FOSS
Research Centre for Sustainable Energy

University of Cyprus
PV Technology

Fundamentals of Building Integrated Photovoltaics

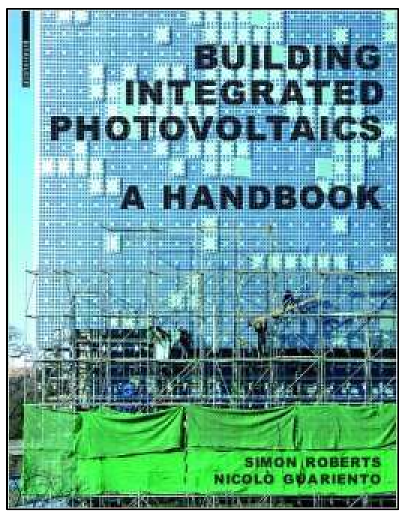
Prof. George E. Georghiou
Director FOSS, University of Cyprus

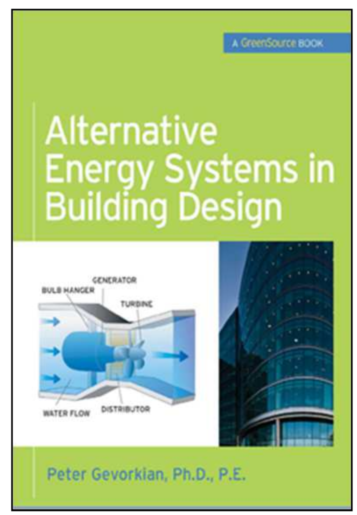
Montevideo, Uruguay, 25-29 March 2019

Outline

Reference books

- S. Roberts and N. Guariento, Building Integrated Photovoltaics – A Handbook, Birkhäuser Architecture; 1st Edition (2009).
- Alternative Energy Systems in Building Design, P. Gevorkian, McGraw-Hill's Greensource Series, 2010





One of the World's Largest PV Parks Agua Caliente, Arizona, USA (290 MWp)

Supplies Energy for 200000 homes

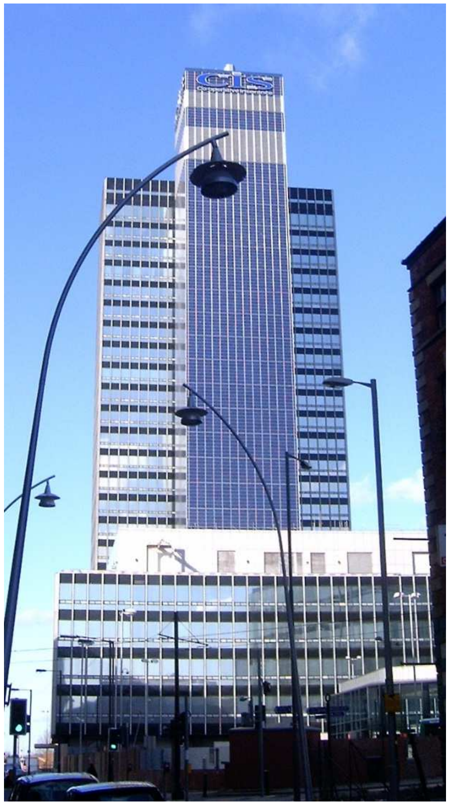
But also utilizing the real advantages of PV

And making PV part of our built environment

FOSS
Research Centre for
Sustainable Energy

Challenges for PV

- Cost
- Efficiency/Energy yield
- Reliability
- Grid/Market integration



FOSS Research Centre for Sustainable Energy

DIEGO Development of quality system through EnerGy Efficency cOurses

Erasmus+

Motivation: Energy Efficiency & NZEBs

Why are we interested in Energy Efficiency and NZEB?

- Buildings responsible for approx. 40% of the total annual energy consumption in Europe.

Buildings → major contribution to:

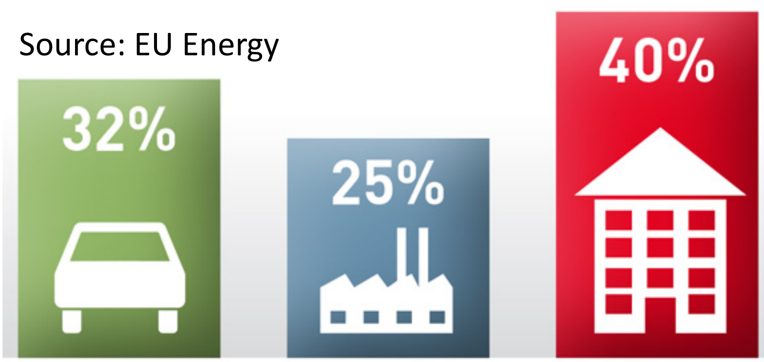
- **final energy consumption** (>40% EU, 37% CY)
- **GHG emissions** (>30%)

→ High financial & environmental cost

Significant potential for:

- **energy savings**
- **GHG emission reduction**

Source: EU Energy

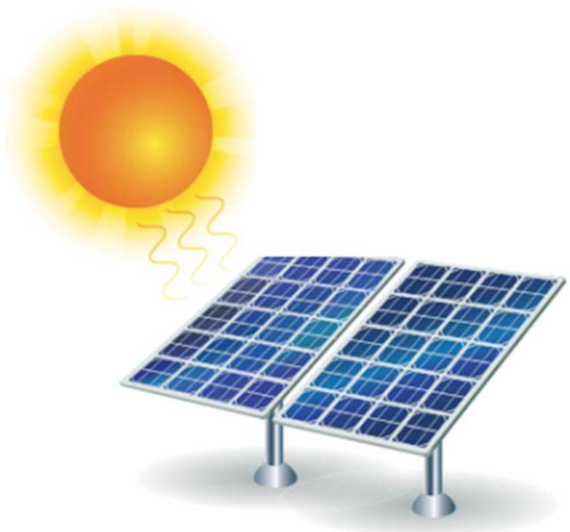


50% for heating/cooling

FOSS Research Centre for Sustainable Energy | DIEGO Development of quality system through EnerGy Efficency cOurses | Erasmus+ | University of Cyprus PV Technology

PV systems in Cyprus

In Cyprus an average yearly solar irradiation (at the plane of array of 30°) of 2000 kWh/m^2/yr yields for a 1 kW PV system at fixed inclination angle of 30° approximately **1700 kWh/kW/yr**



Over a yearly period 2000 kWh/m^2/yr

$$\begin{aligned} Electricity\ yearly &= Solar\ irradiation \times PR \times System\ Power \\ &= 2000 \times 0.85 \times 1 \\ &= 1700 \end{aligned}$$

Over a yearly period **1700 kWh/kW/yr**

Conservative case provided by many installers as a lower threshold: **1500 kWh/kW/yr**

