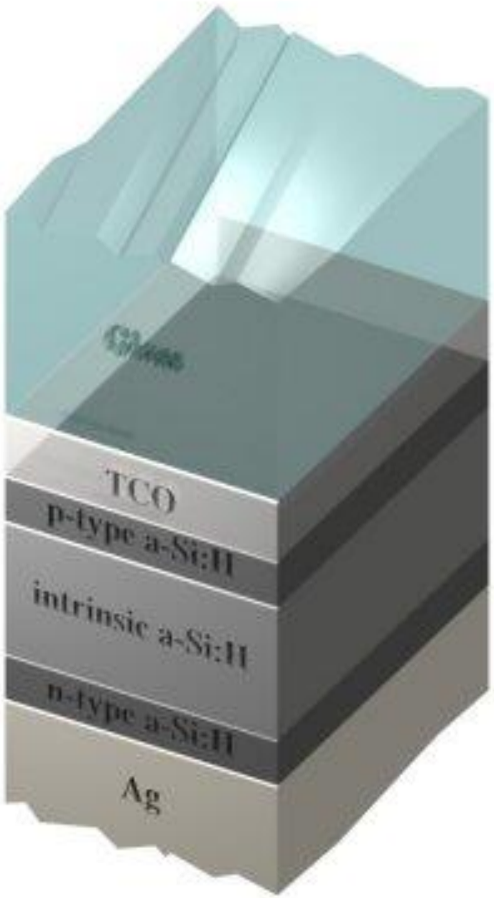


*) with dye, polymer or inorganic absorbers

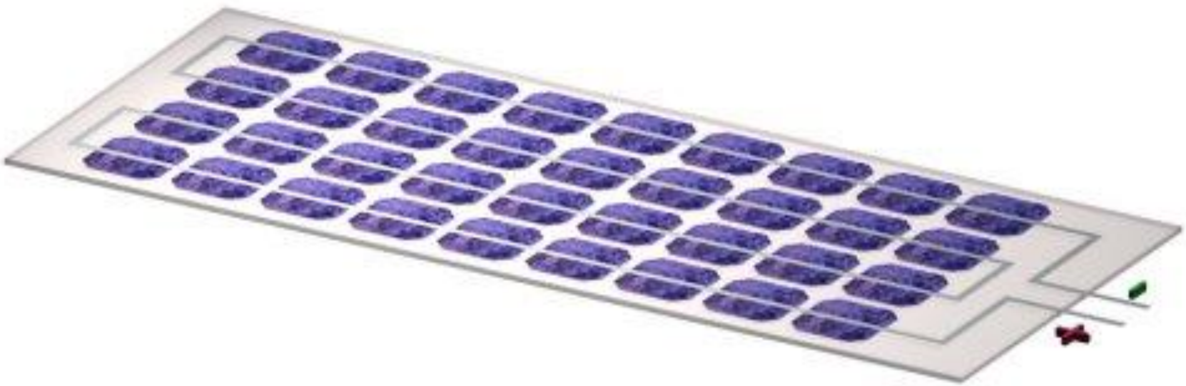
WAFER-BASED SOLAR CELLS



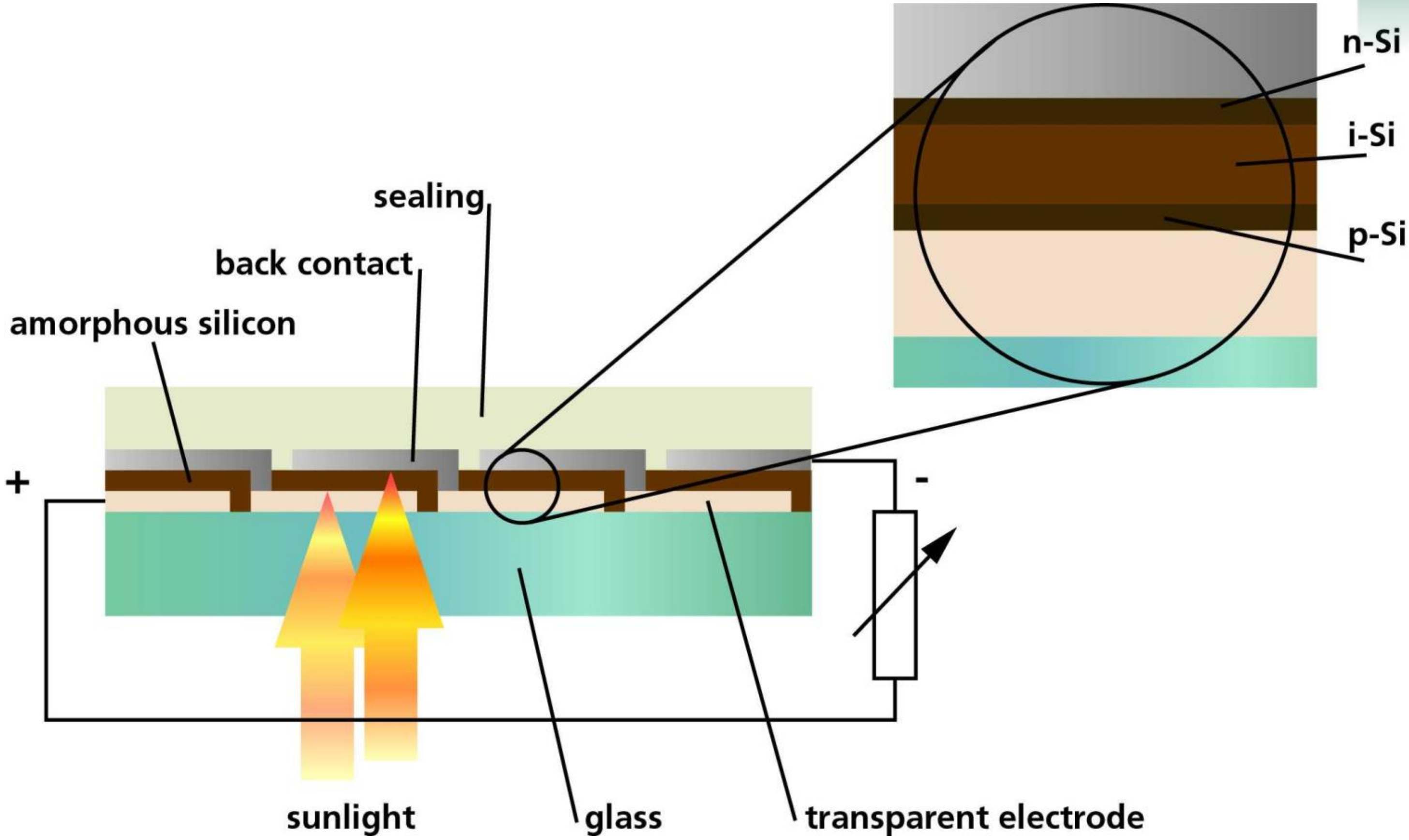
THIN-FILM SOLAR CELL: EXAMPLE a-Si



WAFER-BASED SOLAR CELLS: INTERCONNECTION IN A MODULE

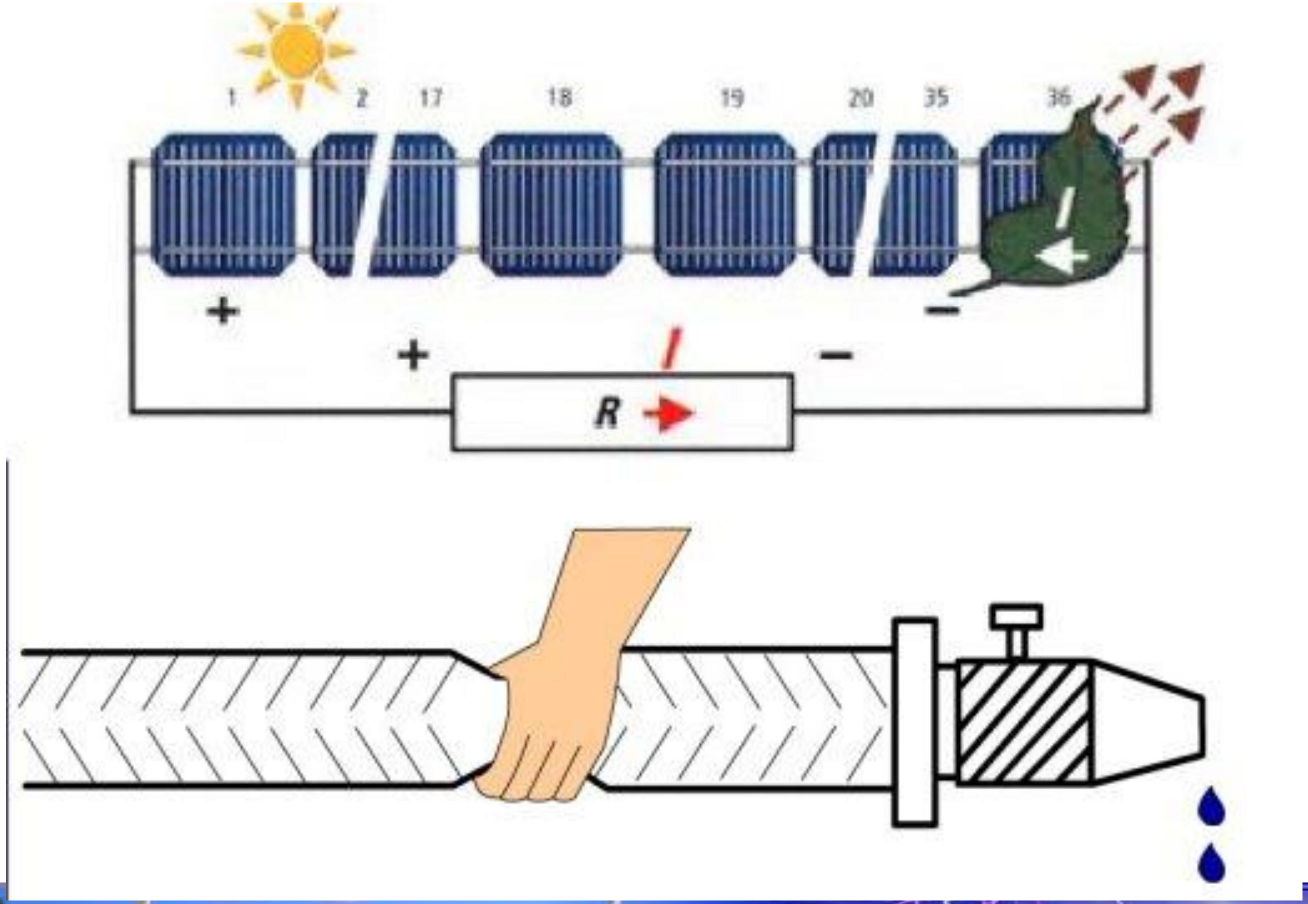


THIN-FILM SOLAR CELLS: INTERCONNECTION IN A MODULE

