The photovoltaic power

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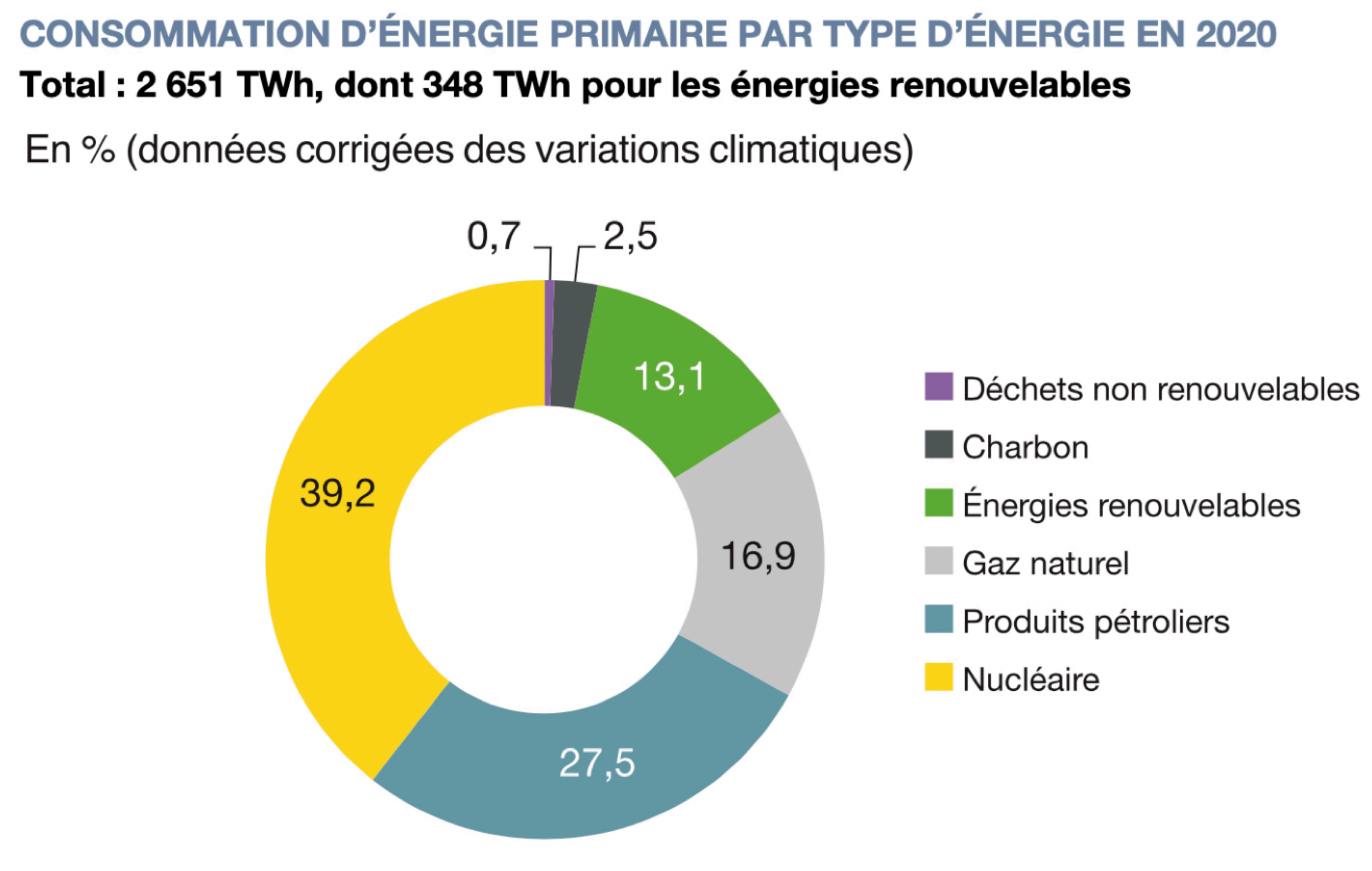
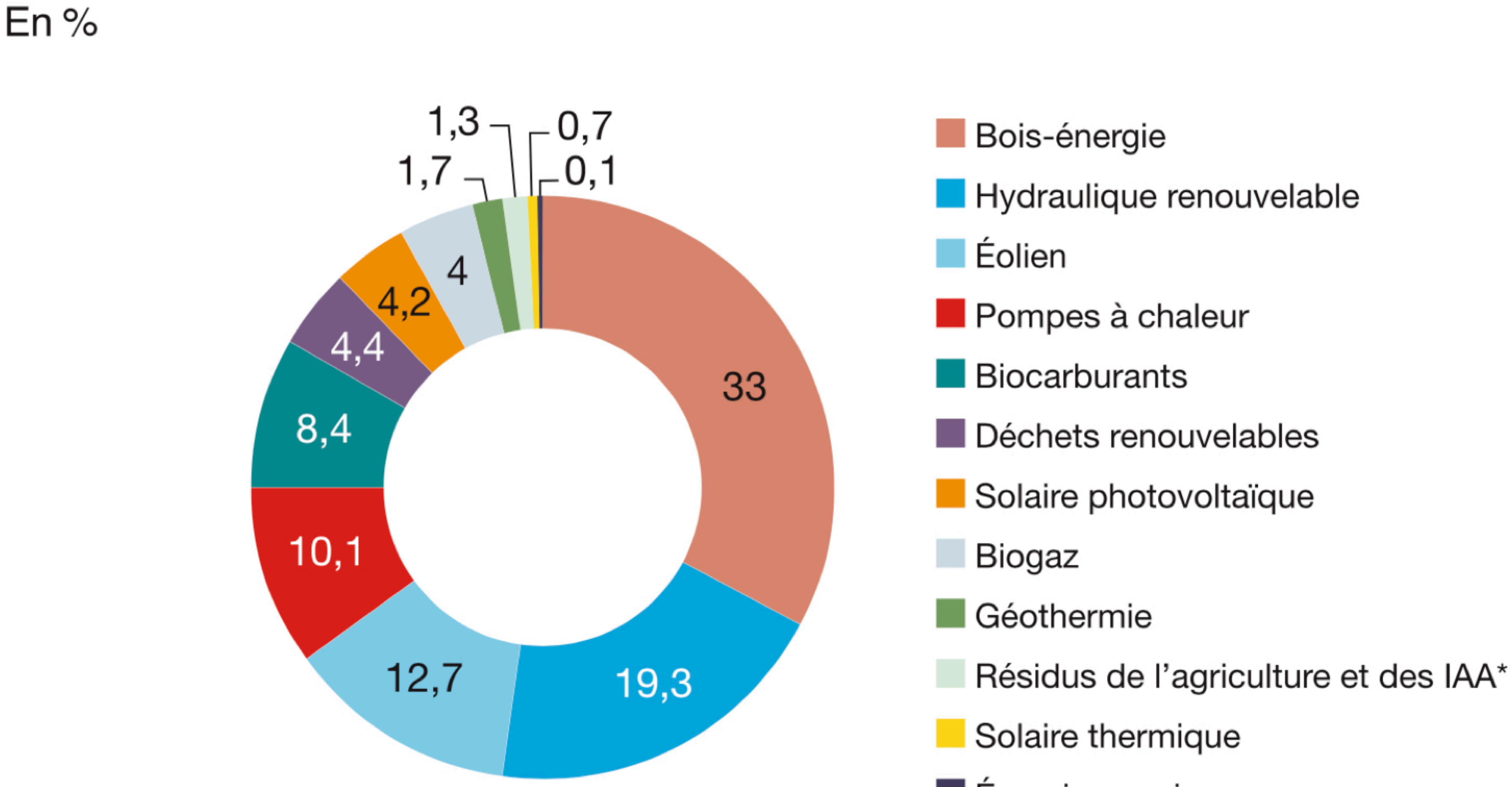
Section I. Energy production (France)