FOSS
Research Centre for Sustainable Energy

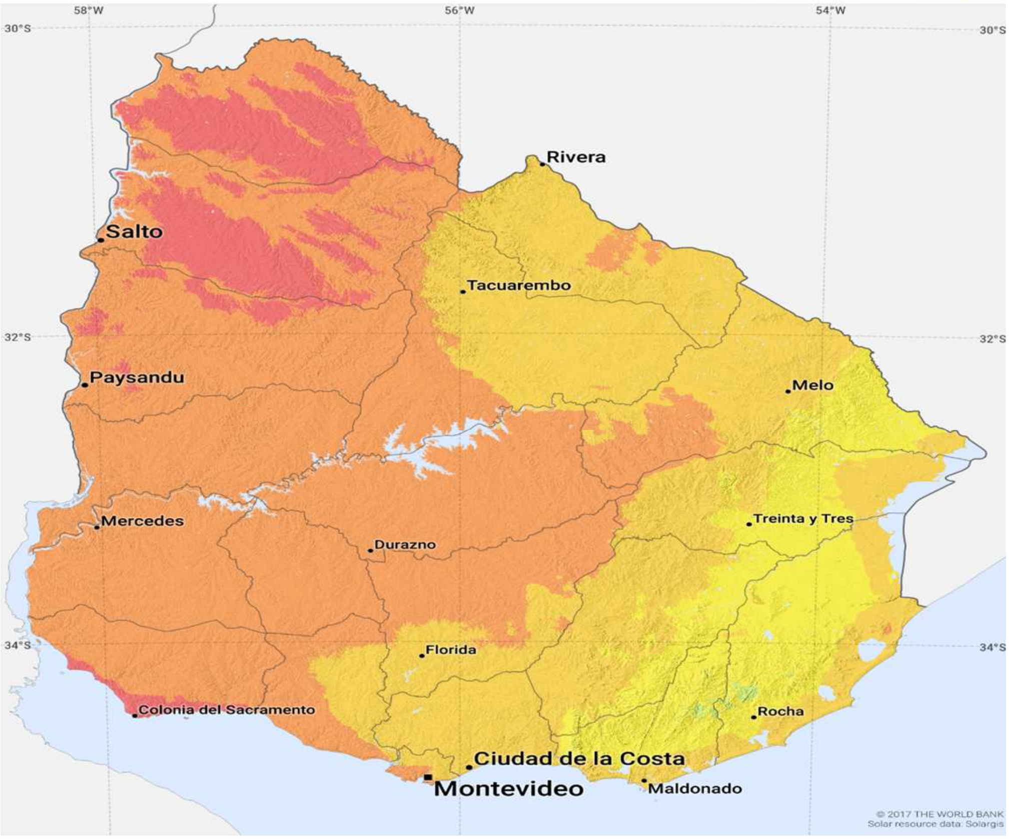
University of Cyprus
PV Technology

SOLAR RESOURCE MAP

PHOTOVOLTAIC POWER POTENTIAL

URUGUAY

WORLD BANK GROUP | THE WORLD BANK | IFC | ESMAP | SOLARGIS



Long term average of PVOUT, period 1999-2015

Daily totals: 4.0 4.2 4.4 kWh/kWp

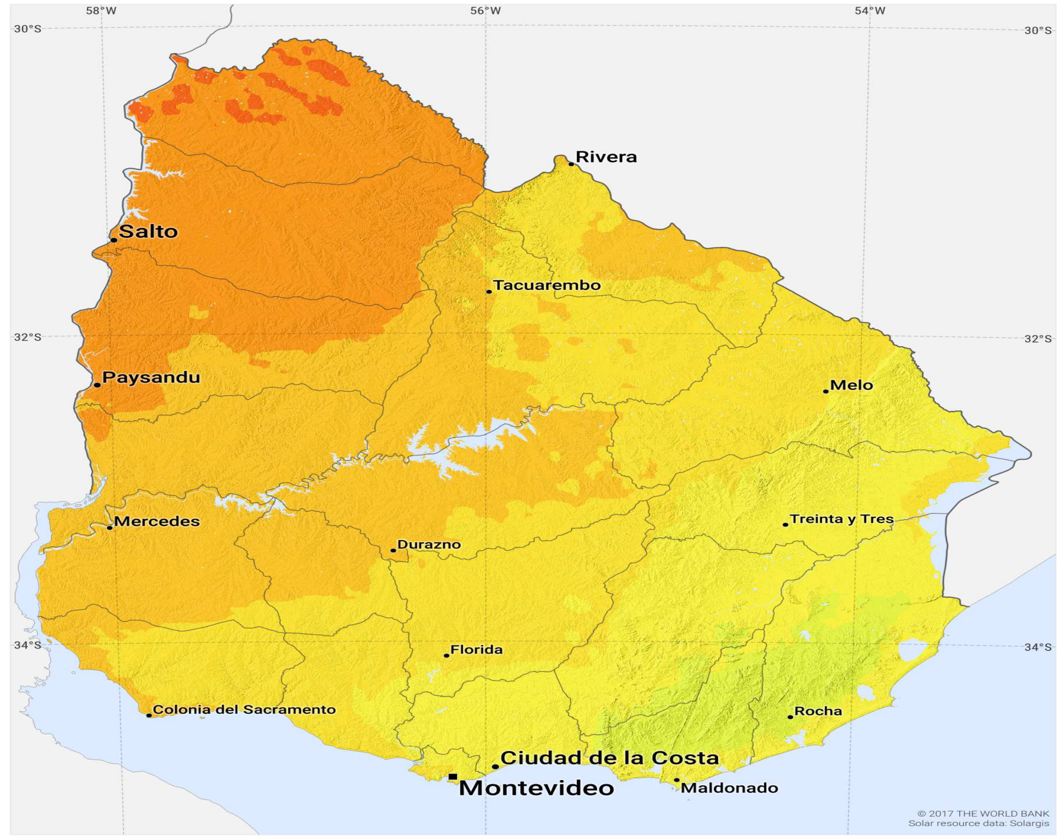
Yearly totals: 1461 1534 1607

SOLAR RESOURCE MAP

GLOBAL HORIZONTAL IRRADIATION

URUGUAY

WORLD BANK GROUP | THE WORLD BANK | IFC | ESMAP | SOLARGIS



Long term average of GHI, period 1999-2015

Daily totals: 4.6 4.8 5.0 5.2 kWh/m²

Yearly totals: 1680 1753 1826 1899

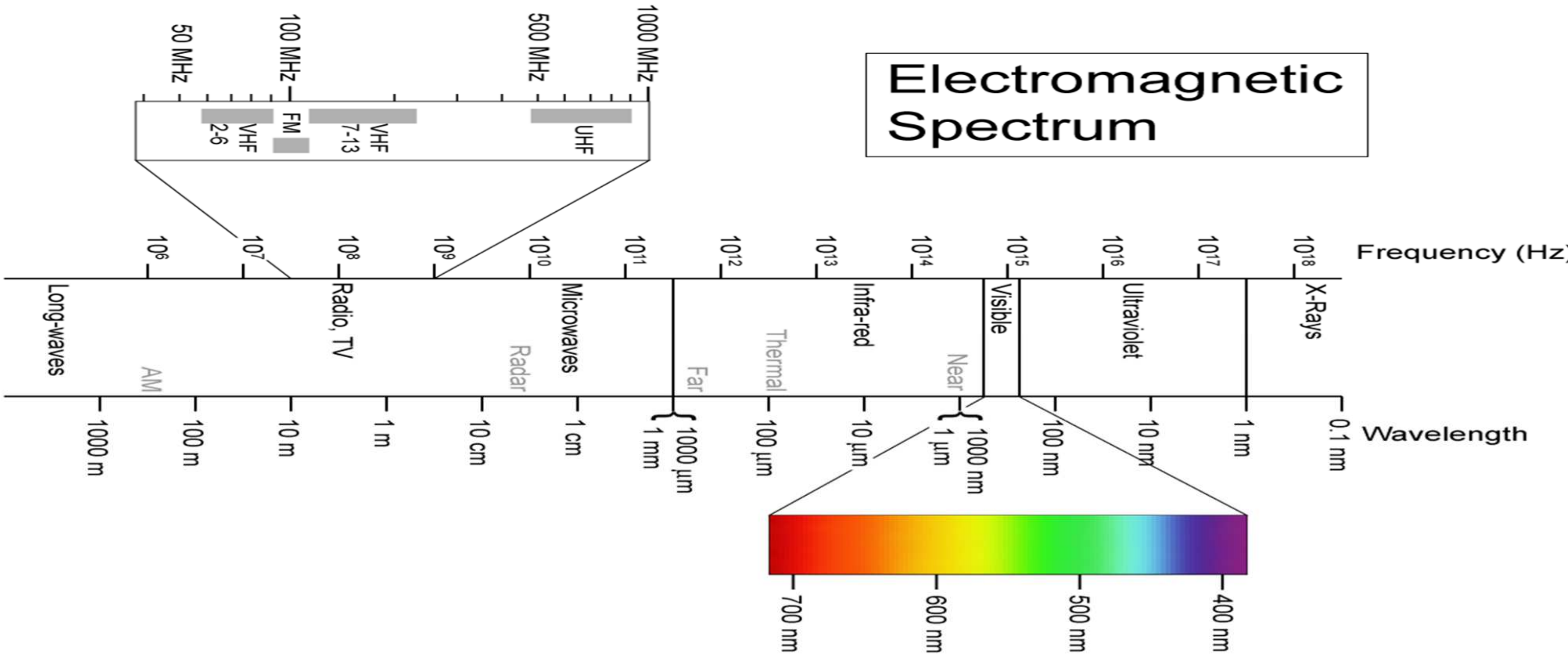
Data for Uruguay (Montevideo)

- Lattitude: 35^{o}S
- Longitude: 56^{o}W
- Global Annual Horizontal Irradiation: 1700 kWh/m^2
- PV out: 1500 kWh/kWp

FOSS Research Centre for Sustainable Energy

University of Cyprus PV Technology

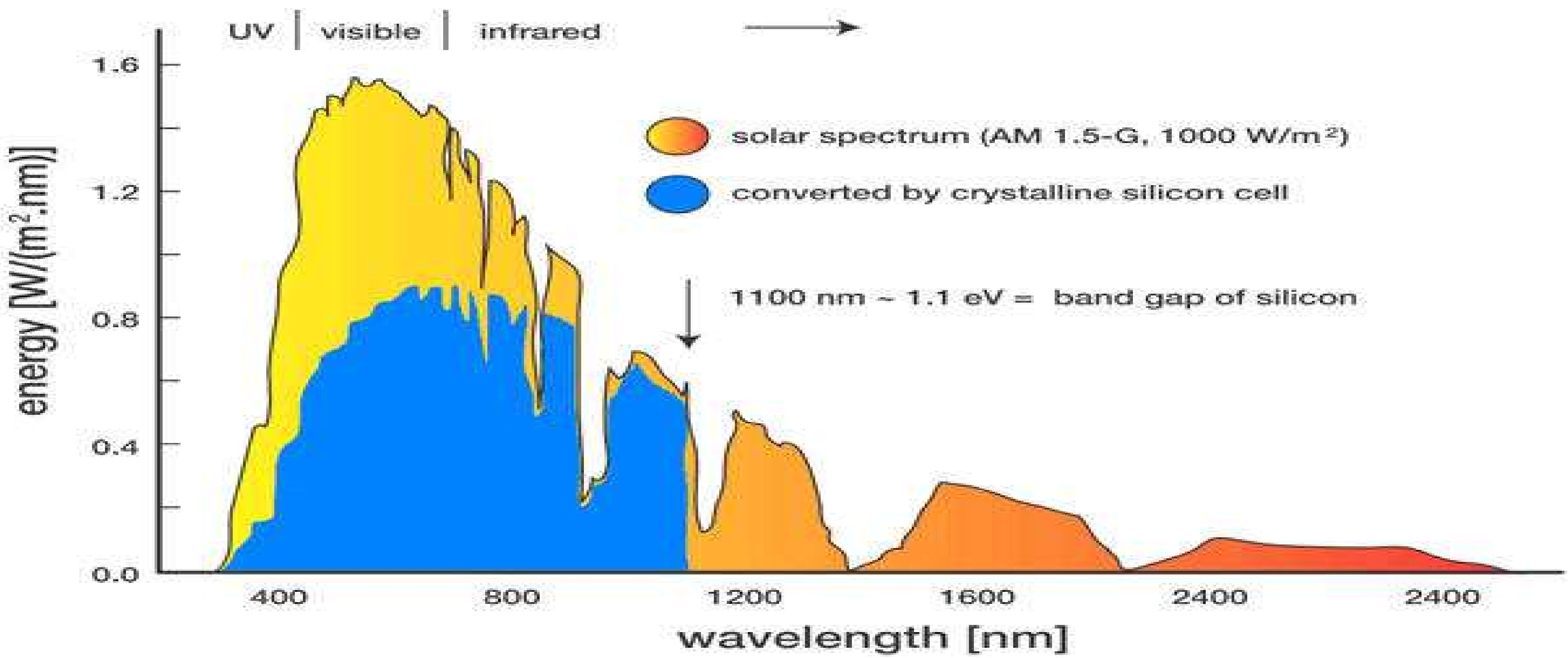
Electromagnetic Spectrum



FOSS
Research Centre for Sustainable Energy

University of Cyprus
PV Technology

Solar Spectrum



BISOL BMO/233-245

BISOL

Monocrystalline Silicon Photovoltaic Modules

Made in Europe

10-year product warranty

Strictly positive power output tolerances

Module presorting for a more profitable investment

Electrical Specifications @ STC (AM1.5, 1,000 W/m², 25 °C):

Module Type		BMO/233	BMO/239	BMO/245
Maximum Power	P_{MPP} [W]	233	239	245
Short Circuit Current	I_{SC} [A]	8.45	8.60	8.70
Open Circuit Voltage	V_{OC} [V]	37.4	37.5	37.8
MPP Current	I_{MPP} [A]	7.85	8.00	8.10
MPP Voltage	V_{MPP} [V]	29.7	29.9	30.2
Solar Cell Efficiency	η_C [%]	16.0	16.4	16.8
Module Efficiency	η_M [%]	14.3	14.6	15.0

Additional power classes available upon request.
Efficiency of modules at low irradiation (200 W/m²) decreases to 95.7 % of efficiency at STC.