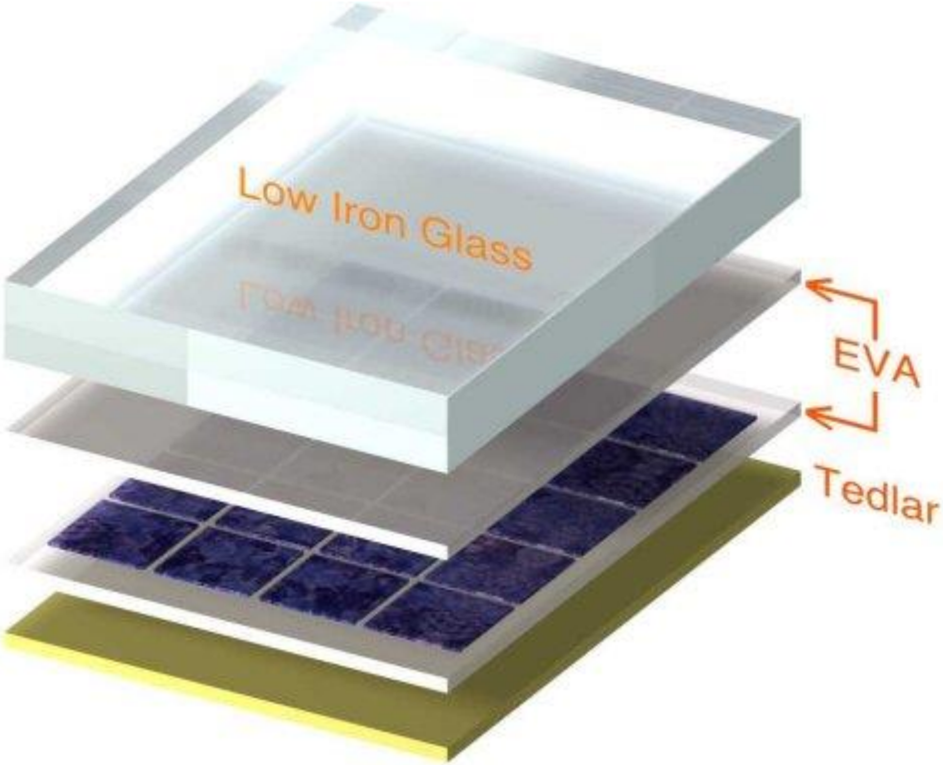


monolithic interconnection in an a-Si module

SERIES CONNECTION IN A MODULE: EFFECT OF PARTIAL SHADOWING



MODULE BUILD-UP: ENCAPSULATION OF SOLAR CELLS



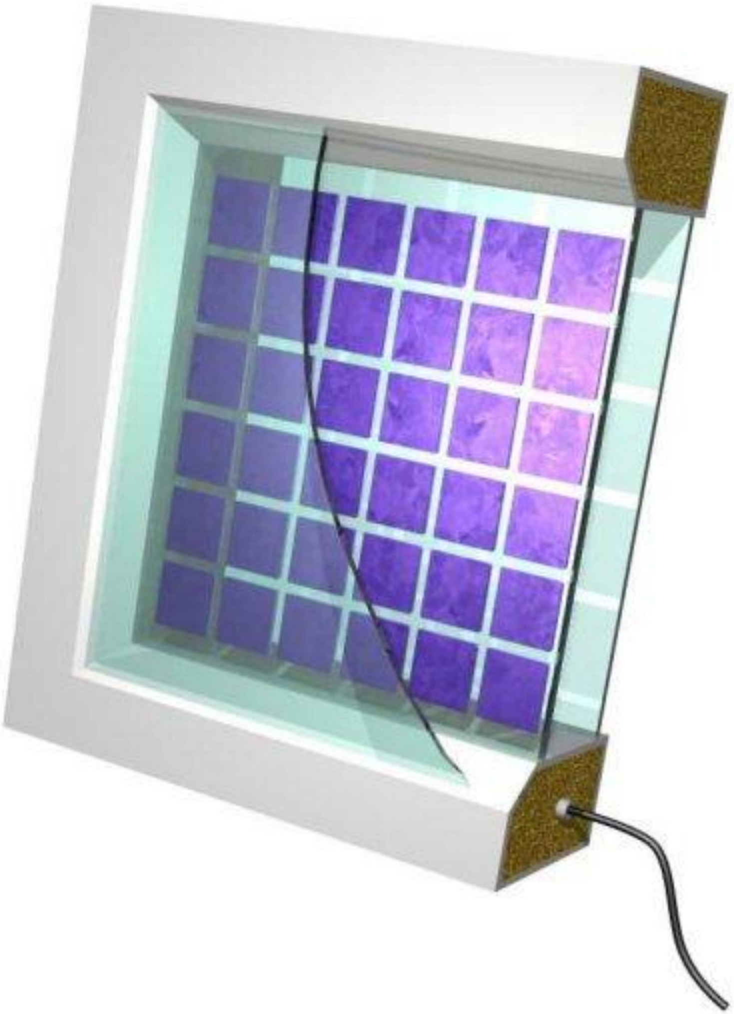
MODULES BASED ON WAFER TECHNOLOGY: CELL DENSITY

COMMERCIAL PV MODULES:
TYPE, SIZE, COLOUR AND FRAMING

COMMERCIAL PV MODULES:
FRAMELESS MODULES (LAMINATES)