PRODUCTION PRIMAIRE D'ÉNERGIES RENOUVELABLES PAR FILIÈRE EN 2020

Total : 322 TWh



** IAA : industries agroalimentaires.*

***Source :** calculs SDES*

Hydro-power in France is distributed like:

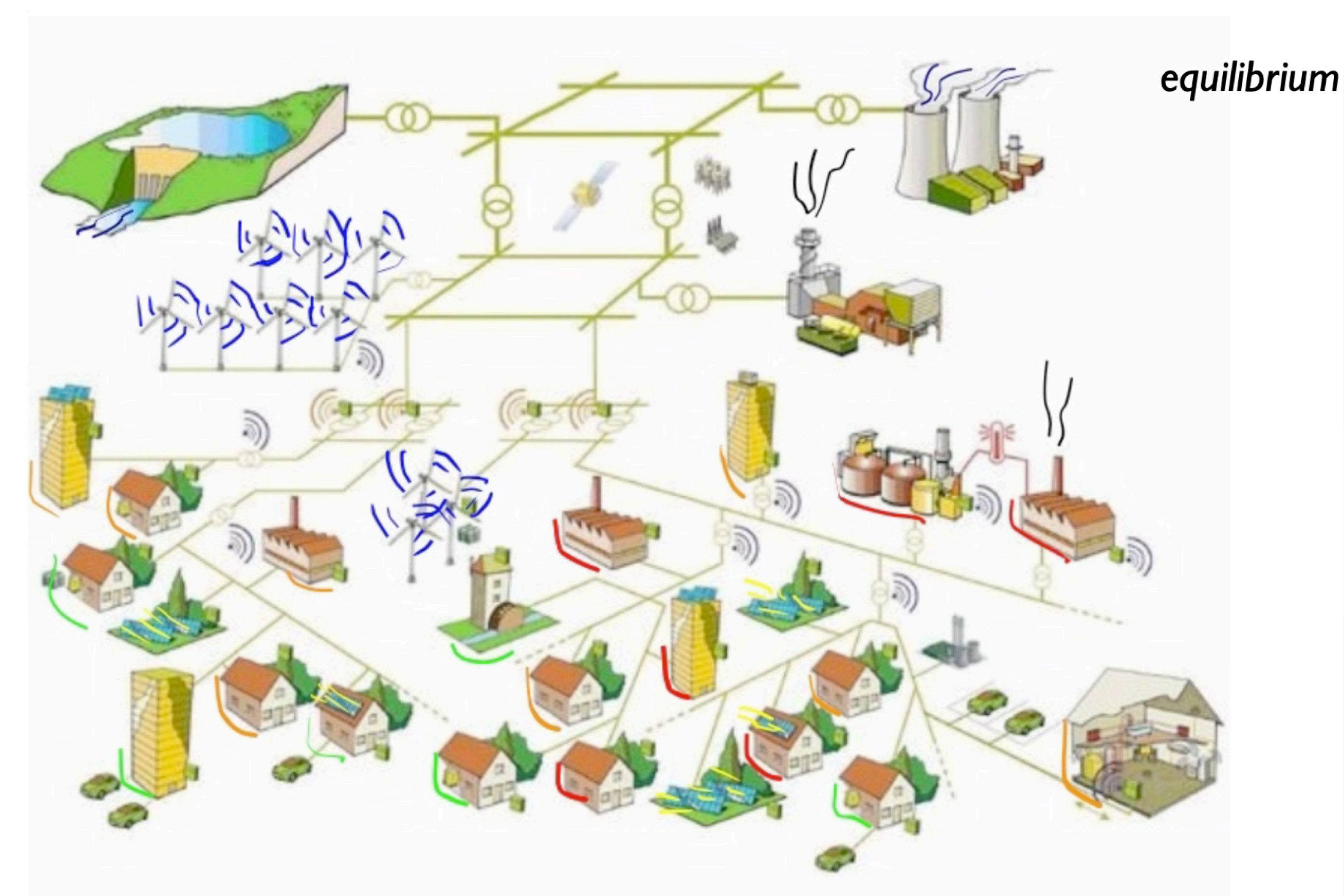
- gravity dams: 55%
- Pumped-storage power stations (STEP): 18%
- run-of-river dams: 27%

Energy lost when not consumed is called "fatal energy"

% of fatal energy in France? now ? and from 100% renewables?

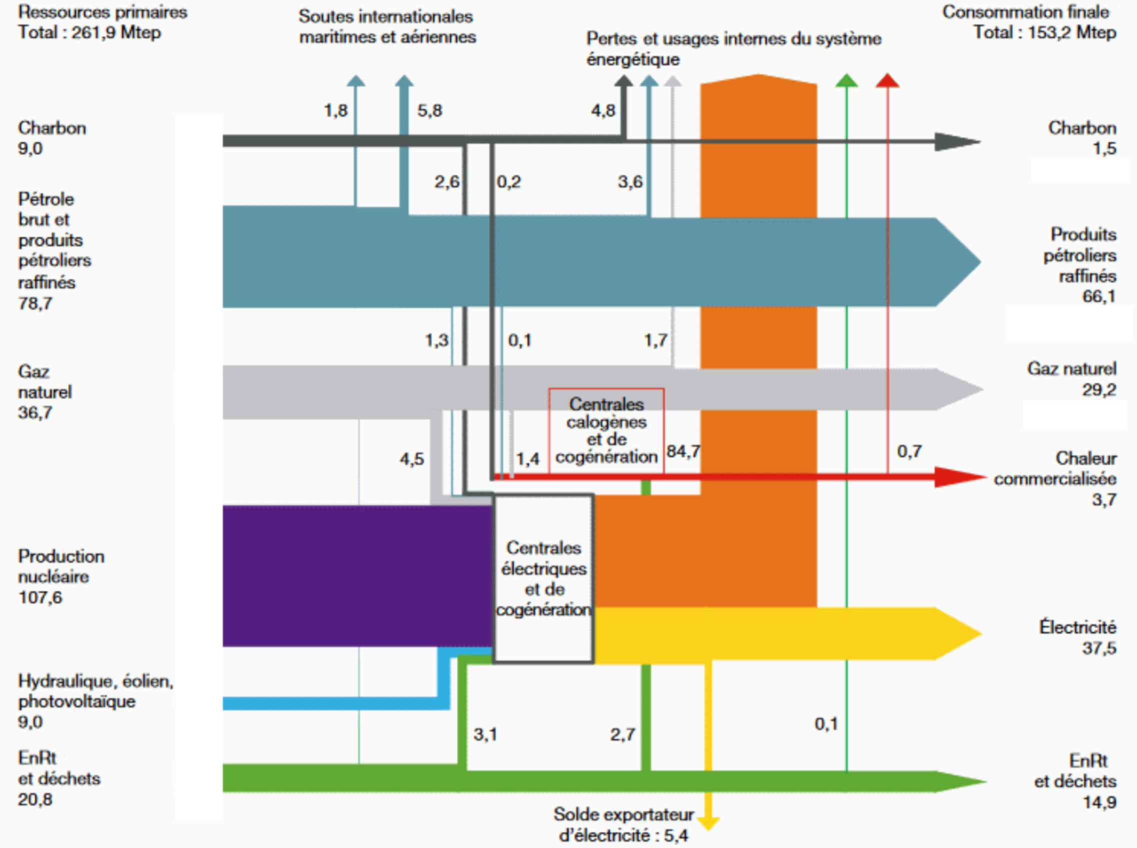
- Now 3.1%→ windmills (1.7%), run-of-river dams(0.7%), photovoltaic(0.6%), thermal solar(0.1%) → 3.1%
- Only renewables → 22.8%