Electrical Specifications @ AM1.5, 800 W/m², Cell Temperature 44 °C:

Module Type		BMO/233	BMO/239	BMO/245
Maximum Power	P_{MPP} [W]	172	176	181
Short Circuit Current	I_{SC} [A]	6.86	6.99	7.07
Open Circuit Voltage	V_{OC} [V]	34.7	34.8	35.1
MPP Current	I_{MPP} [A]	6.35	6.47	6.55
MPP Voltage	V_{MPP} [V]	27.1	27.2	27.6
Solar Cell Efficiency	η_C [%]	14.7	15.1	15.5
Module Efficiency	η_M [%]	13.2	13.5	13.8

Electrical specifications:

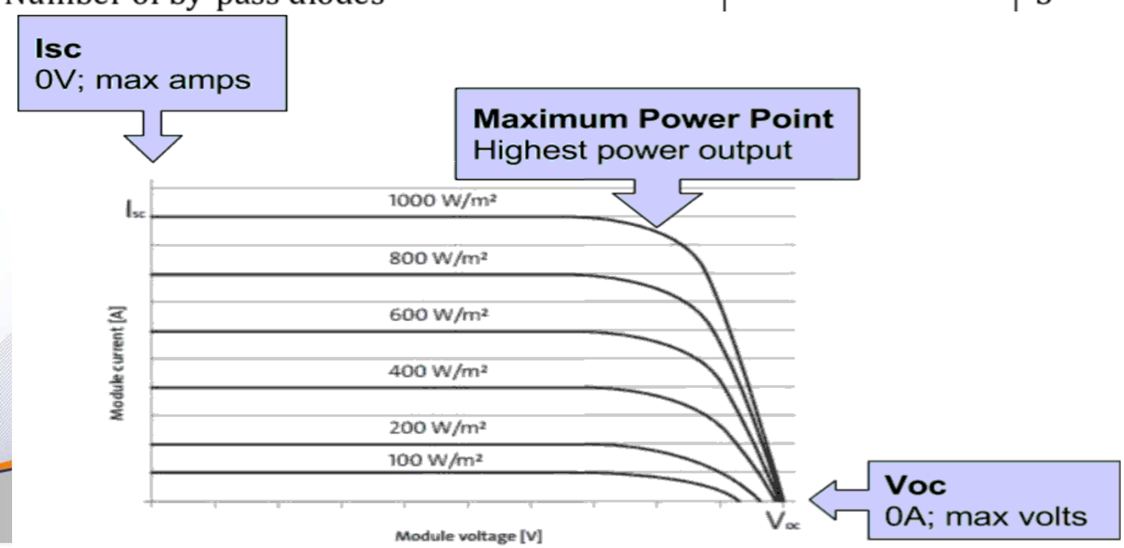
Solar Cell Type	Monocrystalline Silicon
Solar Cell Dimensions	156 mm x 156 mm (6+")
Number of Cells	60 in series
Power Output Tolerance	0/+6 W
Current Temperature Coefficient α	+ 2.9 mA/ °C
Voltage Temperature Coefficient β	- 91.8 mV/ °C
Power Temperature Coefficient γ	- 0.37 %/ °C
Maximum System Voltage	1,000 V (IEC)
NOCT	44° C
Limiting Reverse Current	No external voltage higher than V_{oc} should be applied

Mechanical specifications:

Length x Width x Thickness	1,649 mm x 991 mm x 40 mm (64.92"x 39.02" x 1.575")
Weight	18.5 kg (40.79 lb)
Junction Box, Connectors	Tyco (IP 65) with three bypass diodes

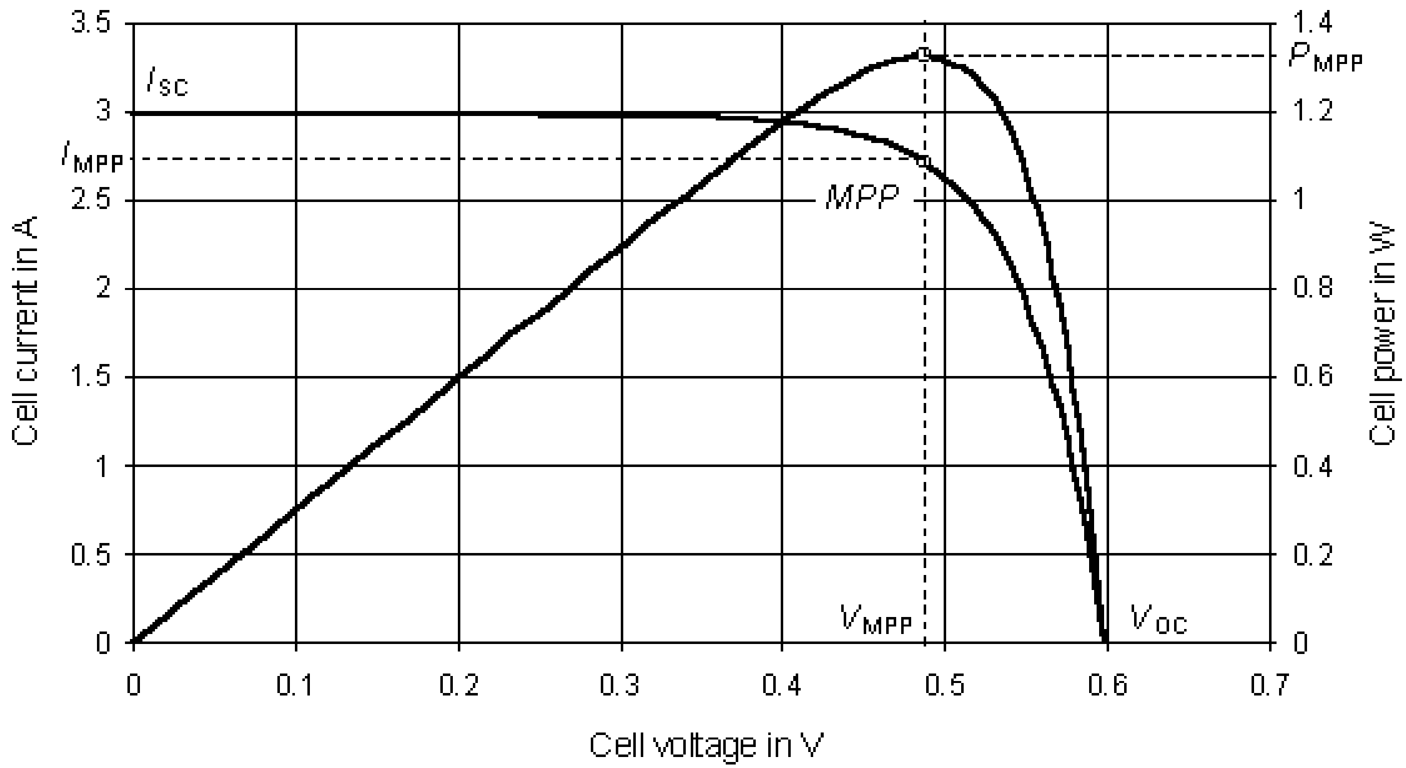
www.bisol.com

Parameter	Notation	Value
Voltage at maximum power point	*Vmpp* (STC) (V)	38.4
Open-circuit voltage	*Voc* (STC) (V)	46.2
Short-circuit current	*Isc* (STC) (A)	8.95
Current at maximum power point	*Impp* (STC) (A)	8.33
Power rating	P_M (STC) (W)	320
Length of module	*Lmod* (m)	0.982
Breadth of module	*Bmod* (m)	1.955
Temperature coefficient of maximum power	%/C	-0.41
Temperature coefficient of open-circuit voltage	%/C	-0.31
Temperature coefficient of short-circuit current	%/C	0.052
Number of cells		72
Number of by-pass diodes		3

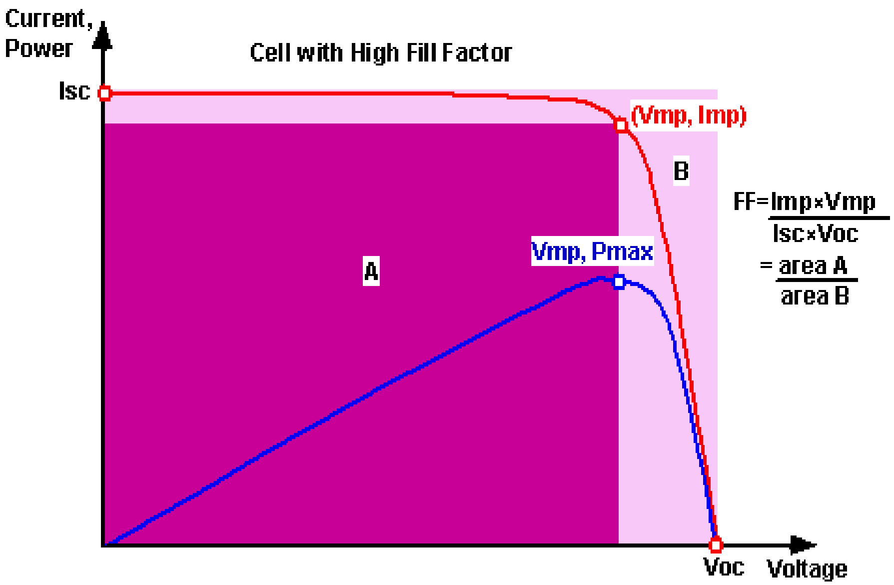


Important Parameters

- Short Circuit Current (Isc)
- Open Circuit Voltage (Voc)
- Maximum Power (Pmpp)
- Efficiency (η)
- Fill Factor
- Performance Ratio (PR)
- Temperature Coefficients
- Standard Test Conditions