COMMERCIAL PV MODULES:
PARTLY TRANSPARENT MODULES

INSULATED (PV) GLASS

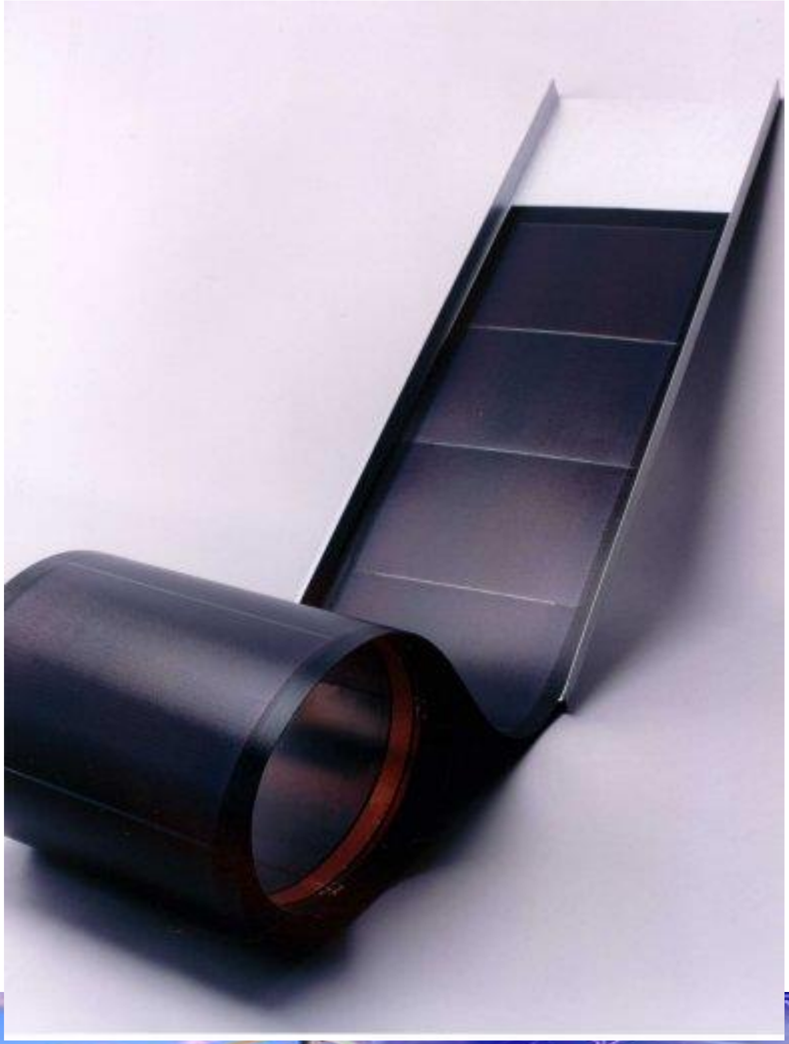


PRECOMMERCIAL PV MODULES: TRANSLUCENT MODULES

window element with a-Si cells

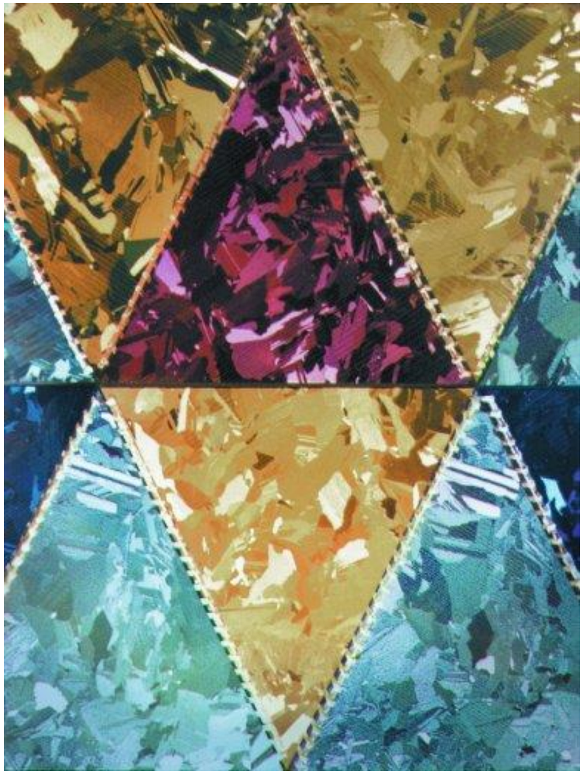
COMMERCIAL PV MODULES: FLEXIBLE MODULES

roofing element with flexible a-Si module



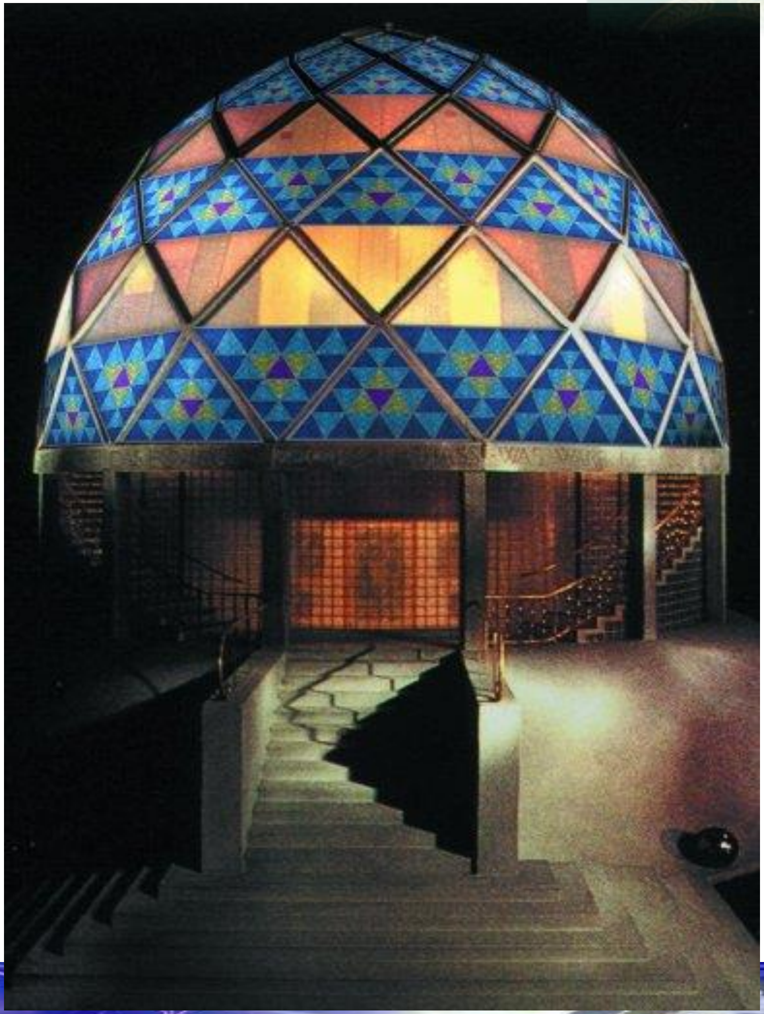
MODULES BASED ON WAFER TECHNOLOGY: SPECIALS

BP SOLAR



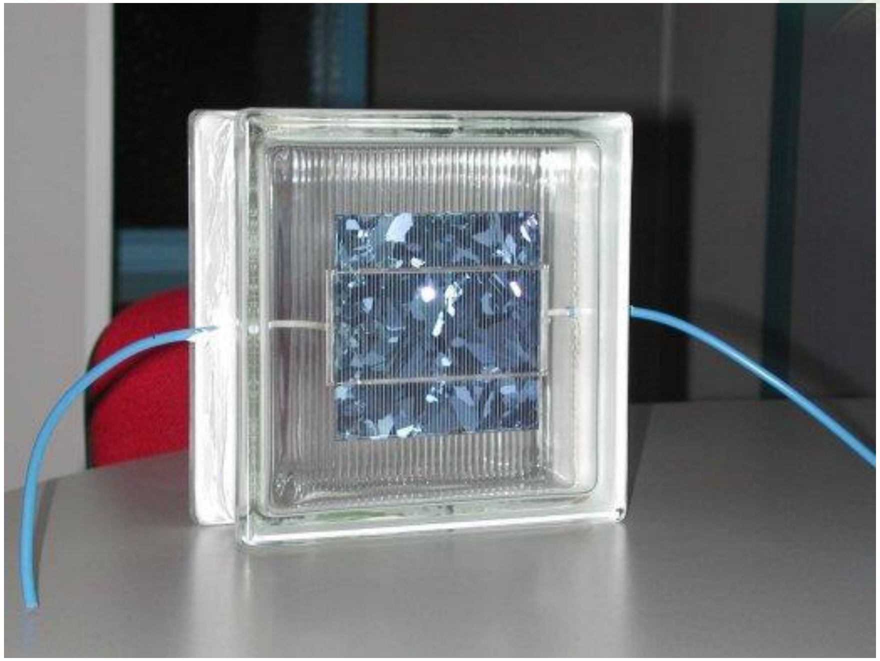
coloured PV cells

note: (15-30% reduced output)



CUSTOM-MADE PV-MODULES

triangular module



PV glass brick

CUSTOM-MADE PV-MODULES

“solar path”

CUSTOM-MADE PV-MODULES

solar chess

PV MODULES & SYSTEMS: RATING

- module and system rating in watt-peak (Wp)

- e.g. a 50 Wp module generates 50 watt of electrical *power* at Standard Test Conditions (STC)

- in addition, or alternatively, the *power* under realistic conditions may be given (which is usually somewhat lower)

- in some cases also the actual *energy* production under practical conditions (over a certain period of time) will be given or guaranteed

note: *Standard Test Conditions are 25^{o}C, 1 sun = 1000 W/m^{2}, AM 1.5, normal incidence)*