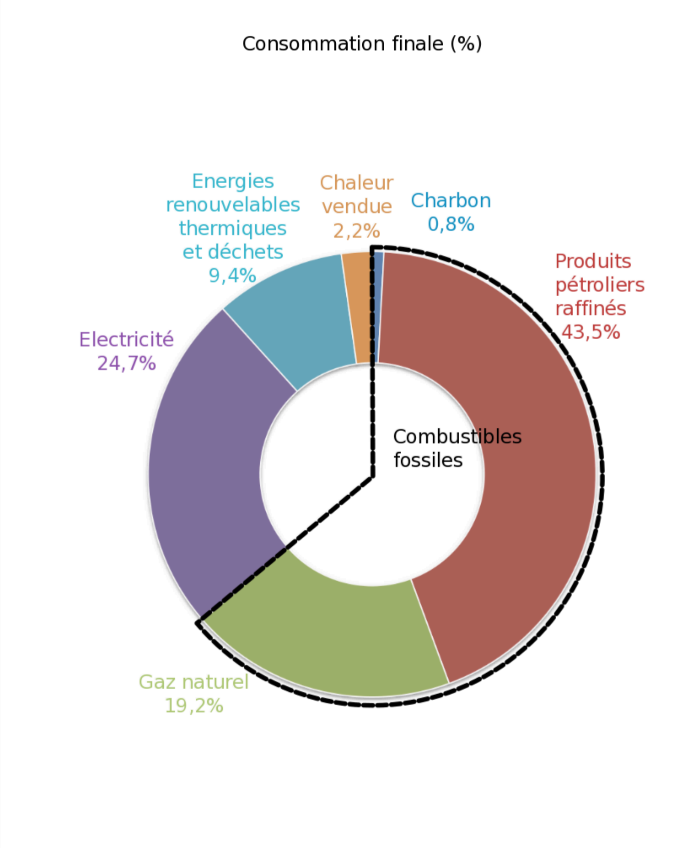
Production and consumption must be balanced (anytime)



From primary to final energy

1 unit of final electricity = 2.58 units of primary energy





Photovoltaic technologies

3 major families:

1. First-generation: crystalline silicon (dominant market)
   more than 90% of the global PV market
2. Second-generation: thin-film technologies
3. Third-generation: emerging and advanced technologies

and Polycrystalline Silicon (18-21% efficiency) but no more on market

Crystalline Silicon Technologies

Monocrystalline Silicon (Mono-Si)

- Cells are cut from a single silicon crystal.
- Uniform dark appearance.

Typical commercial efficiency (2025-2026)

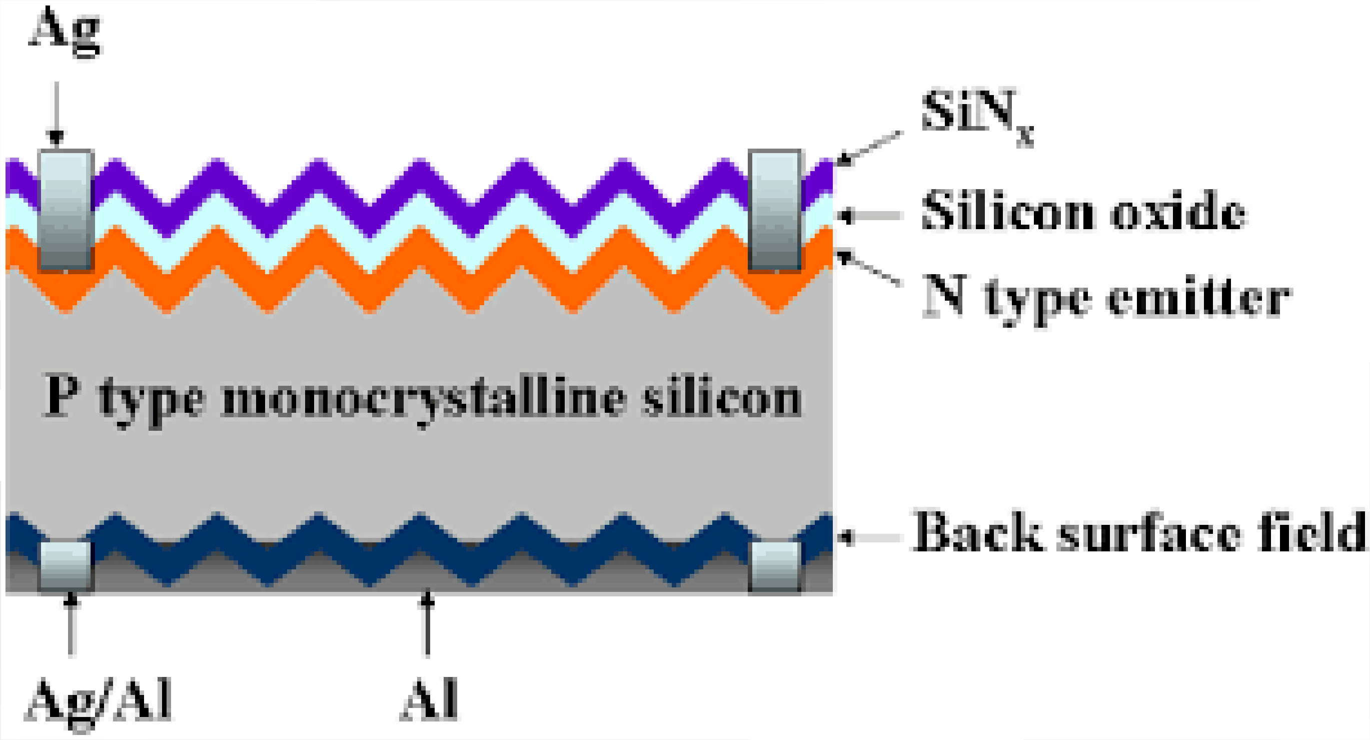
- Module efficiency: 21–24%
- Best commercial modules: 24–25%
- Laboratory records: Silicon cells: >27%

Advantages

- Highest efficiency among mass-market technologies
- Good longevity (>30 years)
- Excellent reliability