Efficiency, Fill Factor and Performance Ratio

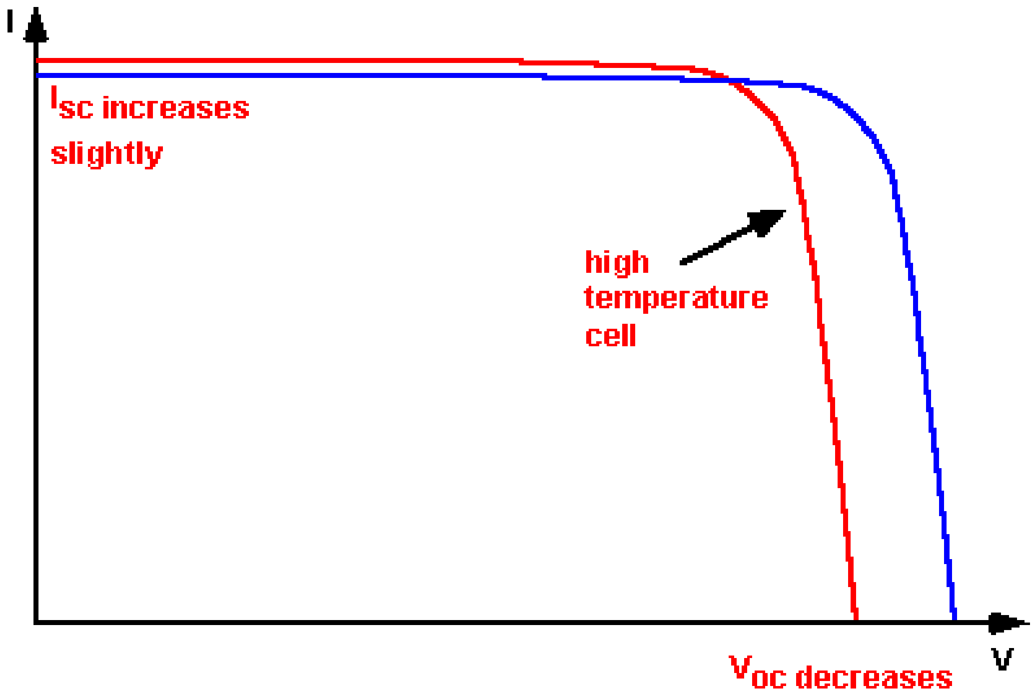


$$FF = \frac{V_{MPP} \times I_{MPP}}{V_{OC} \times I_{SC}}$$

$$\eta = \frac{P_{MPP}}{G \times Area}$$

$$PR = \frac{Actual\ Energy\ Yield}{Ideal\ Energy\ Yield}$$

Temperature Coefficients



$$\frac{dP_{MPP}}{dT} = \gamma = -0.42\ \%/K$$

$$\frac{dI_{SC}}{dT} = \alpha = +0.05\ \%/K$$

$$\frac{dV_{OC}}{dT} = \beta = -0.33\ \%/K$$

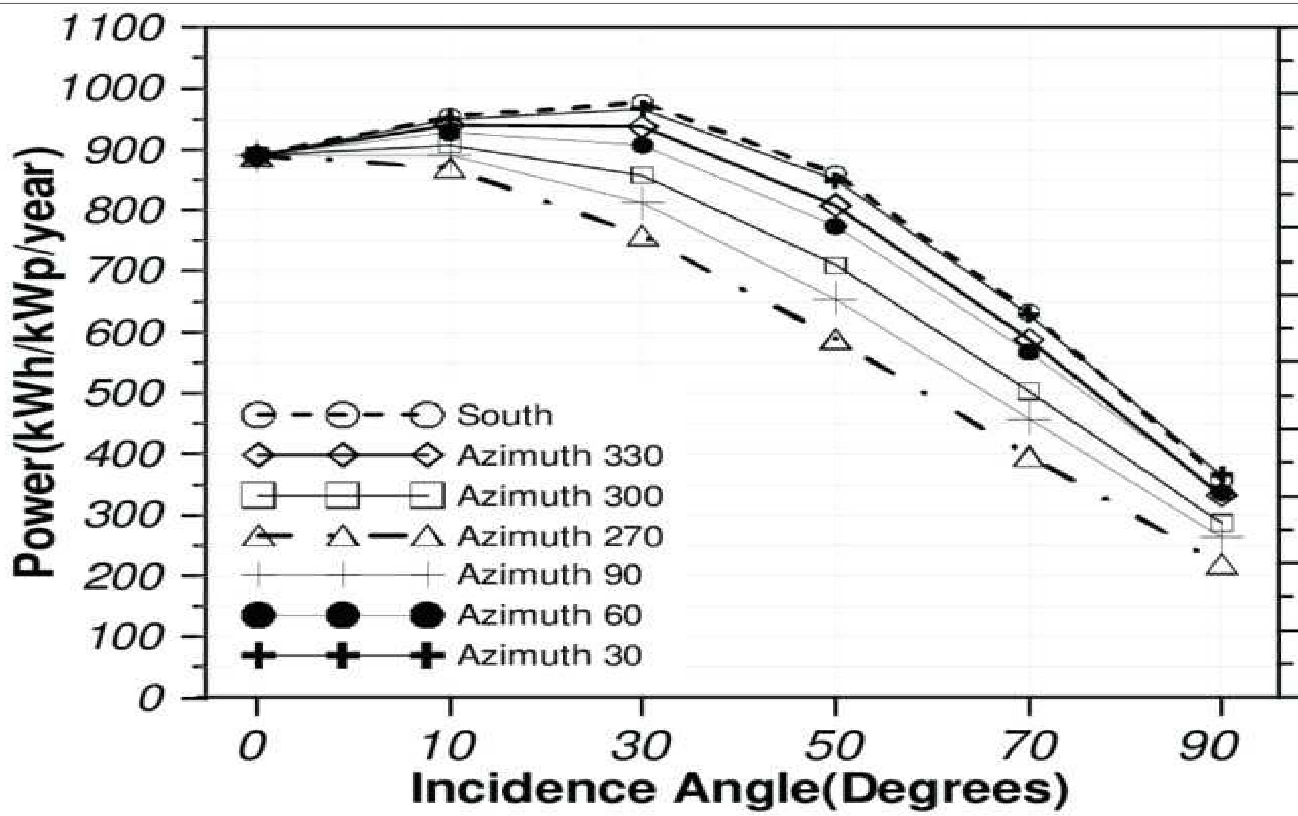
Standard Test Conditions

- The most common way to compare modules is by their peak-power specification given as watts peak or Wp.
- This rating is made at a well-defined set of conditions known as standard test conditions (STC):
  - the actual temperature of the PV cells (25 °C),
  - the intensity of irradiance (1 kW/m^2), the spectral distribution of the light (air mass 1.5 or AM 1.5, the spectrum of sunlight that has been filtered by passing through 1.5 thicknesses of the earth's atmosphere).

Nominal Operating Cell Temperature (NOCT)

- Irradiance level of 800 W/m^2
- Ambient temperature of 20 °C
- Wind velocity of 1 m/s
- Open rack.

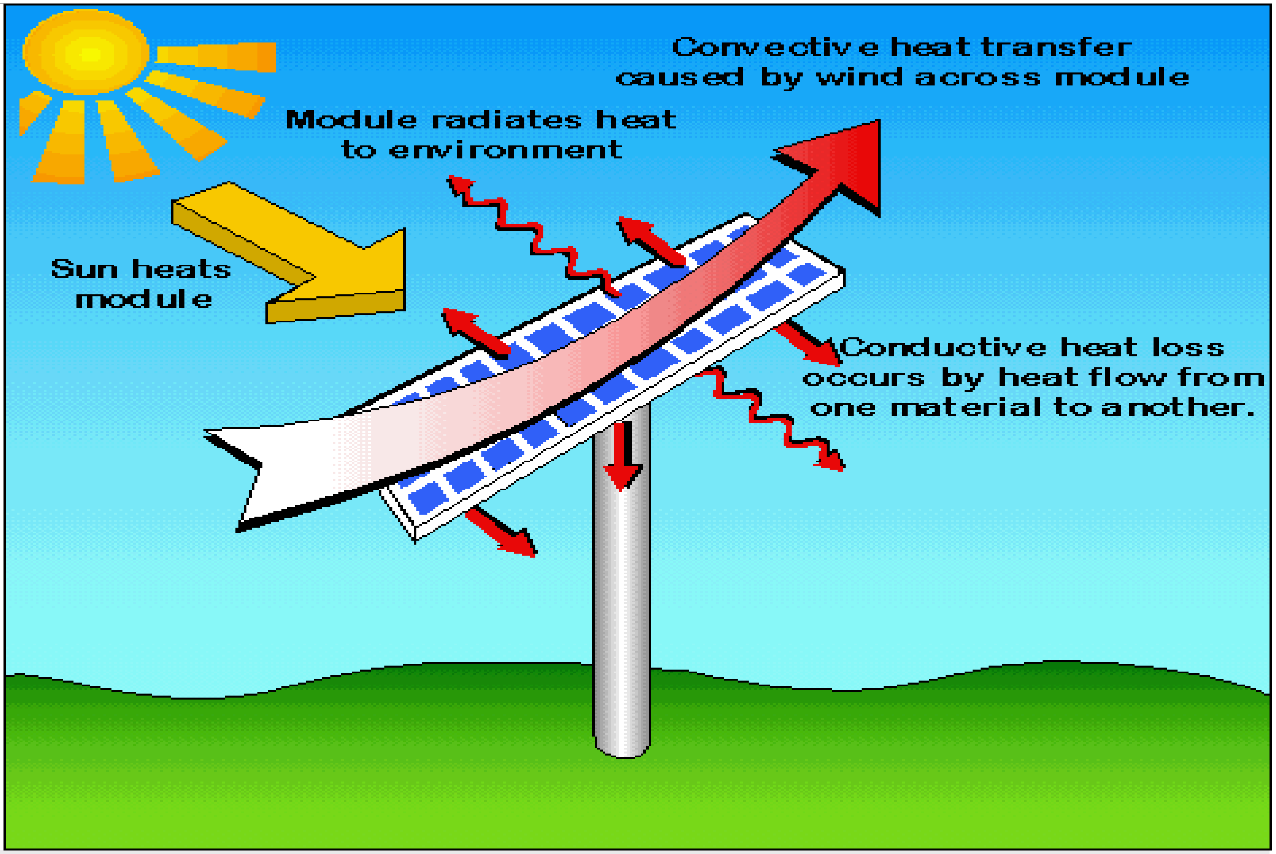
Power output as a function of the angle of incidence