EFFECT OF OPERATING CONDITIONS

temperature

- module efficiency decreases with temperature:

  typically 0.2-0.5%/K (relative), depending on module technology

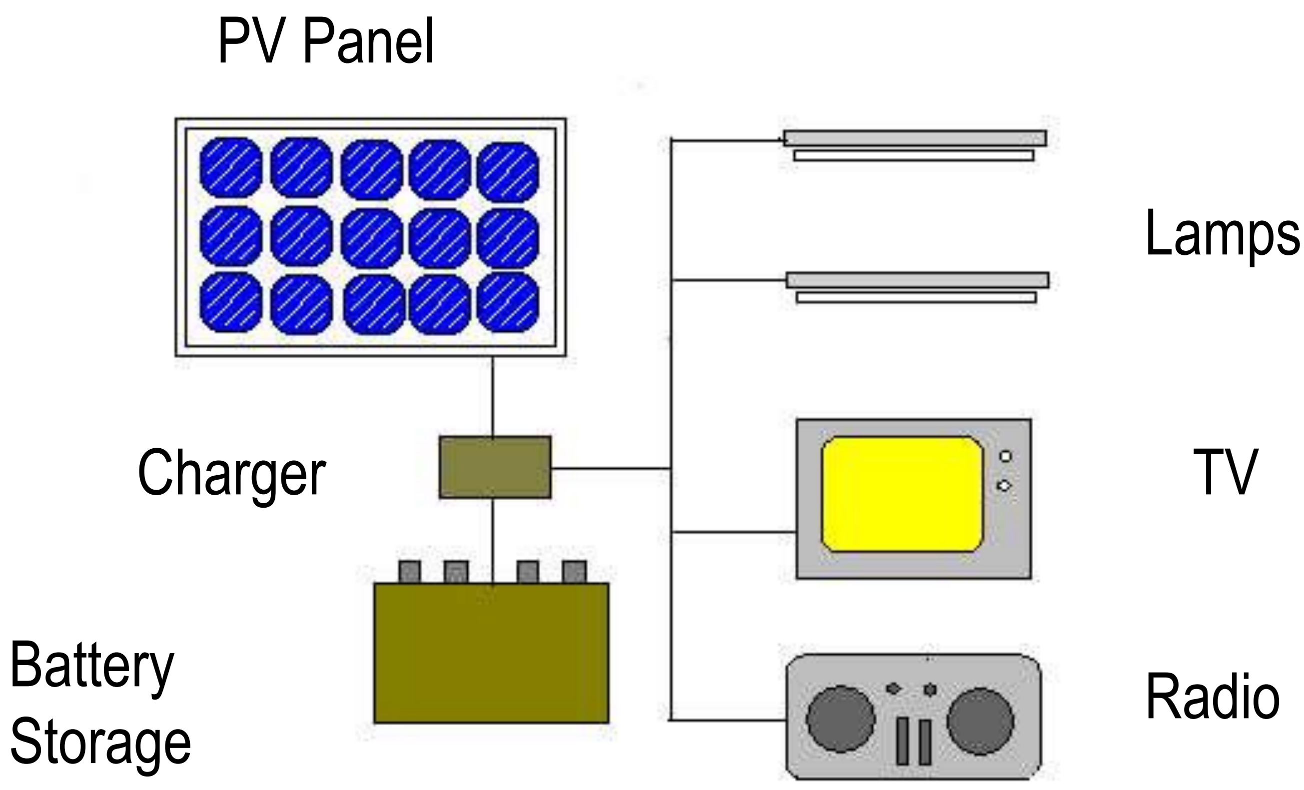
light intensity

- module efficiency decreases with light intensity:

  generally weak dependence from 1 to 0.1/0.2 sun, below 0.1/0.2 sun strongly dependent on module technology and type

note: *nameplate rating generally at Standard Test Conditions (STC; 25^{o}C, 1 sun = 1000 W/m^2, AM 1.5, normal incidence)*

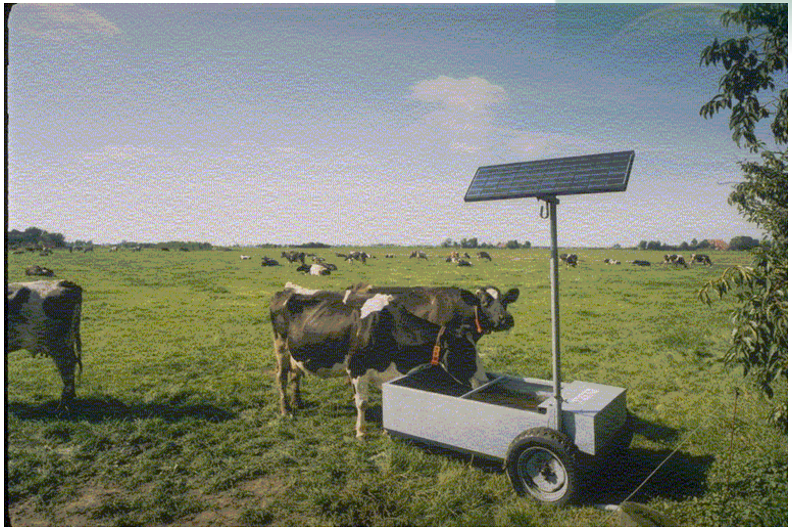
PHOTOVOLTAIC SYSTEMS – Standalone System



PV SYSTEMS

stand-alone systems

- consumer products
- telecom
- leisure
- water pumping
- lighting & signalling
- rural electrification
- etc.



PV SYSTEMS

energy yield dependent on:

- solar insolation (location)

- system power rating (in watt-peak, Wp)

- “system efficiency” (performance ratio):

- module efficiency under *practical* conditions
- inverter, regulator, battery (if applicable) & cable losses, etc.
- system availablitity

STAND-ALONE PV SYSTEMS

charge regulator

- protect battery from over- and underloading
- prevent reverse current from battery to module when dark

battery

- simple lead-acid (“car battery”) to advanced solar battery or NiCd, etc.
- provide short- (day), mid- (week-month) or long-term (season) storage
- operate for long period (>4 years) if properly maintained
- requires replacement within module lifetime

STAND-ALONE PV SYSTEMS: EXAMPLE SOLAR HOME SYSTEM

typical energy yield 50 Wp solar home system: (assume 2000 kWh.yr insolation)

- net module production: 70 kWh/year = 200 Wh/day
- including storage losses = 150 Wh/day

energy services provided:

- 3 x 8 W TL lamp x 3 hrs = 72 Wh/day
- 1 x 40 W B/W TV set x 2 hrs = 80 Wh/day
- TOTAL = 152 Wh/day

Design example – PV array

MPPT

Total energy demand

$$Minimum\,W_p = \frac{745Wh/day}{4.5h/day} = 165.6W$$

Equivalent sun hours

$$Number\ of\ panels = \frac{165.6W}{100W_p} = 1.7 \approx 2\,panels$$

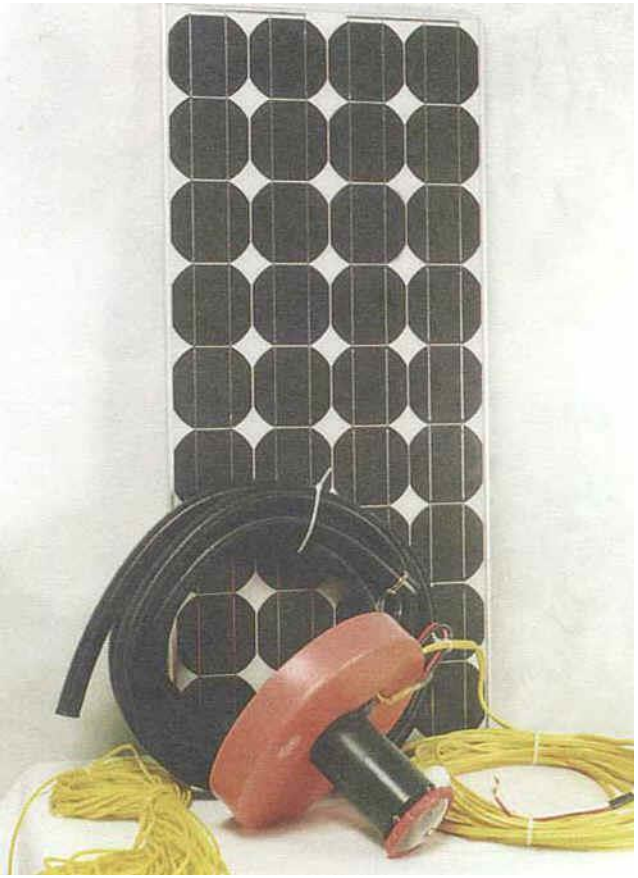
Electrical Data

Maximum Power at STC*	100 W
Optimum Operating Voltage (V_{mp})	18.9 V
Optimum Operating Current (I_{mp})	5.29 A
Open Circuit Voltage (V_{oc})	22.5 V
Short Circuit Voltage (I_{sc})	5.75 A
Module Efficiency	15.47%
Maximum System Voltage	600 VDC UL
Maximum Series Fuse Rating	15 A