Disadvantages

- More energy-intensive manufacturing
- Higher cost than some alternatives

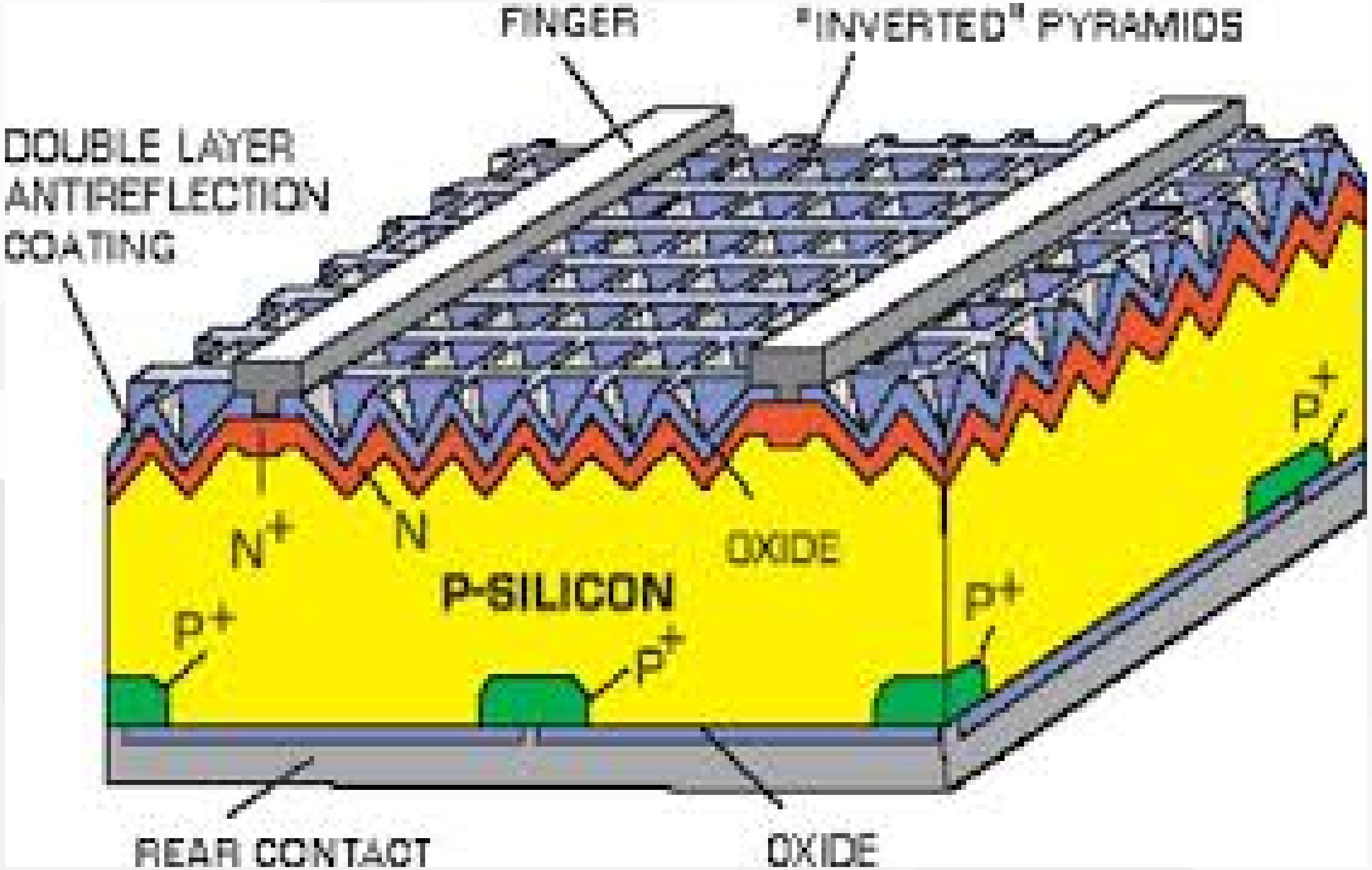

Ag
SiNx
Silicon oxide
N type emitter
P type monocrystalline silicon
Back surface field
Ag/Al
Al

PERC (Passivated Emitter and Rear Cell)

A refinement of conventional monocrystalline cells.

Typical efficiency : 21–23%

- Mature technology
- Being progressively replaced by TOPCon and HJT.


FINGER
"INVERTED" PYRAMIDS
DOUBLE LAYER
ANTIREFLECTION
COATING
N+
N
OXIDE
P-SILICON
P+
P+
P+
P+
REAR CONTACT
OXIDE

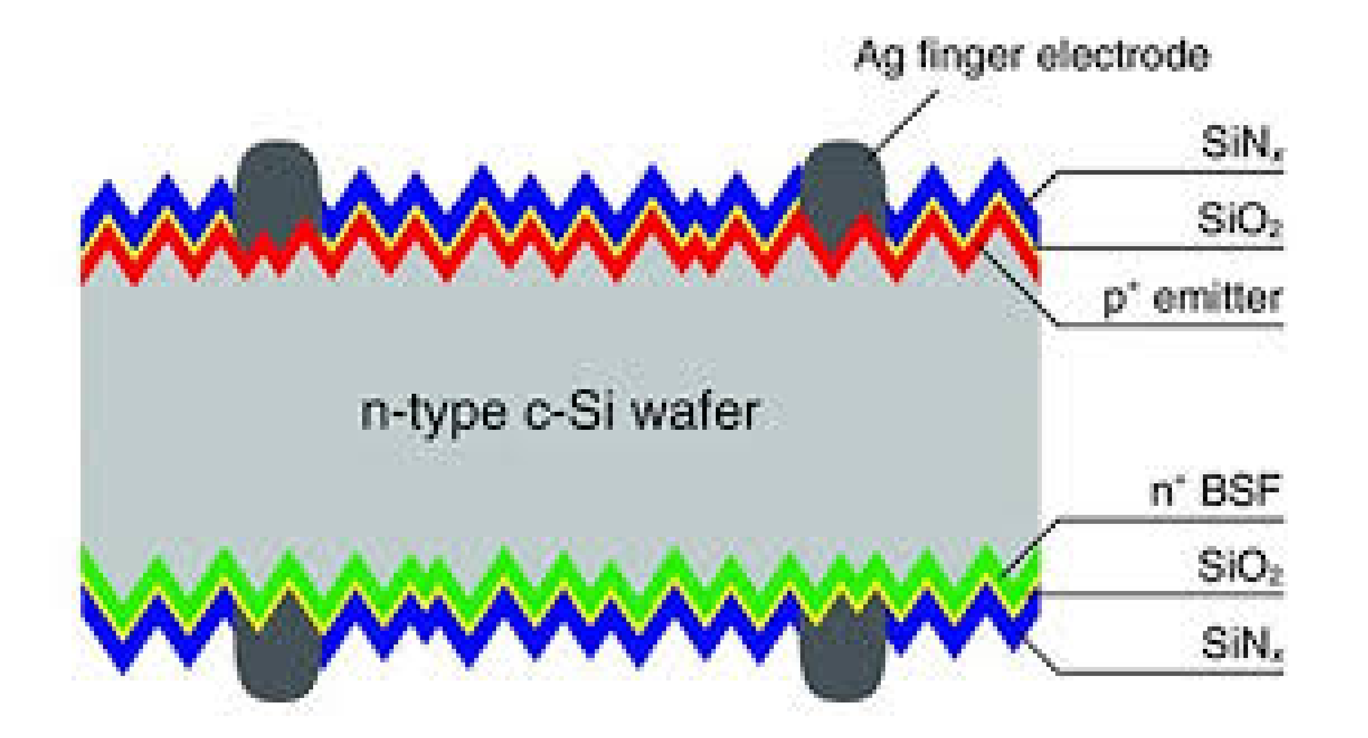
TOPCon (Tunnel Oxide Passivated Contact)