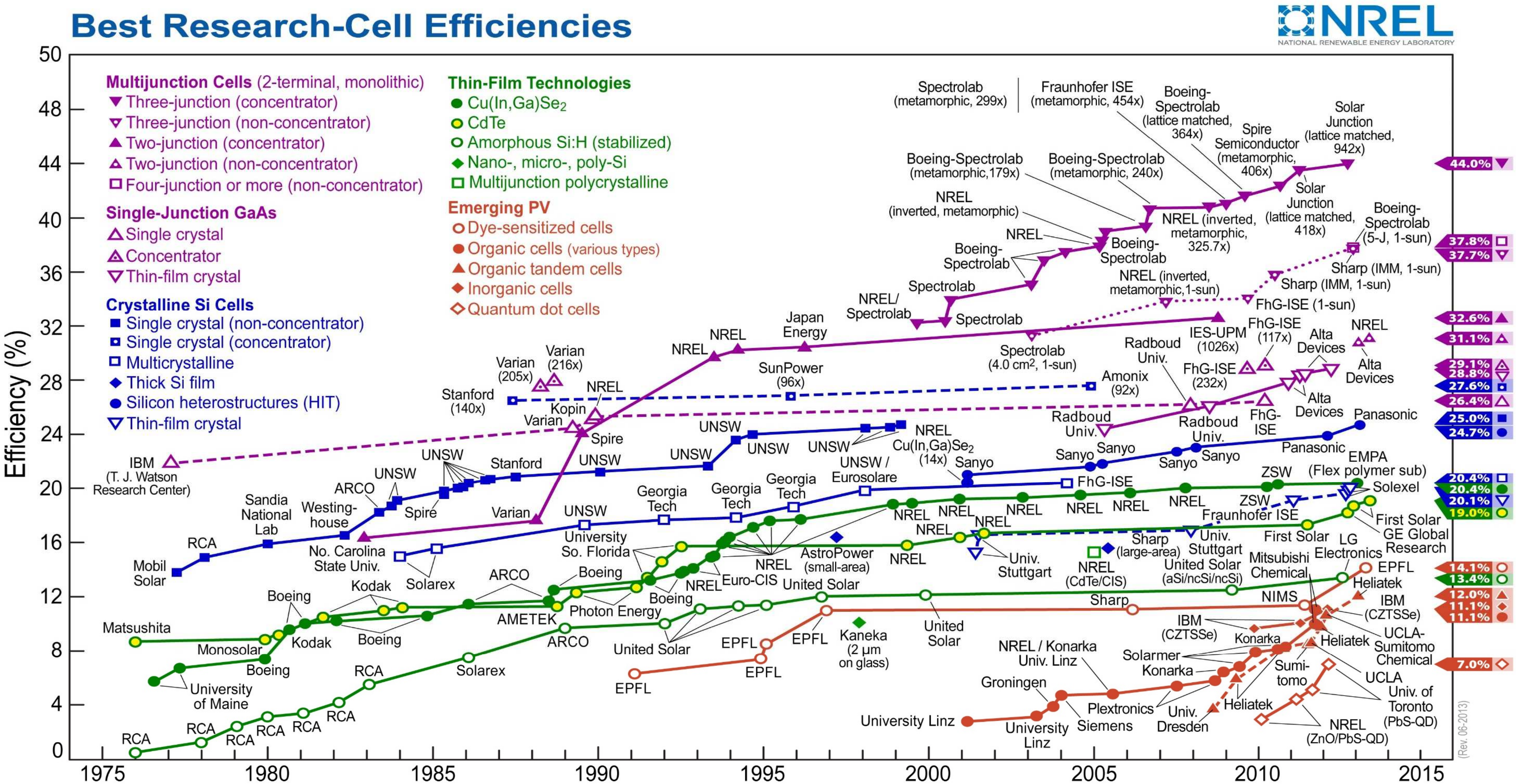
Source: Power Output Characteristics of Transparent a-Si BiPV Window Module, Solar Cells - Thin-Film Technologies

Heat Loss

- Conduction
- Convection
- Radiation



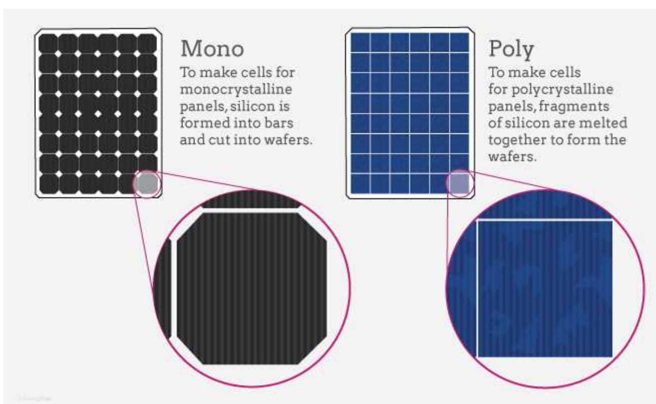
Best Research-Cell Efficiencies

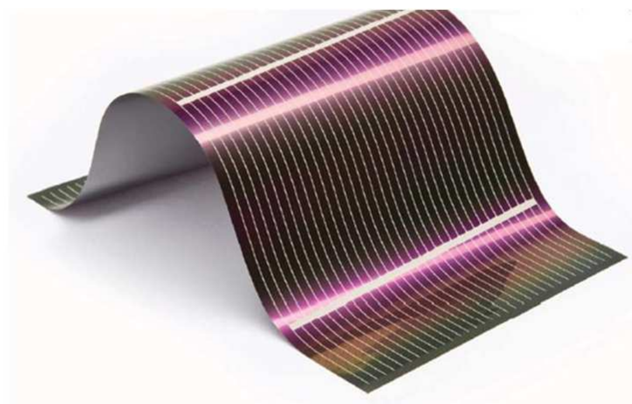


FOSS Research Centre for Sustainable Energy — DIEGO Development of quality system through EnerGy Efficency cOurses — Erasmus+ — University of Cyprus PV Technology

PV technology materials

- The active materials of PV cells can be classified:
  - **Crystalline Silicon** (mono/polycrystalline Silicon):
    sliced from ingots or castings or grown as thin slices from ribbons.
  - **Thin-film:** deposited as a thin layer on a low cost backing.
- In 2017, 95% of the world PV market was crystalline silicon.





PV technology materials: Monocrystalline Silicon cells

- Usually manufactured from a single crystal ingot of high purity, most commonly grown by the Czochralski method (crucible process).
- Diameter: 12.5 or 15 cm (4 or 5 inches).
- Ingot is cut into thin slices which are processed to make PV cells.
- The circular shape is cut away for better packing into a module.
- Cell shapes produced can be round, semi-round or square.

PV technology materials: Polycrystalline Silicon cells

- Alternative way of silicon PV cells.
- The starting material is melted and cast in a cuboid form.
- As the silicon solidifies, large crystals are formed with grain sizes from a few millimetres to a few centimetres.
- Ingot is cut into bars and then sliced into thin wafers that are used to make the cells, similar to the completion of single crystal cells.
- Slightly less expensive than Monocrystalline Silicon but also slightly less efficient.

PV technology materials: Thin-film cells

- Constructed by depositing extremely thin layers of PV materials onto a superstrate (front glass) or onto a substrate (module backside).
- Connections between the cells are an integral part of the cell fabrication so the PV module is made at the same time.
- Amorphous Silicon (a-Si), Copper Indium Diselenide (CIS) and Cadmium Telluride (CdTe) are used as the active semiconductor materials.
- Lower material and energy consumption and capability for high automation of module production offer considerable cost savings.
- However, efficiency is lower than for crystalline silicon technology.

CIS

CdTe

Current status

- Currently, most PV modules are installed on roofs/facades using a metal structure.
- PV system: Additional or applied structural element with the sole function of generating energy.

Current status

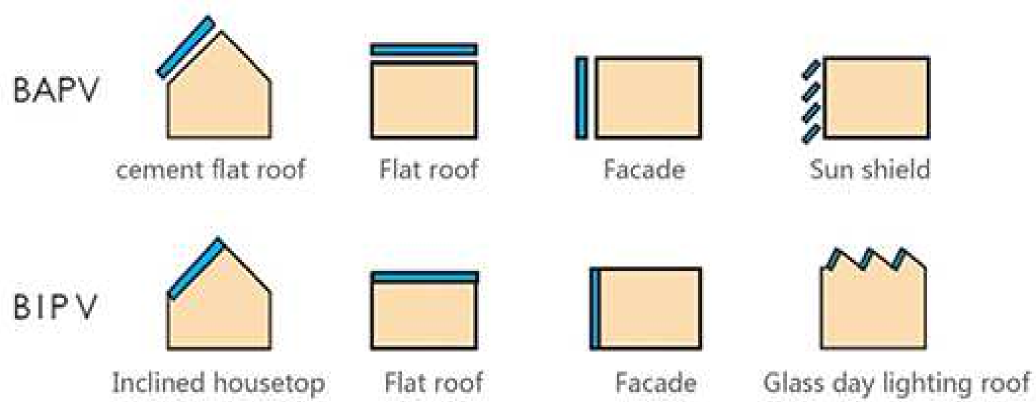
- In contrast, increasing application of PVs in which the system, as well as having the function of producing electricity, also takes on the role of a building element.



PV **is** the roof!

BAPV and BIPV definition

- BAPV (Building Applied Photovoltaics):
  - regular PV systems that are generally installed on top of roofs.
- BIPV (Building Integrated Photovoltaics):
  - PV systems integrated into the building envelope elements, such as construction materials as roof tiles and ceramic or glass facades.



BAPV and BIPV definition

- BAPV (Building Applied Photovoltaics):
  - regular PV systems that are generally installed on top of roofs.

• Metal Sheet Roof Mounting System

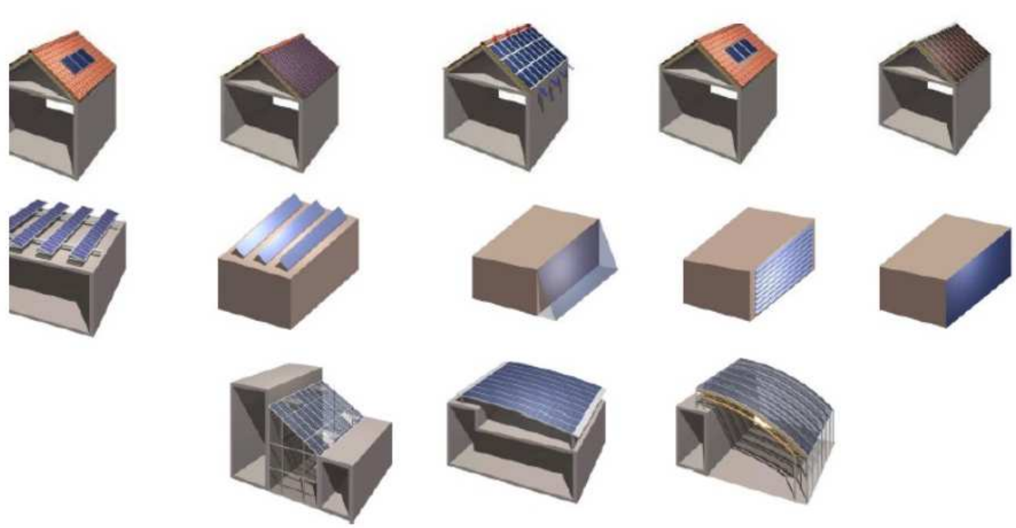
• Tile-on Roof Mounting System

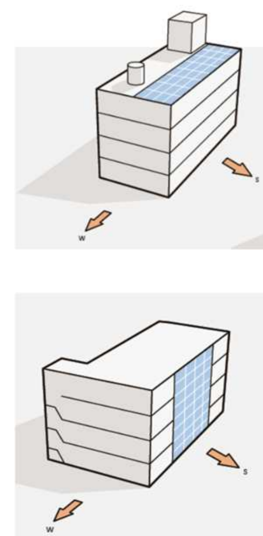
• Windstream Mounting System

• Flat Roof Mounting System

BAPV and BIPV definition

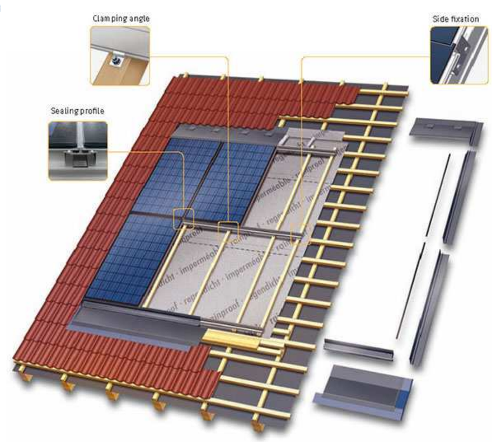
- BIPV (Building Integrated Photovoltaics):
  - PV systems integrated into the building envelope elements, such as construction materials as roof tiles and ceramic or glass facades.