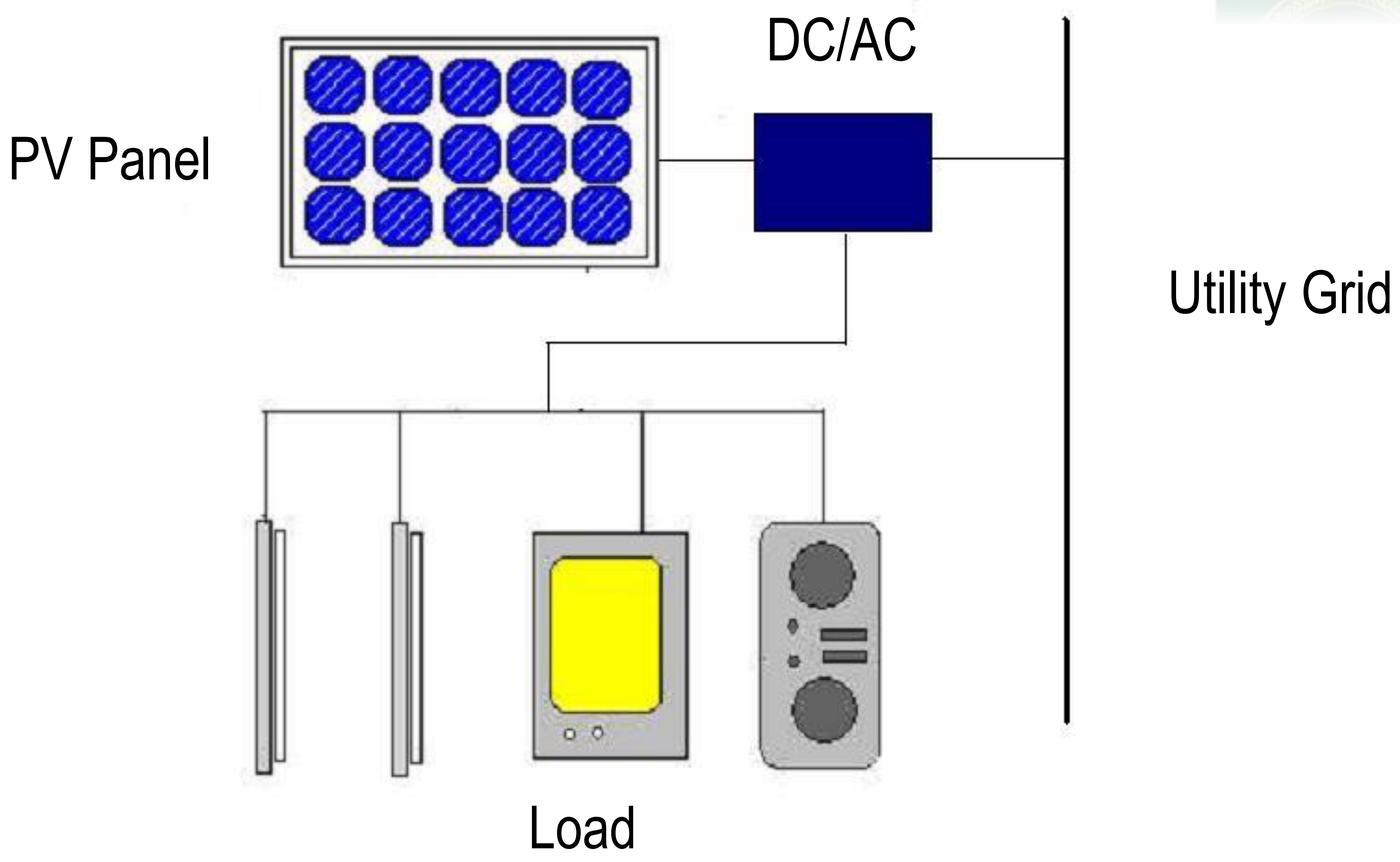
Thermal Characteristics

Operating Module Temperature	-40°C to +80°C
Nominal Operating Cell Temerature (NOCT)	47±2°C
Temperature Coefficient of Pmax	-0.44%/°C
Temperature Coefficient of Voc	-0.30%/°C
Temperature Coefficient of Isc	0.04%/°C


9 11:42AM



PHOTOVOLTAIC SYSTEMS – Grid connected



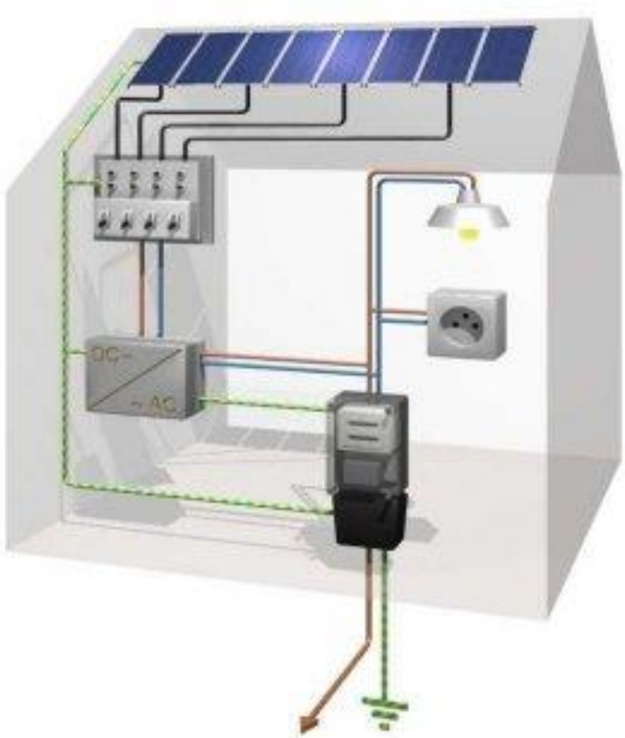
GRID-CONNECTED PV SYSTEMS

Japan

- ground-based
- integrated
  - roof-top & façade
  - sound barriers
  - etc.

(typical yield: 750-1500 kWh_e/kWp·year, depending on location)

GRID-CONNECTED PV SYSTEMS



key components in a
grid-connected PV system

GRID-CONNECTED PV SYSTEMS

CIGS rooftop PV system (NL)

GRID-CONNECTED PV SYSTEMS

inverter

- efficient DC/AC conversion
  (typical average efficiency ≥90%)
- maximum power point tracking (MPPT)
- high-quality output
  (low harmonic distortion, etc.)
- safe and robust operation
  (no island operation, protection against
  indirect lightning strikes, etc.)
- long lifetime

GRID-CONNECTED PV SYSTEMS

building integrated PV at ECN

COOLING
THERMAL EFFECT ON PV

Mind local shading and possible hot spots!

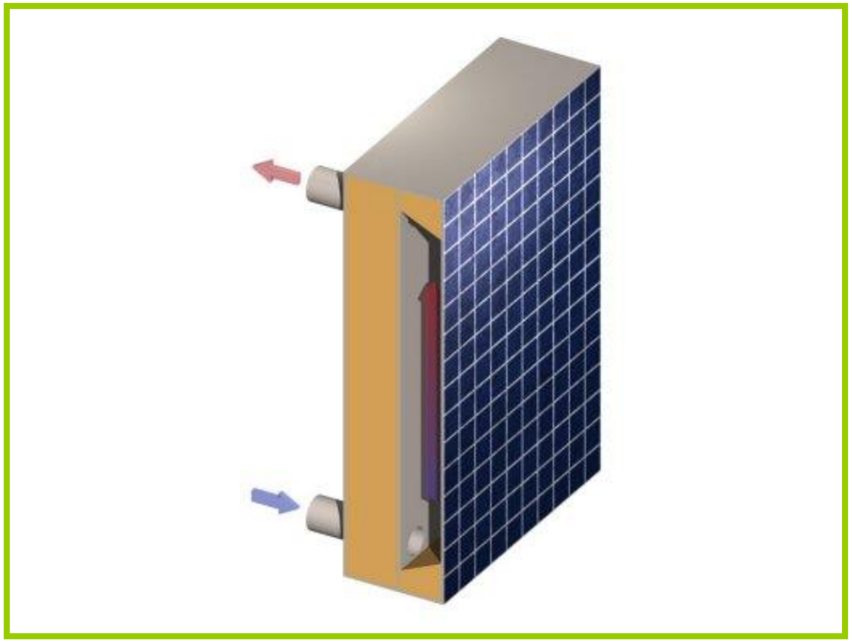
COOLING - THERMAL EFFECT ON SURROUNDING MATERIALS