Currently the dominant premium technology, rapidly replacing PERC

- Commercial modules: efficiency 22–24.5%
- Cells: efficiency 25–27%

Advantages

- Better low-light performance
- Lower degradation
- Compatible with existing silicon production lines


Ag finger electrode
SiN_x
SiO_2
p^+ emitter
n-type c-Si wafer
n^+ BSF
SiO_2
SiN_x

HJT (Heterojunction Technology)

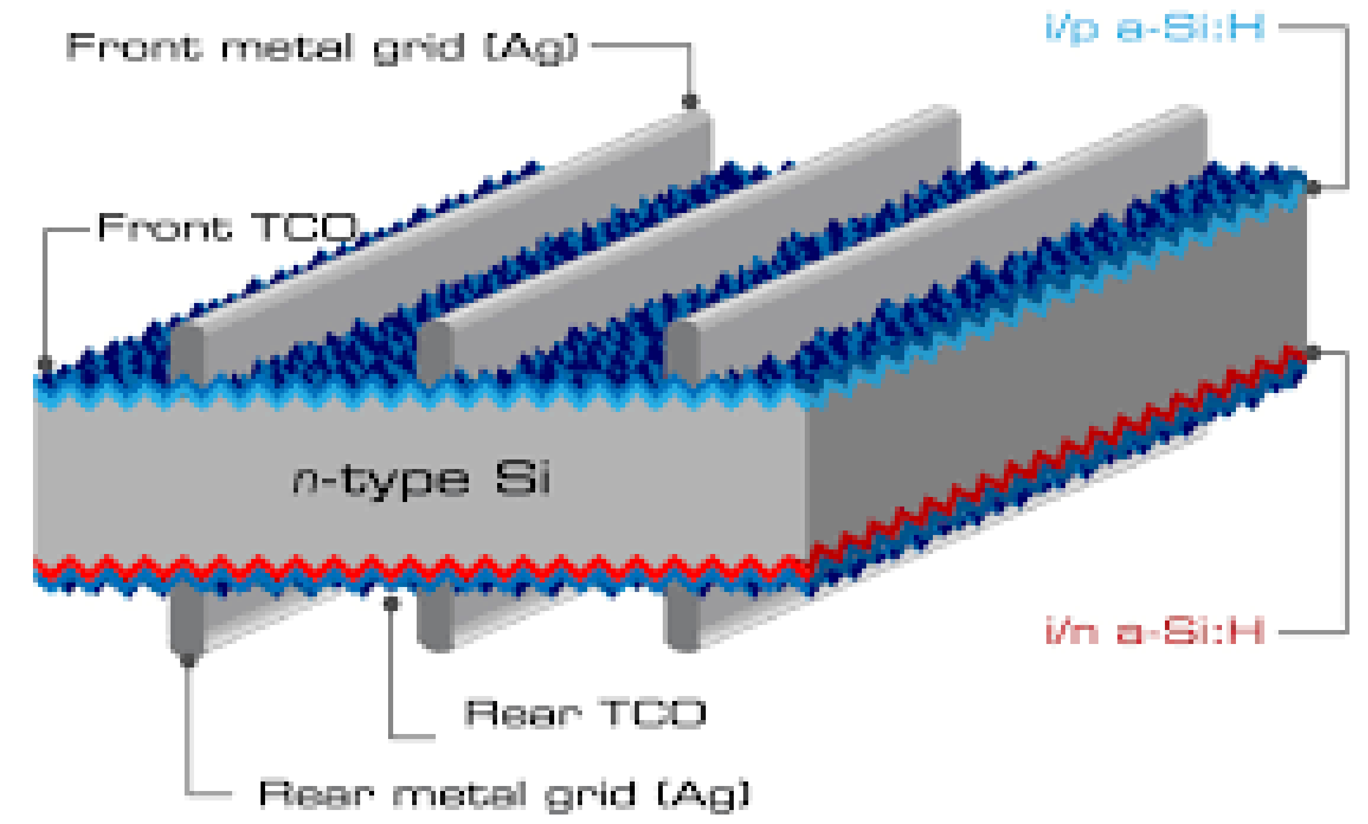
Combines crystalline silicon and thin amorphous silicon layers.

- Commercial modules: efficiency 23–25%
- Cells: efficiency 26–27%

Advantages

- Excellent temperature behavior
- High bifacial gain
- Low degradation

Disadvantages : higher manufacturing cost


Front metal grid (Ag)
i/p a-Si:H
Front TCO
n-type Si
i/n a-Si:H
Rear TCO
Rear metal grid (Ag)

IBC (Interdigitated Back Contact)

Used in premium modules.

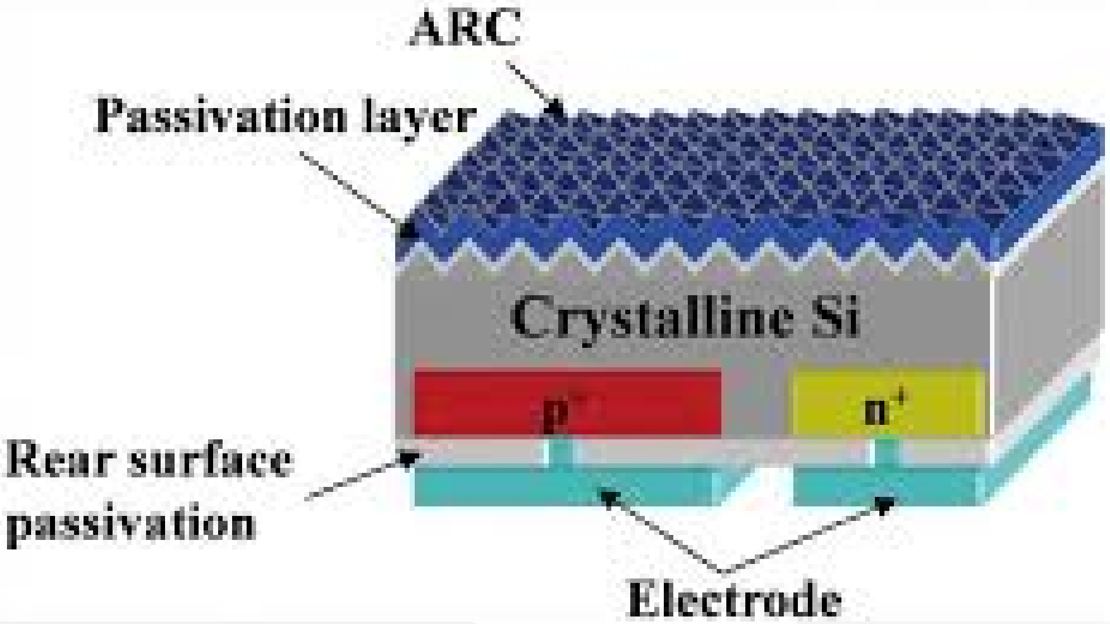
- Commercial modules: efficiency 23–25%
- Cells: efficiency >27%

Advantages

- No front-side metallic contacts
- Very high efficiency
- Attractive appearance

Example: Maxeon modules.