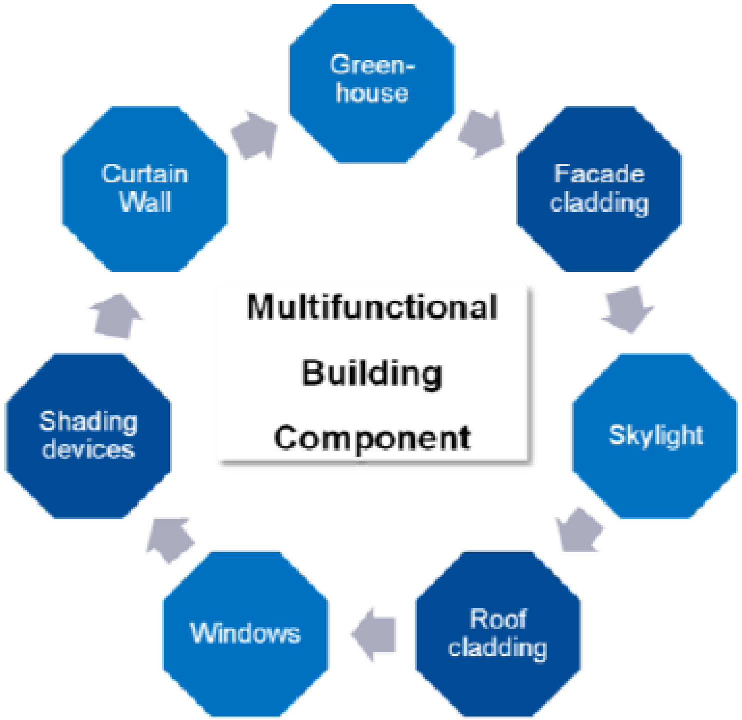
BAPV and BIPV definition

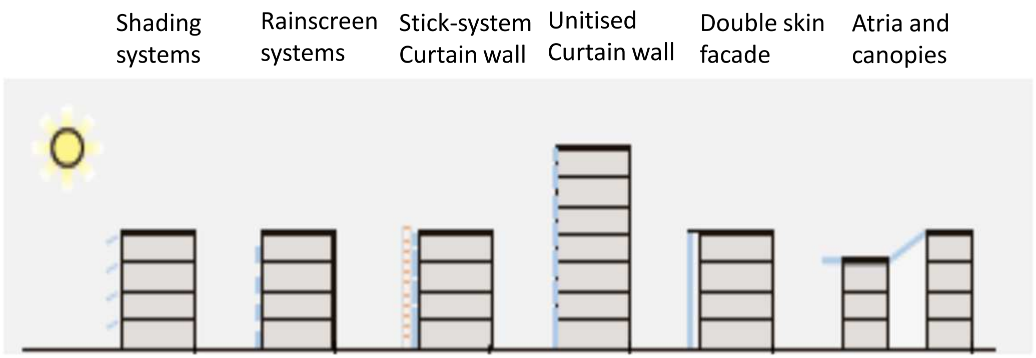
Some BIPV examples.



SolarBuildingTech, n.d.; Schüco, 2014

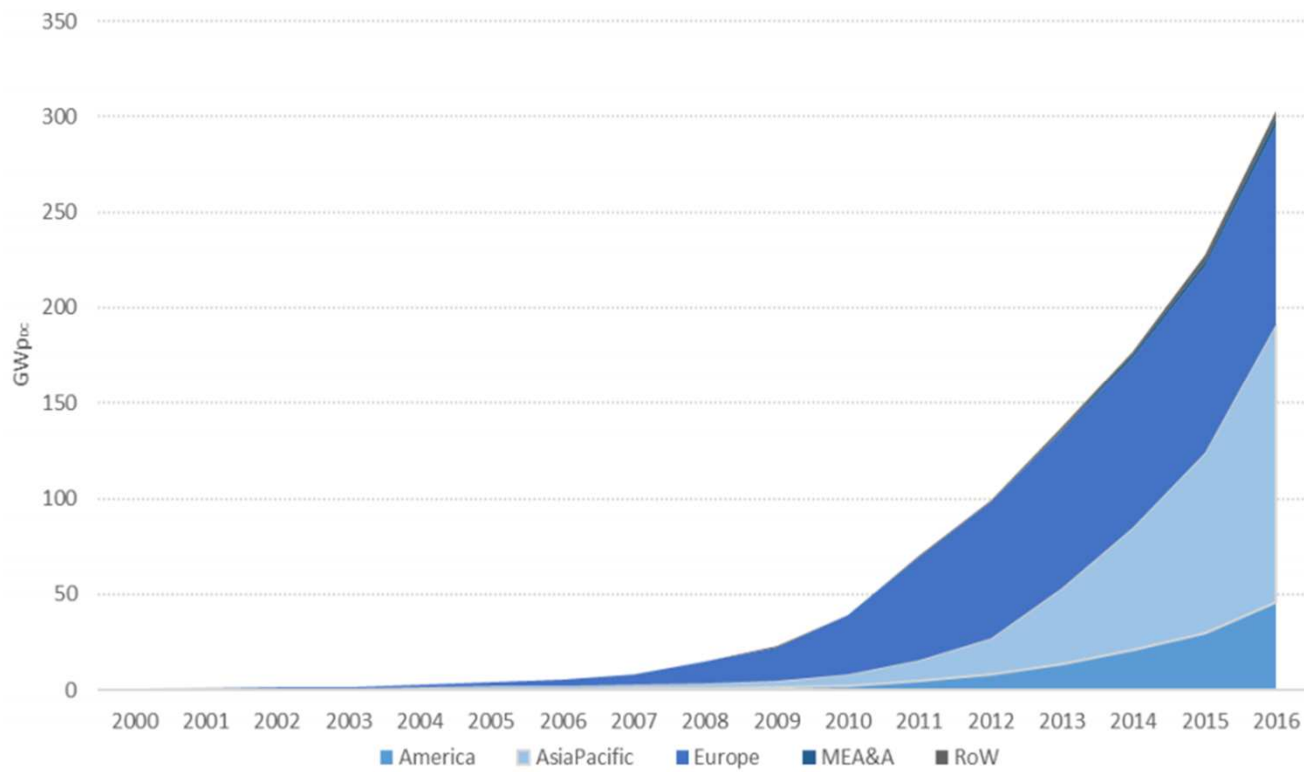
BIPV applications



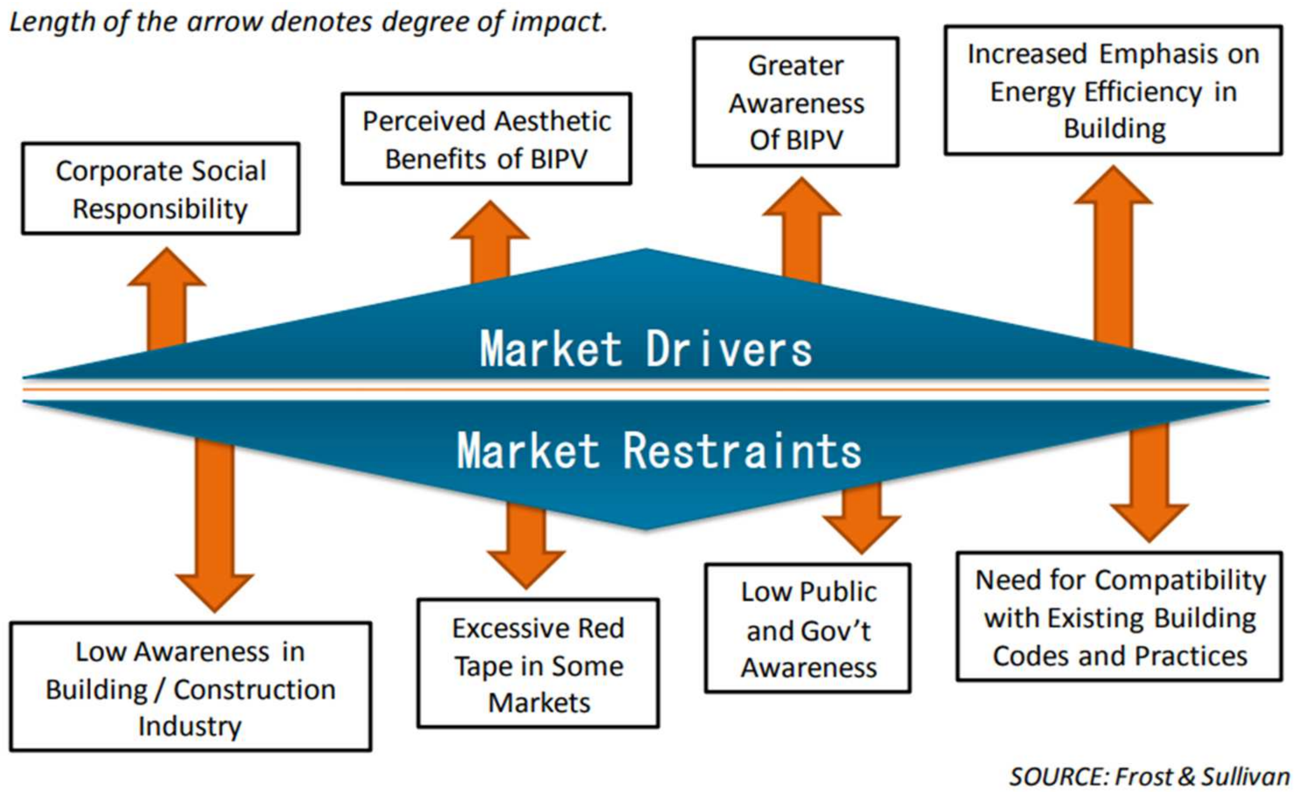


Market development for BIPV

Low penetration in the overall PV market but as PV technology becomes mature and the cost/performance balance is steadily improving, integration into buildings is steadily encouraged especially in the concept of NZEBs.