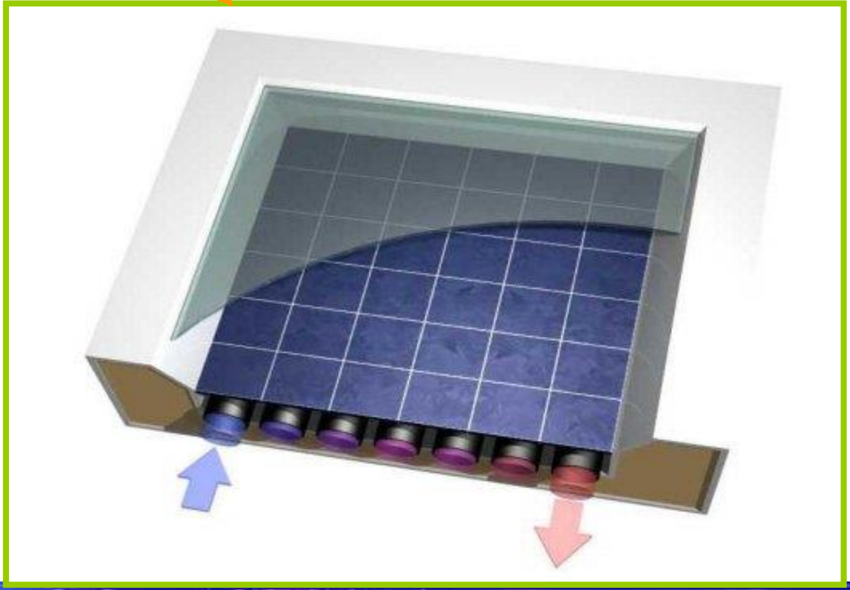
- The temperature difference between PV and ambient up to 40°C (in summer up to 70°C)
- insulated PV at the rear side - higher temperatures
- air gap at the rear side preferable
- too high temperature: roofing material can melt (bituminous materials!)
- tear, leaking or breaking of the PV laminate can appear
- expansion space usually available

POWER & HEAT
PRINCIPLES OF PV-THERMAL

combined generation of heat and electricity

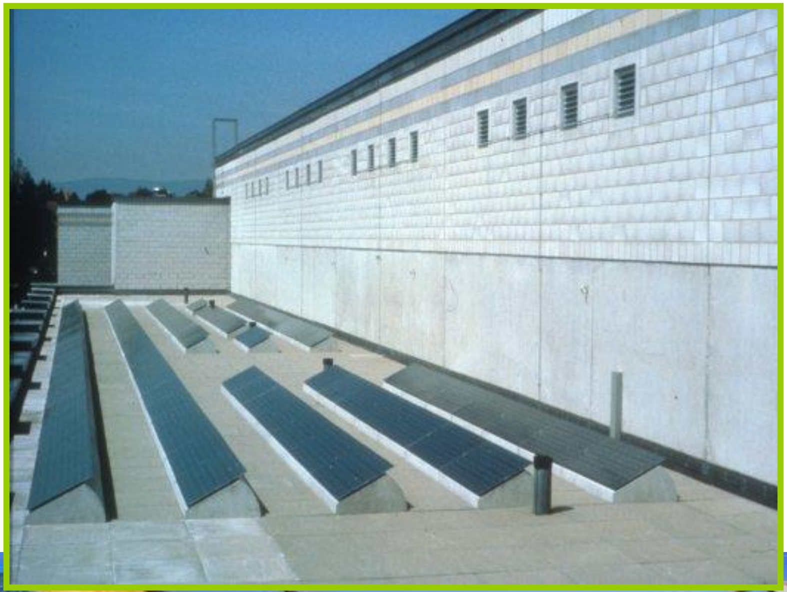
POWER & HEAT
AIR and FLUID FLOW TRANSFER

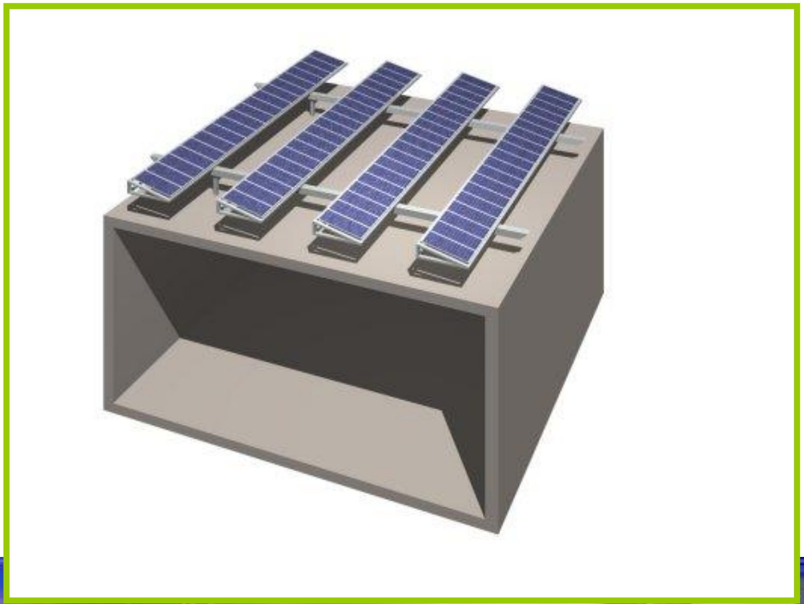




FLAT ROOFS
mounting options

- Support structure on the roof
- Gravity mounted or fixed mounted
- Optimal orientation & tilt
- Limited covered area due to mutual shading





FLAT ROOFS
support structure

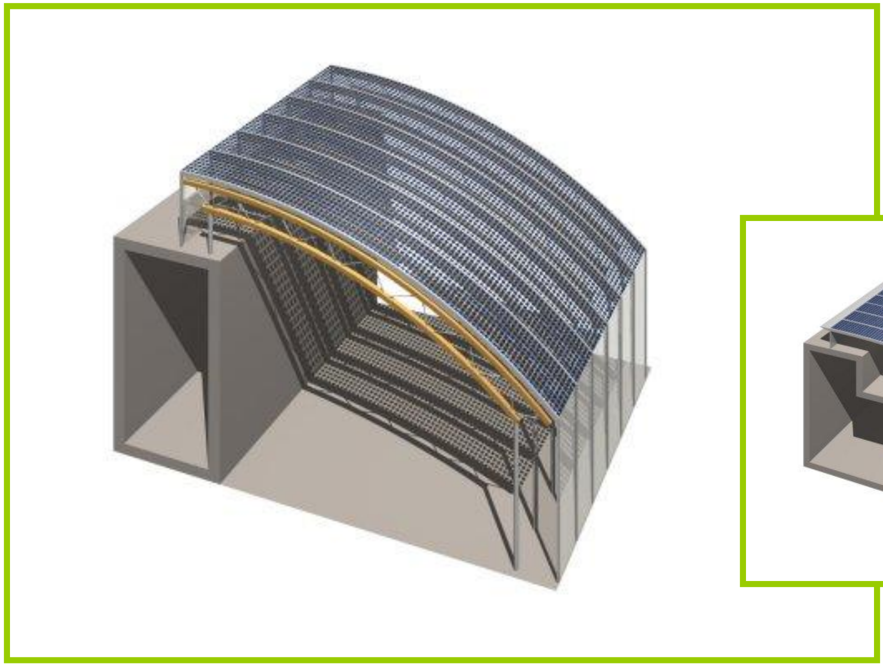
- **metal support structure**
- **alternatives: concrete, plastics**

GROUND-BASED PV ARRAYS

- **similar concept as for roofs**
- **metal support structure on concrete foundations**
- **good accessibility**
- **possibility of sun tracking**
- **high land consumption**
- **theft problem**

FLAT & SLOPED ROOFS: PV PARASOL

- PV covered roof construction as a parasol reduces heat load
- with or without water-retaining function



SLOPED ROOFS mounting options

STAND-OFF

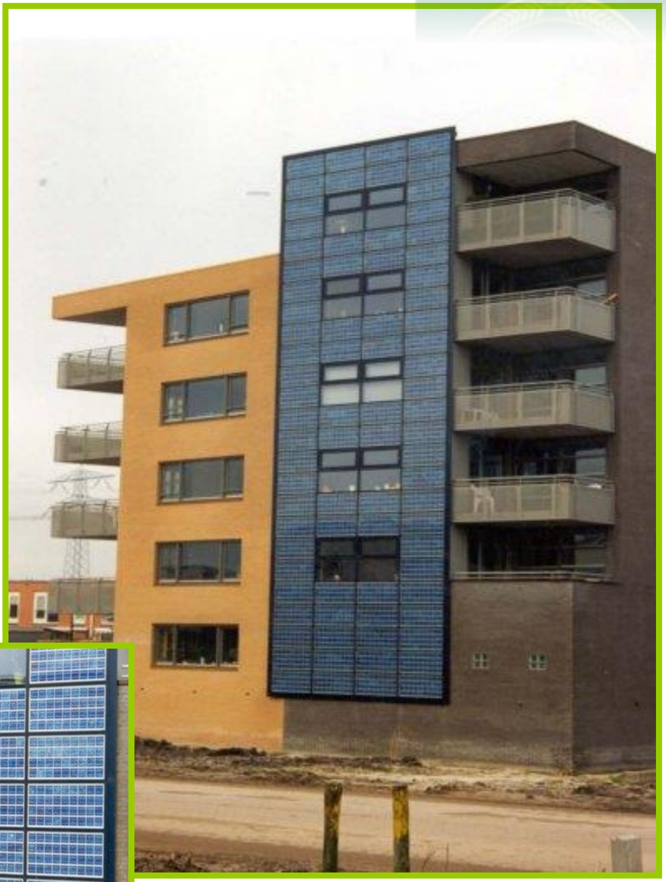
- support structure
- suitable for retrofits
- cooled from the rear
- easily mounted and replaced