Interdigitated back contact (IBC) cells



Thin-Film Technologies

Cadmium Telluride (CdTe)

- Commercial modules: efficiency 18–21%

Major manufacturer

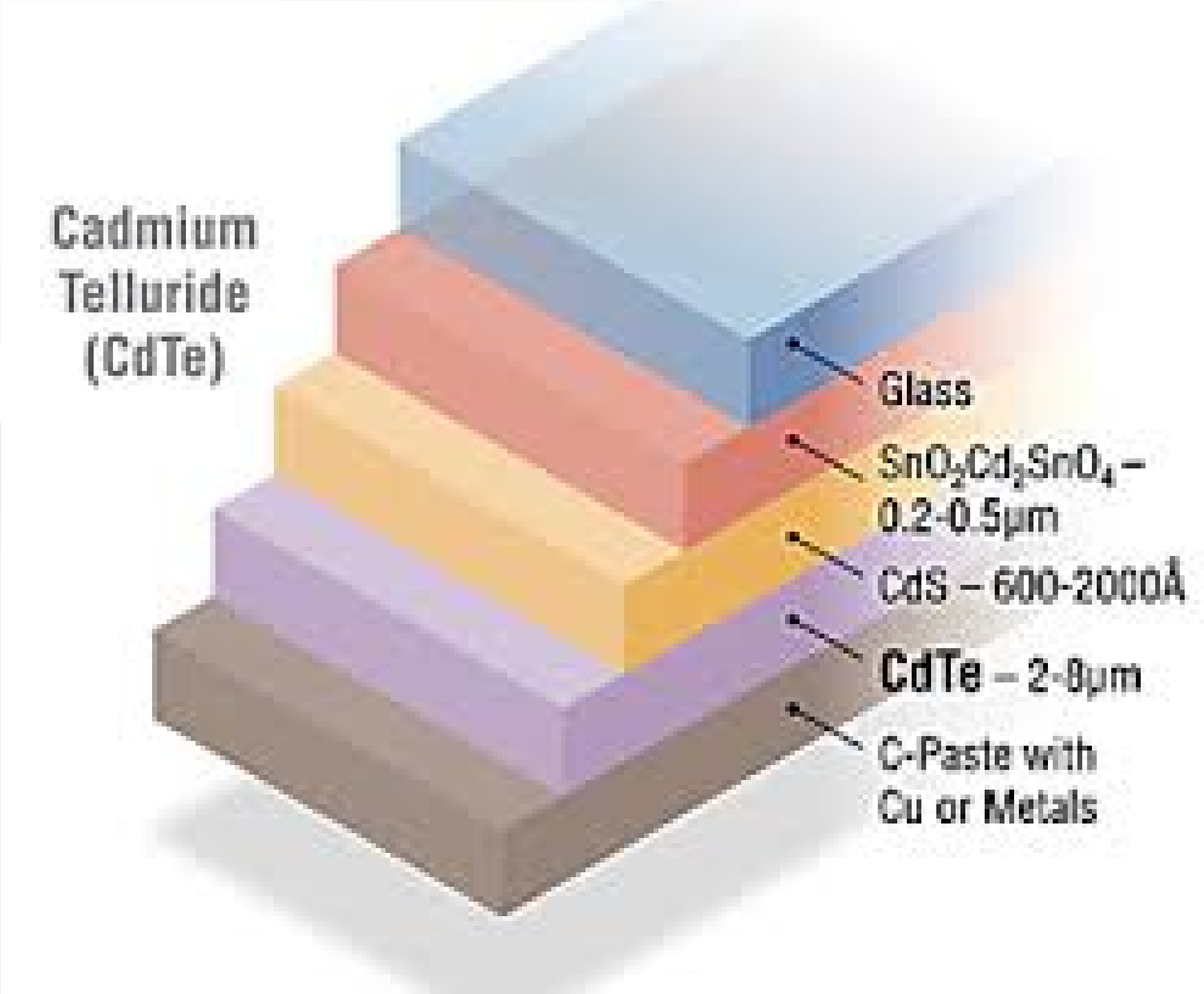
- First Solar

Advantages

- Low manufacturing cost
- Good performance in hot climates
- Lower sensitivity to shading

Disadvantages

- Contains cadmium
- Lower efficiency than premium silicon


Cadmium
Telluride
(CdTe)
Glass
$SnO_2Cd_2SnO_4$ –
0.2-0.5μm
CdS – 600-2000Å
CdTe – 2-8μm
C-Paste with
Cu or Metals

CIGS (Copper Indium Gallium Selenide)

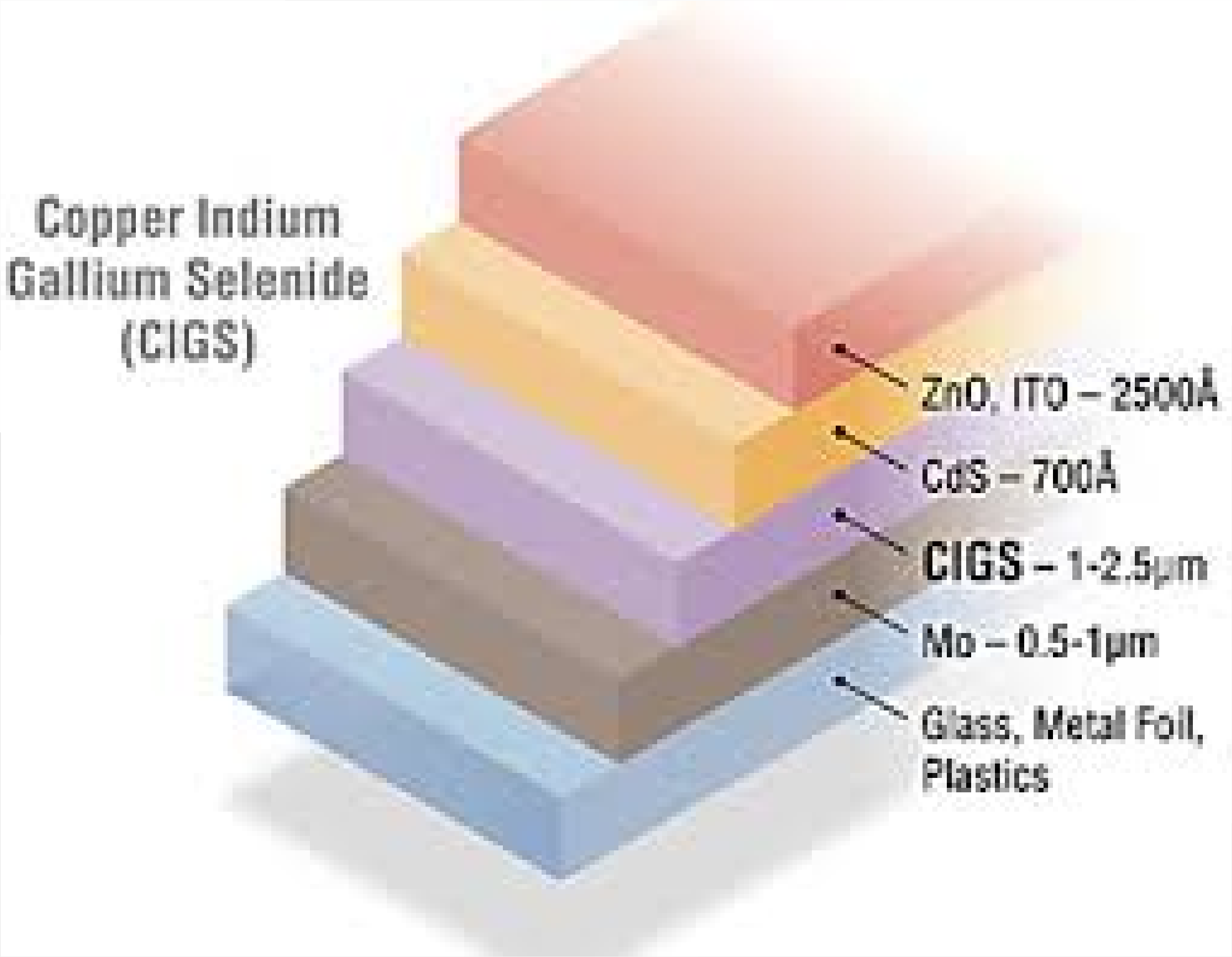
- Commercial modules: efficiency 15–20%
- Best cells: 23–24%