Market drivers for BIPV



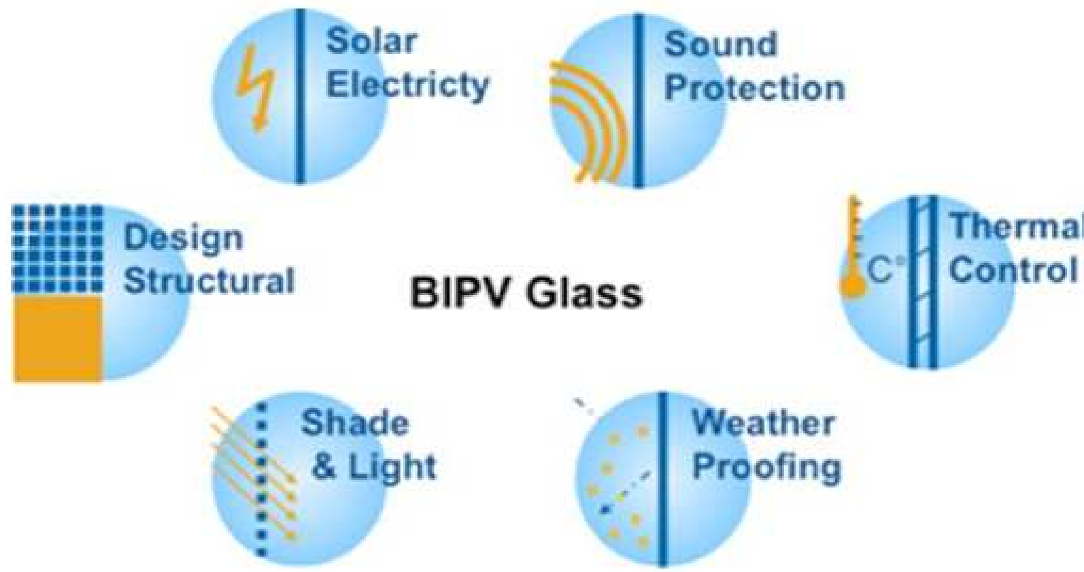
BIPV multi-functionality

Main functions to take over from conventional construction materials:

- Moisture protection
- Insulation
- Heating
- Cooling
- Managing natural lighting
- Sunscreens
- Limited transmittance (semi-transparent)
- Etc.

BIPV multi-functionality

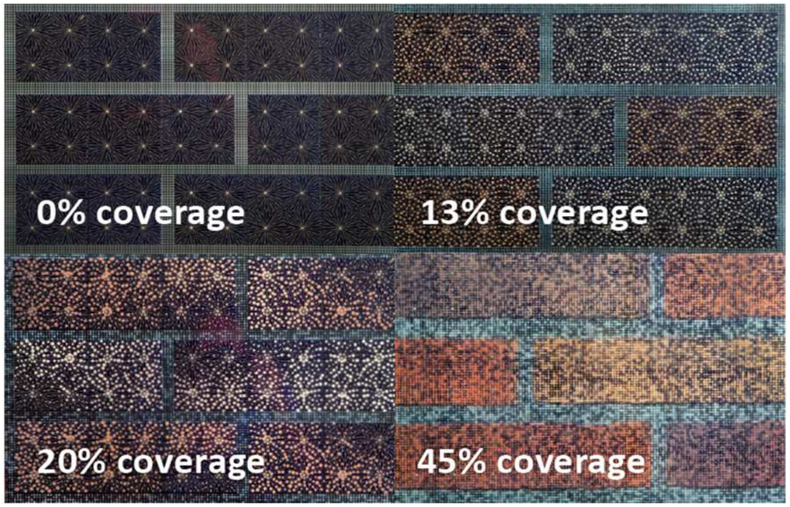
- BAPV less complicated
- BIPV take into account:
  - Requirements of construction materials (insulation, ventilation, etc.)
  - Architectural design
  - Optimal conditions for energy production
  - Financial aspects
  - Buildings regulations



BIPV multi-functionality

- Secondary functions: Design/Aesthetics
- To ‘enhance’ architectural appearance → **Architects making a stronger statement!**

PV-sunscreen (BISEM, 2012)



DSD PV: PV modules partly covered with a full color print (ECN).

Advantages of BIPV

- Lower costs (considering that a building element is replaced)
- No rural/unoccupied area required
- Electrically self-sufficient
- Lower electricity losses
- Increased aesthetics
- Decreased heat-transmittance
- Decreased harmful irradiance
- Internal shading
- Creating awareness for BIPV
- Interesting marketing-strategy

(Decreased heat-transmittance, Decreased harmful irradiance, Internal shading:) Improved internal environment → **comfort!**

Advantages of BIPV

- Ideal for use in the dense urban landscape

Table I. Potential of BIPV (Source: D. Fraile Montoro, 2008)*.

Available Roof Surface					
	Net Available Solar Surface (Km²)	Installable PV "Potential" (GW)	Estimated Electricity production (Twh/year)	Residential Electricity consumption 2006 (TWh/year)	% of PV
Europe (75%: Germany, France, UK, Italy, Spain)	3.723	465,4 (8m²/Kwp)	511,9	859	59%
		161,9 (23m²/KWp)	178,1		20%
USA	4.563	570,4 (8m²/Kwp)	570,4	1351	42%
		198,4(23m²/KWp)	198,4		14%
Japan	1.050	131,3 (8m²/Kwp)	118,1	229	51%
		45,7 (23m²/KWp)	41,1		18%

* Facades not included.

Disadvantages/barriers of BIPV

- Lower electricity performance (non-optimal orientations, thin-films, etc).
  - Cell-efficiency reduction
  - Compensation with more installation space on buildings apart from roof
- (Partial)-shading
- BIPV is experienced as ‘too difficult’
  - Shortage of specialists
- Critics on aesthetics

Legal, admin & market barriers

BIPV not new (more than 20 years!) → But still: under-developed niche

Legal & administrative barriers:

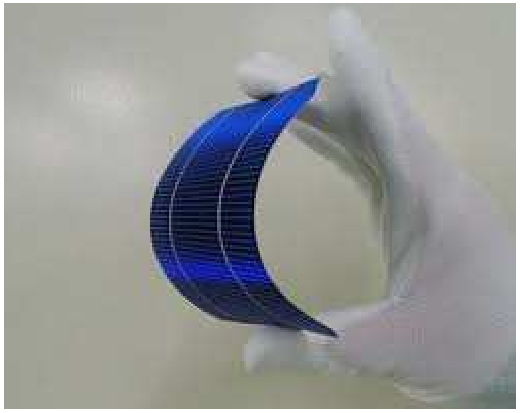
- Not yet defined as **energy-efficient technology** in many places
  → complex planning policies & procedures (e.g. not possible on most historic buildings)

Market barriers:

- **Costly** compared to BAPV (added value as **multifunctional building element not recognized** yet)
- **'Language' problem** between **PV industry** and **building sector**:
  different units of measurement e.g. *architects/planners: kWh/m2 but PV community: kWh/KWp*
  (not familiar with concept of watt power, prefer estimation of PV module price $/m2)
- **Perception obstacle**:
  Advantages for architects and end-users not clearly defined; don't see it as **valuable asset**; don't see it as **aesthetically-pleasing**; lack of information?

Technical barriers

- Predominant use of mature yet costly c-Si in envelopes (at minimal sunlight & high temperatures → poor performance).
- Thin-film challenges: Optimal system orientation, weather ability, lifetime, lack of standards/building codes, performance, competitive pricing.



Technical barriers

Lack of own/specific standards for BIPV:

- Combining functionality of building materials & PV → new standards should address **materials/architectural/safety/electrical issues** & long-term **performance** issues
- **Complex** as requirements for standards (e.g. buildings) are mostly **related to a country or region** → a BIPV manufacturer must comply with **different standards** depending on country of application

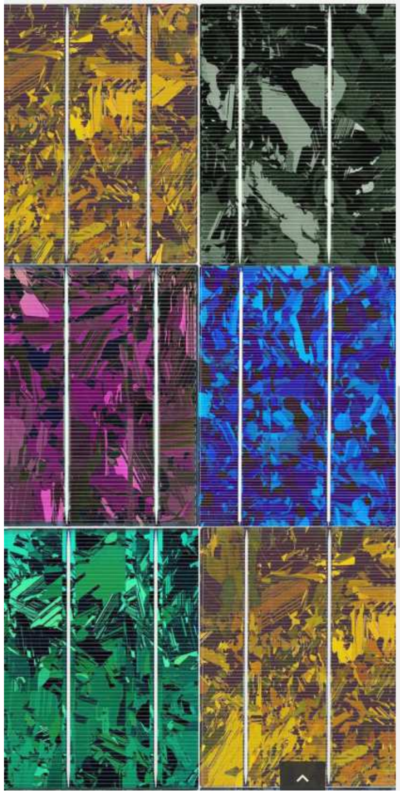
PV module standards	**Building** standards
IEC International Electrotechnical Commission	ISO International Organization for Standardization
CENELEC European Commission for Electrotechnical Standardization	CEN European Committee for Standardization

BIPV products – Customisation

Characteristics:

- Material:
  - Crystalline, Thin-film, other
- Transparency:
  - Opaque, semi-transparent, transparent
- Colouring
- Shapes
- Sizes (cell, module)
- Distance between cells in a module
- Flexibility

→ **Variety of customisation!**



BIPV products – Tiles

BIPV products – Tiles (Vatican City)

- 1st PV plant for Vatican next to St. Peter's
- 2,394 dark solar modules cover roof of the 'Paolo VI' audience hall (221.59 KWp)
- The solar panels replaced the 4,800 degraded concrete tiles
- Rigid rules of Italian & International Restoration Chart.
- Optimal adaptation to the shape of the building - challenging architectural design

Figure 11. The BIPV plant on the roof of the Vatican 'Paolo VI' hall is magnificent example of philological restoration coupled to clean electricity generation. BIPV at its best. (Photo credit: energia e ambiente Srl).