INTEGRATED

- good integration possible
- no mutual shading
- mind water tightness and ventilation

FAÇADES
mounting options

- might be cost-effective
 (replaces traditional cladding material)
- risk for damage on the ground floor
- not the optimal tilt
- aesthetically challenging

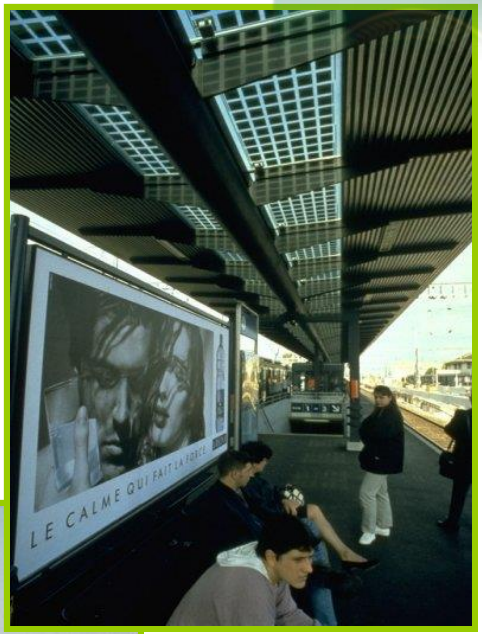


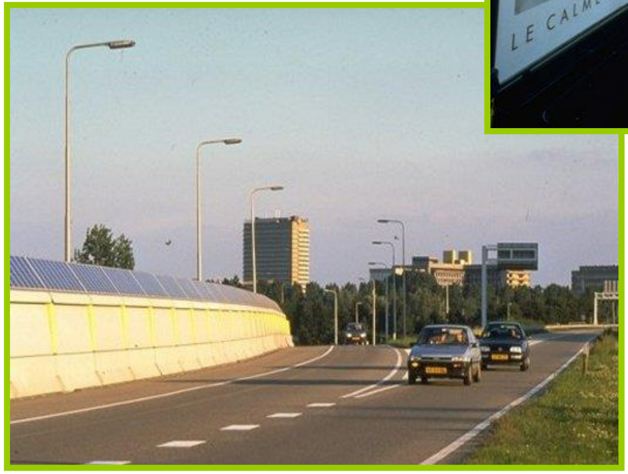
COMBINED FUNCTIONS SHADING DEVICES

- ideal for PV modules integration
- suitable both for new and existing buildings
- excellent combination of passive cooling, daylighting control and energy production

OTHER OBJECTS

- sound barriers
- bus stops
- roofs of railway platforms or bus stations
- along the railways
- information boards, etc.



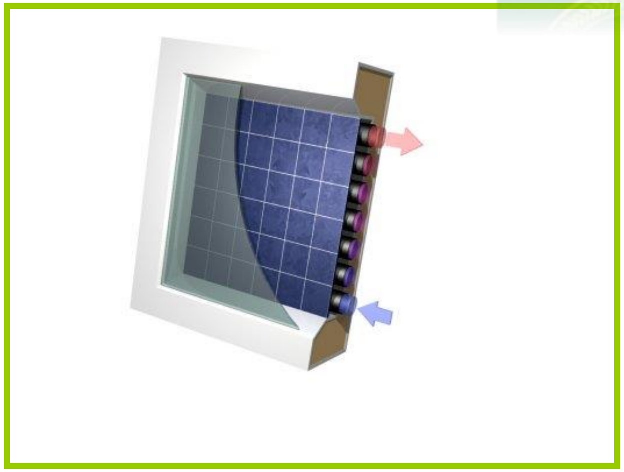


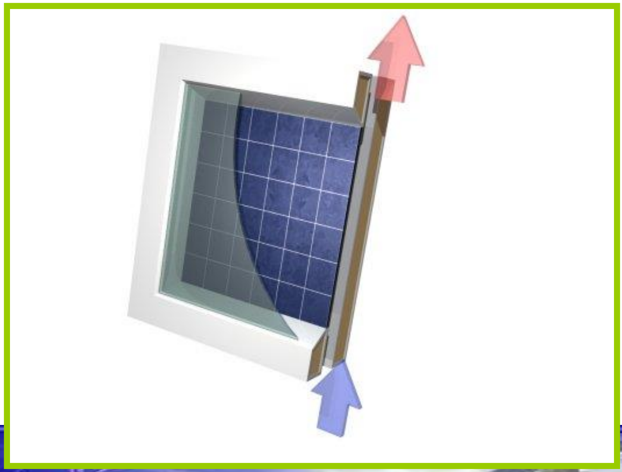
OTHER OBJECTS

COMBINED FUNCTIONS PV-THERMAL

Hybrid collectors with medium:

AIR or WATER





- cooling PV improves efficiency
- heat can be used
  - in summer (hot water)
  - in winter (space heating)
- attractive in case the available roof surface is limited