Advantages

- Flexible modules possible
- Lightweight
- Good low-light performance

Applications

- Building-integrated photovoltaics (BIPV)
- Portable systems


Copper Indium
Gallium Selenide
(CIGS)
ZnO, ITO – 2500Å
CdS – 700Å
CIGS – 1-2.5μm
Mo – 0.5-1μm
Glass, Metal Foil,
Plastics

Amorphous Silicon (a-Si)

- Commercial modules: efficiency 6–10%

Current role

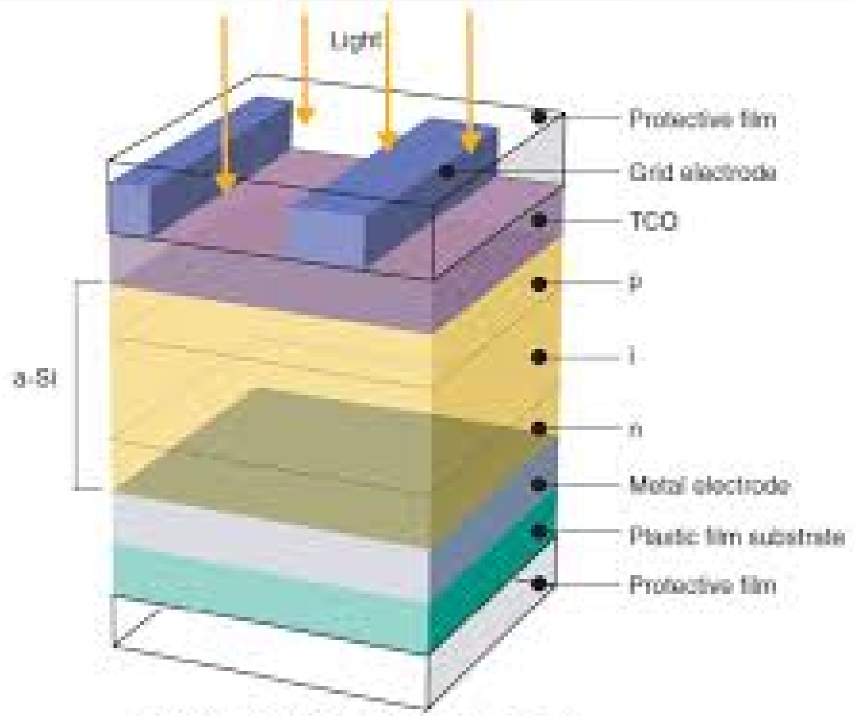
- Small electronic devices
- Specialized applications

Advantages

- Flexible
- Low cost

Disadvantages

- Strong degradation
- Low efficiency



Amorton Film Configuration

Emerging Technologies

Perovskite Solar Cells

- Laboratory cells: efficiency >27%
- Tandem perovskite-silicon: efficiency >34%

Advantages

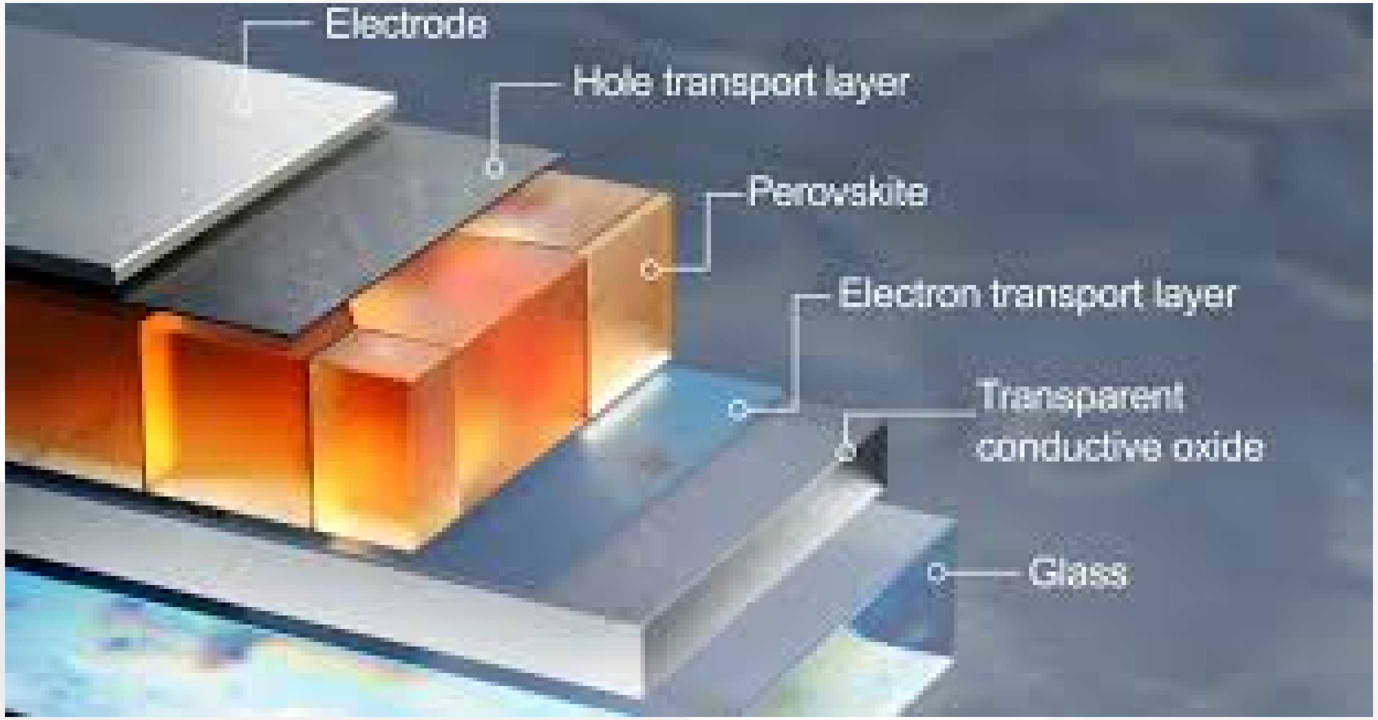
- Potentially low manufacturing cost
- Very high efficiency potential

Main challenge

- Long-term stability

Expected commercialization

- Increasingly available during the 2025–2030 period.