BIPV products – Full roof solution

Zanetti et al., 2017

BIPV products – Solar cell glazing

- Options for windows, facades, roofs.
- Variety of materials and distances between cells.
- Different colours & transparencies
  - Variable transparency 10-50%
- Modules transmit daylight and serve as water and sun protection
  - E.g. greenhouse use
- Good efficiency in non-optimal positions
- Glass-glass frameless design for improved aesthetics

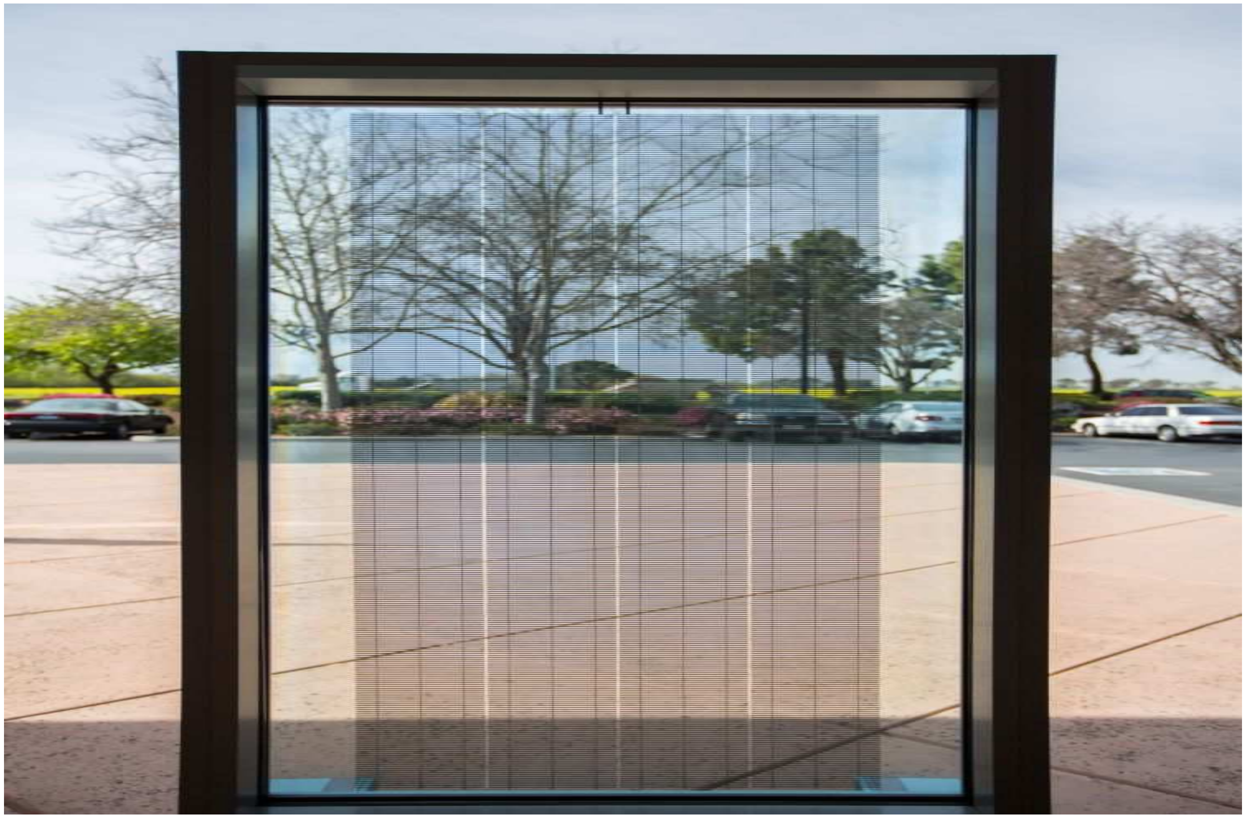
Bifacial Flexible Module

Source: https://www.pv-tech.org/products/jolywoods-bifacial-paving-module-boasts-front-power-of-430w-efficiency-of-2

FOSS
Research Centre for
Sustainable Energy

University of Cyprus
PV Technology

Semi Transparent Modules



Source: https://www.pv-tech.org/products/solaria-provides-powervision-series-of-customized-architectural-glass-modul

Glass Glass BIPV modules

Source: https://www.pv-tech.org/products/aleo-solar-designs-elegante-monocrystalline-glass-glass-module-for-bipv-app

BIPV products – Solar cell glazing

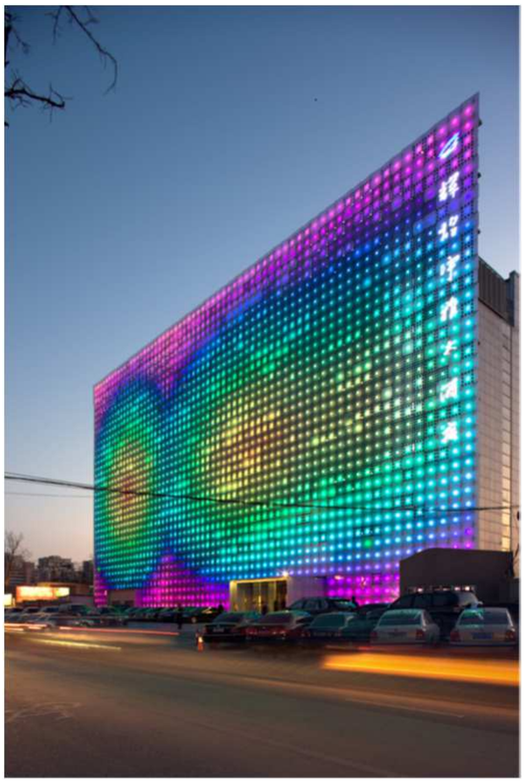
Polysolar, UK

Kameleon solar

BIPV products – Atria and canopies

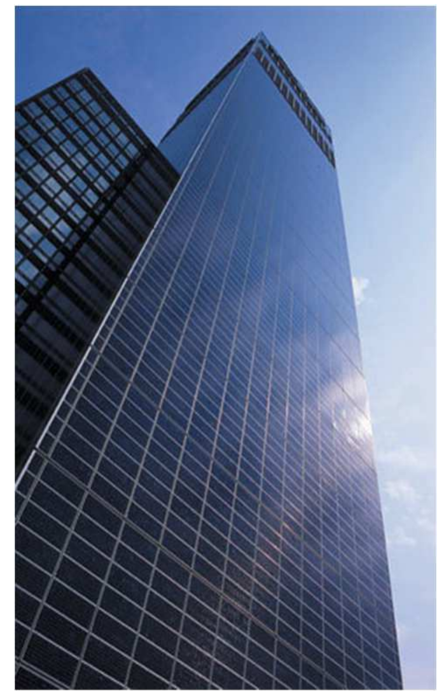
- Canopies are similar to atria consisting of horizontal or gently inclined faces, high on a building.

BIPV products



*Greenpix Zero Energy Media wall: The largest color **LED display** combined with a **PV-system** in the **glass curtain wall***

CIS Tower in Manchester



BIPV characteristics – Design life

- **Design life** of **building envelopes** and their **components** depends on the **building use**.
- Three types of elements must be considered:
  - **Replaceable elements**:
    intended to last less than the design life of the building and for which replacement has to be considered at design stage, e.g. double-glazed units (20–25 years).
    BIPV is in this type!
  - **Maintainable elements**:
    intended to last the design life of the building with periodic treatment and maintenance, e.g. weathering gaskets.
  - **Lifelong elements**:
    intended to last the design life of the building without maintenance, e.g. cladding framing members.

BIPV characteristics – Safety

- Safety is a standard consideration with all electrical installations.
- Contact with the front surfaces of PV modules poses no danger.
- Particular issues that apply to PV installations:
  - Current is produced during a wide variety of light conditions (PV modules can only be "switched off" by covering with something opaque).
  - Less familiarity within the building industry with DC compared with AC.
  - Voltages can be higher than the familiar 230 V single-phase AC.
- Safety issues should be well documented for both installers and maintenance personnel.

BIPV characteristics – Acoustic performance

- Primarily a function of the glazing mass and composition, and the quality of the internal seals to stop air leakage.
- Sound insulation of curtain walls can be improved by installing sound attenuating infill and making construction as airtight as possible.

BIPV characteristics – Natural lighting

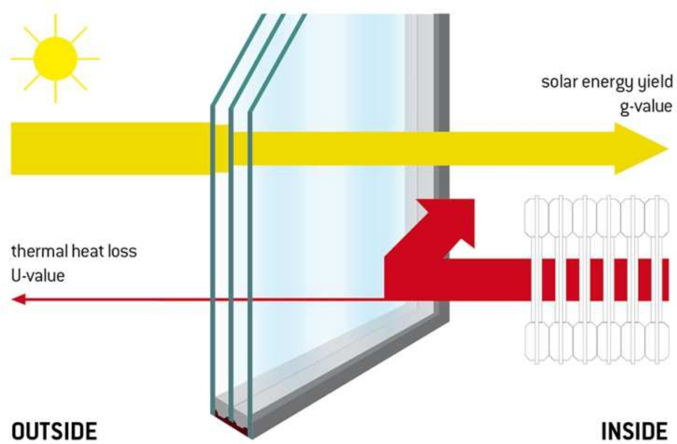
Amount of incoming natural light and visual contact with exterior defined by:

- Number of windows with incorporated cells.
- Number of cells incorporated in the windows.

Onyx, 2017

BIPV characteristics – Thermal performance

- Building envelope needs to:
  - mediate transfer of heat between internal and external environment.
  - create a comfortable indoor environment while using the minimum amount of energy.
- Important parameters for the thermal performance:
  - U-value: Heat losses
  - G-value: Solar heat gains



Van Dyk, 2017

BIPV characteristics – Air/Weather-tightness

- Building envelope: Air-tightness & Weather-tightness
  - Air-tightness:
    The façade design should incorporate continuous air barriers to minimize air infiltration through the fabric.
  - Weather-tightness:
    A building facade needs to be weather-tight. Cladding design should incorporate multiple lines of defence against water ingress.

Case studies: Rainscreen systems

- The Co-operative Insurance Tower in the UK
- PV specifications:
  - Area: 3972 m^2
  - Peak power specification: 391 kWp
  - Power output: 183,000 kWh/y (estimated)

Case studies: Stick-system curtain wall

- Tobias Grau GmbH Head Office in Germany
- PV specifications:
  - Area: 179 m^2
  - Peak power specification: 18 kWp
  - Power output: 10,800 kWh/y (estimated)


Case studies: Unitised curtain wall

- Alan Gilbert Building in Australia
- PV specifications:
  - Area: 426 m^2
  - Peak power specification: 46 kWp
  - Power output: 40,000 kWh/y (estimated)

Solar Roofs (Tesla/Solar City)

Source: https://www.pv-tech.org/products/tesla-solarcity-launches-multiple-styled-solar-roof-tiles-replicating-origi

FOSS
Research Centre for
Sustainable Energy

University of Cyprus
PV Technology

Some more demo sites

https://www.pvsites.eu/project/demo-sites/

https://www.youtube.com/watch?v=4OG2CVyxv8w

https://www.youtube.com/watch?v=fCzEm-ZrCuo

FOSS Research Centre for Sustainable Energy | DIEGO Development of quality system through EnerGy Efficency cOurses | Erasmus+ | University of Cyprus PV Technology

Conclusions

- BIPV: PV elements used to replace conventional building materials in parts of the building envelope
- Increasingly being incorporated into new buildings as a source of electrical power.
- Advantage of BIPV over common non-integrated systems
  - The initial cost can be offset by reducing the amount spent on building materials and labour that would normally be used.
- Legal, admin, market & technical barriers inhibiting market development and expansion.
- Optimal method of installing RES in urban, built-up areas where underdeveloped land is scarce and expensive.
- Their widespread use is expected to become the backbone of European NZEB targets for 2020.

The value of PV!

https://www.youtube.com/watch?v=ckHVU7DKZAs

Thank you for your attention!

Prof. George E. Georghiou
Director FOSS

University of Cyprus
1 University Avenue
New University Campus
P.O. 20537
1678, Nicosia

Tel: +357 22 894397
Email: geg@ucy.ac.cy
Website: www.pvtechnology.ucy.ac.cy

Acknowledgment

Partners