COMBINED FUNCTIONS NATURAL LIGHTING

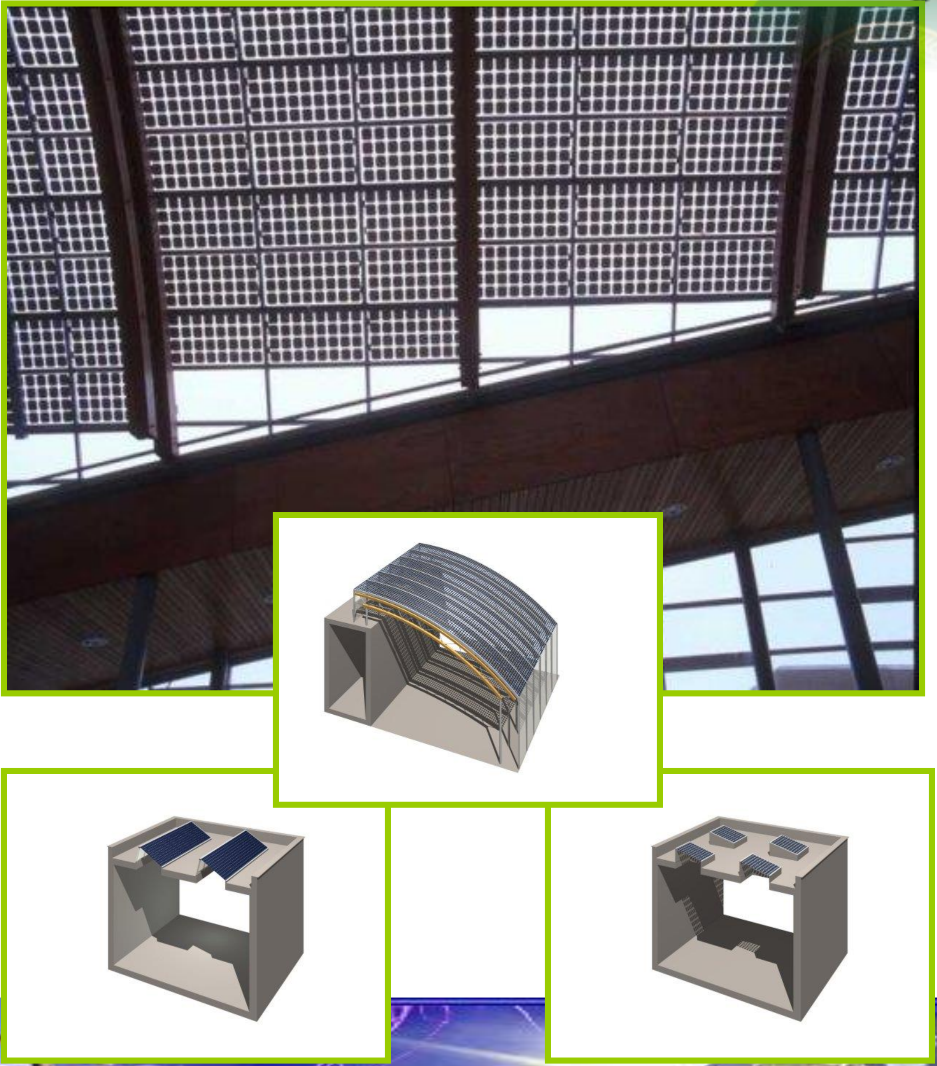
SKY LIGHTS

- PV at the South side
- light from the North

ideal for workshops

TRANSPARENT or TRANSLUCENT PV

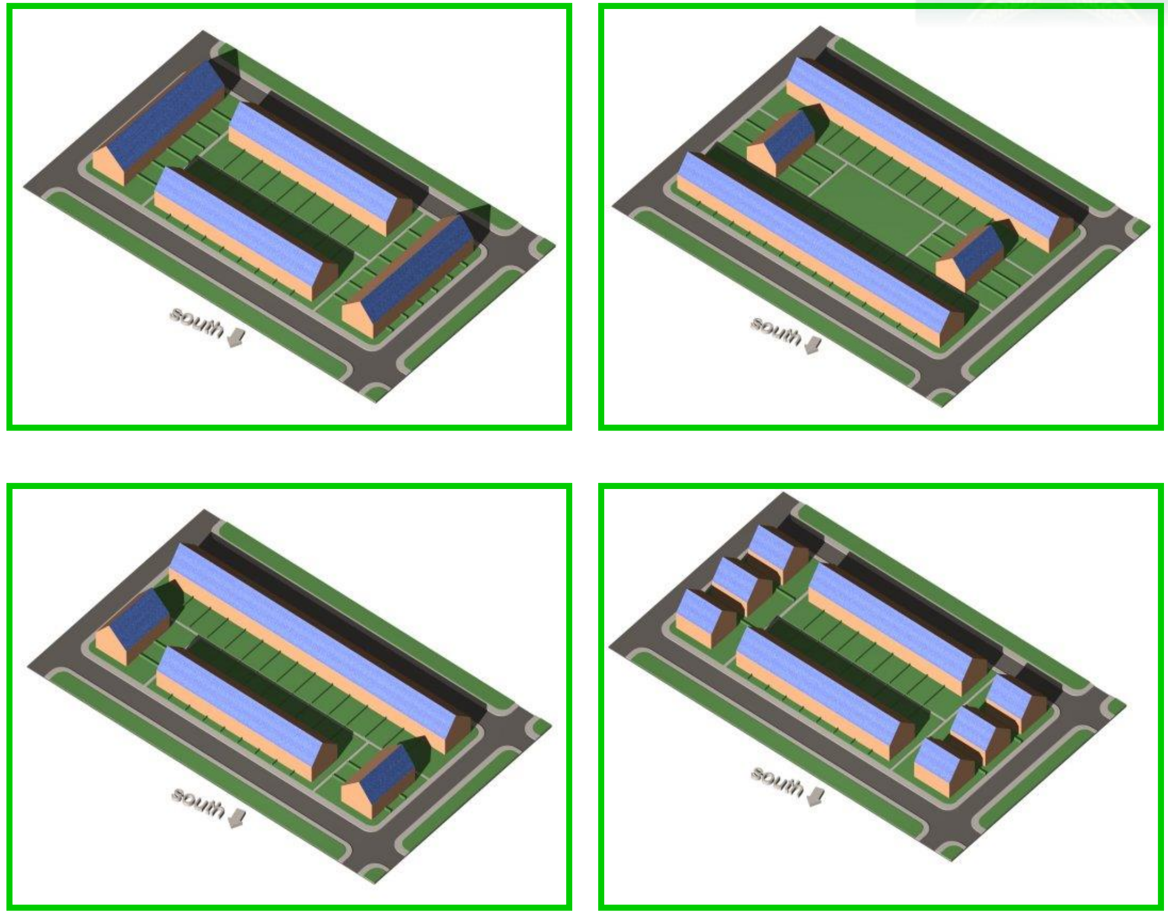
- opaque solar cells laminated in double glass
- space between cells 1-3 cm
- diffuse or tempered light
- interesting shadow patterns



ORIENTATION & TILT
location, building & planning

orientation & tilt

- influences the yield considerably
- southern orientation preferable (northern hemisphere)
- count with the right orientation while planning a residential area
- mind possible mutual shading



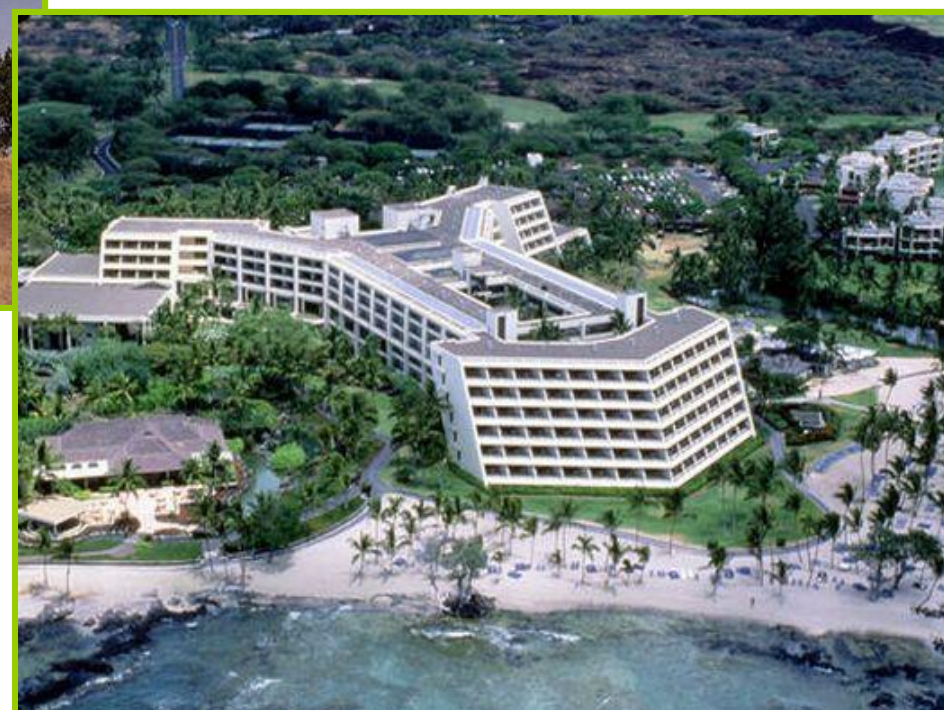
M.ART

ORIENTATION & TILT
sun tracking

Sun tracking system

- movable along one axis (horizontal)
- movable along two axes
- sun tracking sensor
- lamellas with integrated PV modules
- integrated in a façade
- cost-benefit ratio questionable

RESIDENTIAL & COMMERCIAL BUILDINGS



ENVIRONMENTAL ISSUES

- **energy pay-back time systems** *(grid-connected systems)*
  - **now 4-8 years (EU)**
  - **future (<10 years) 1-2 years**
- **materials consumption**
  - **avoid hazardous or scarce materials**
  - **some alternatives required (for Ag, e.g.)**
  - **recycling to be developed further**

EXAMPLE - SIZING OF STANDALONE SYSTEM

- Step 1 – Determine the Load Available Sunlight, PV Array Size and Battery Bank Size
- Step 2 – Calculate PV System Costs

EXAMPLE - SIZING OF STANDALONE SYSTEM

Appliance	AC or DC Watts		Hours Used/ Day		Watt Hours/ Day
Ceiling Fan	100	x	8.0	=	800
Coffee Maker	600	x	0.3	=	180
Clothes Dryer	4,856	x	0.8	=	3,885
Computer	75	x	2.0	=	150
Computer Monitor	150	x	2.0	=	300
Dishwasher	1,200	x	0.5	=	600
Lights, 4 Compact Fluorescents	4x15	x	5.0	=	300
Microwave Oven	1,300	x	0.5	=	650
Radio	80	x	4.0	=	320
Refrigerator	600	x	9.0	=	5,400
Television	300	x	8.0	=	2,400
Vacuum Cleaner	600	x	0.2	=	120
VCR	25	x	8.0	=	200
Washing Machine	375	x	0.5	=	188
Total					15,493

EXAMPLE - SIZING OF STANDALONE SYSTEM

Step 1. Determine the load, available sunlight, array size, battery bank size:

a. Determine the energy load required in watt-hours (Wh) per day. Multiply the number of watts the load will consume by the hours per day the load will operate (see Table 1). Multiply your result by 1.5.

Total Wh per day required: ________Wh

b. Determine the hours per day of available sunlight at the site (see Figure 1).

Total available sunlight: _______ hrs/day

c. Determine the PV array size needed. Divide the energy needed (1.a.) by the number of available sun hours per day (1.b.).

Total array size required: _______ Watts

d. Determine the size of the battery bank (if one is desired). Multiply the load (1.a.) by 5 (result is watt-hours, Wh). Then divide by the battery voltage (for example, 12 volts) to get the amp-hour (Ah) rating of the battery bank.

Total Battery Bank Required: _______ Ah

EXAMPLE - SIZING OF STANDALONE SYSTEM

Step 2. Calculate the cost of the PV system needed for this application:

a. Multiply the size of the array (1.c.) by $5 per watt.

Cost estimate for PV array: $ __________

b. If a battery bank is used, multiply the size of the battery bank (1.d.) by $1 per amp hour.

Cost estimate for battery bank: $ __________

c. If an inverter is used, multiply the size of the array (1.c.) by $1 per rated watt.

Cost estimate for Inverter: $ __________

Subtotal: $ __________

d. Multiply the subtotal above by 0.2 (20%) to cover balance of system costs (wire, fuses, switches, etc.).

Cost Estimate for Balance of System: $ __________

Total Estimated PV System Cost: $ __________