Electrode
Hole transport layer
Perovskite
Electron transport layer
Transparent
conductive oxide
Glass

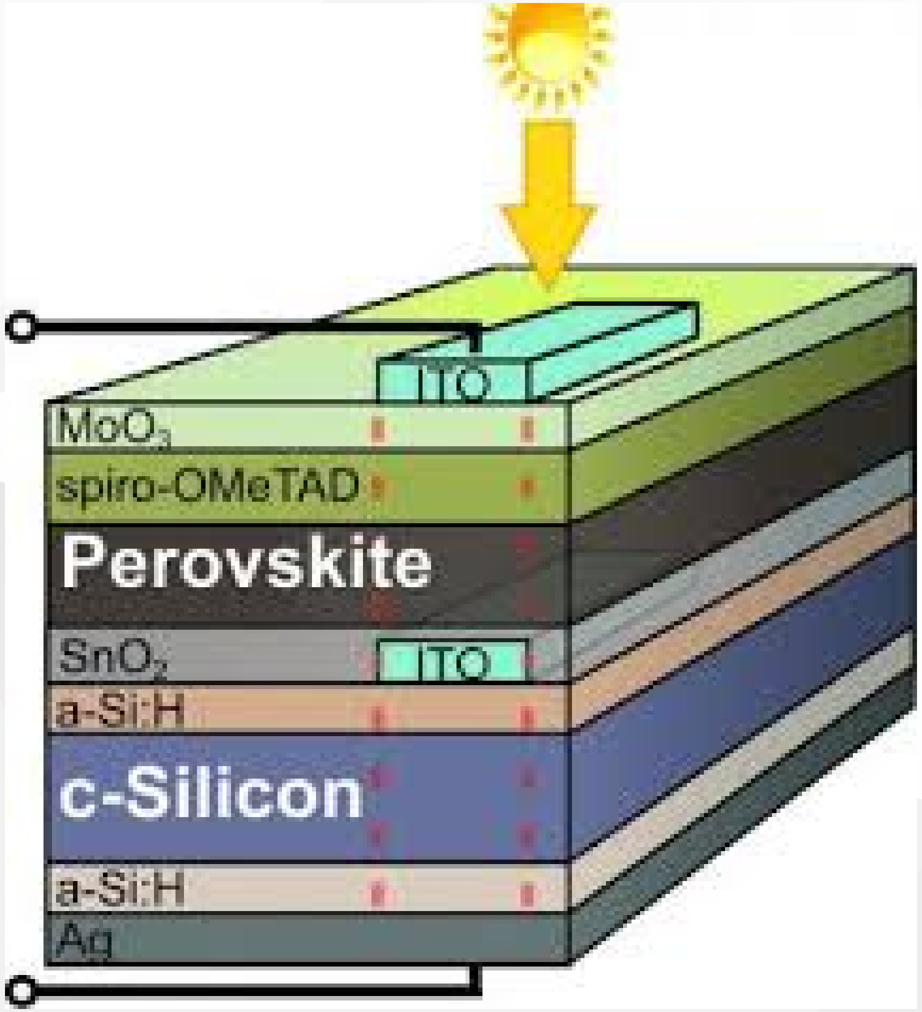
Perovskite-Silicon Tandem

The most promising future technology.

- Commercial pilot modules: efficiency 26–30%
- Laboratory records: efficiency >34%

Potential

- Could exceed the practical limits of conventional silicon.


ITO
MoO3
spiro-OMeTAD
Perovskite
SnO2
ITO
a-Si:H
c-Silicon
a-Si:H
Ag

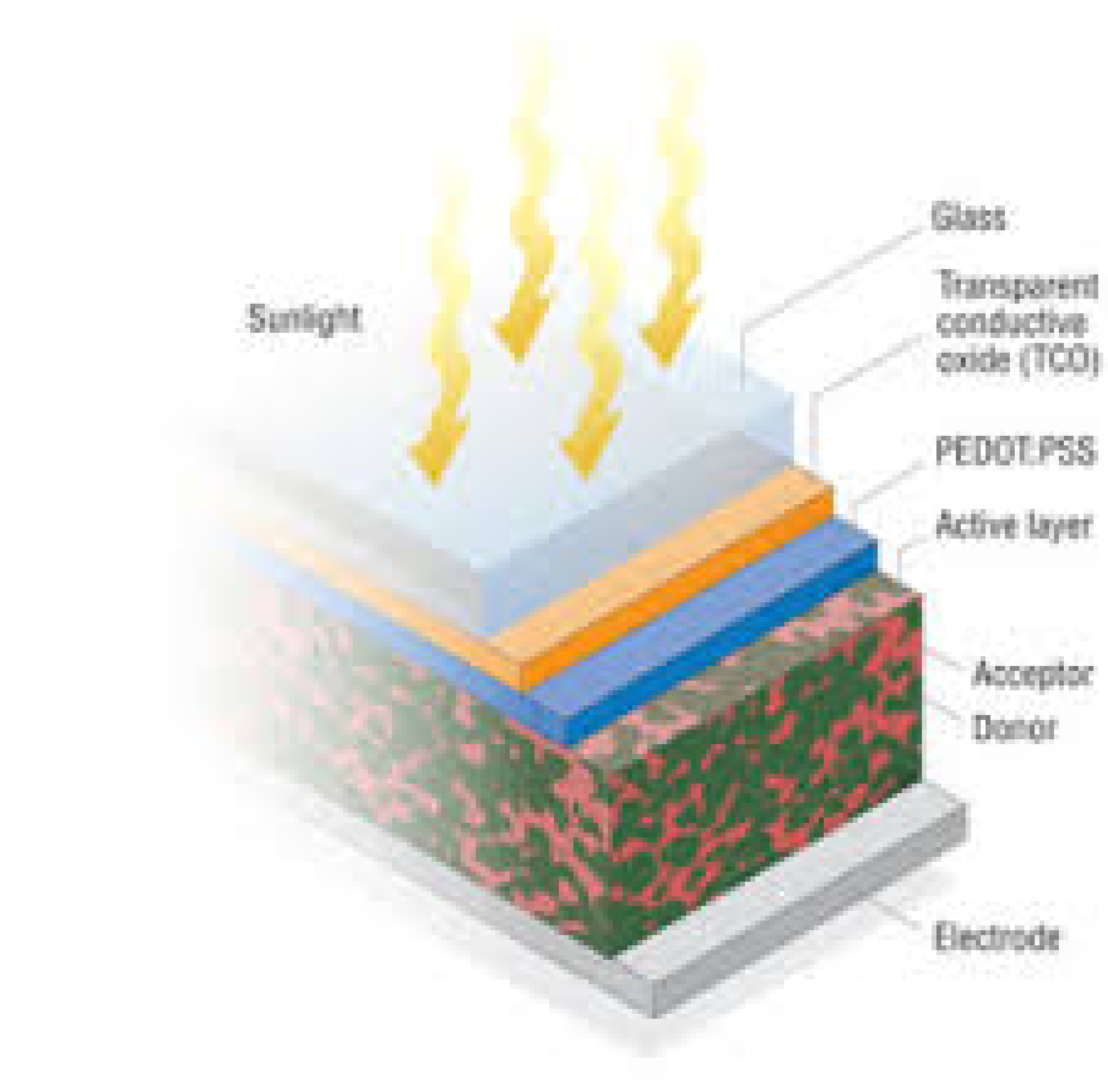
Organic Photovoltaics (OPV)

- Commercial modules: efficiency 10–18%

Made from carbon-based semiconducting materials

Advantages

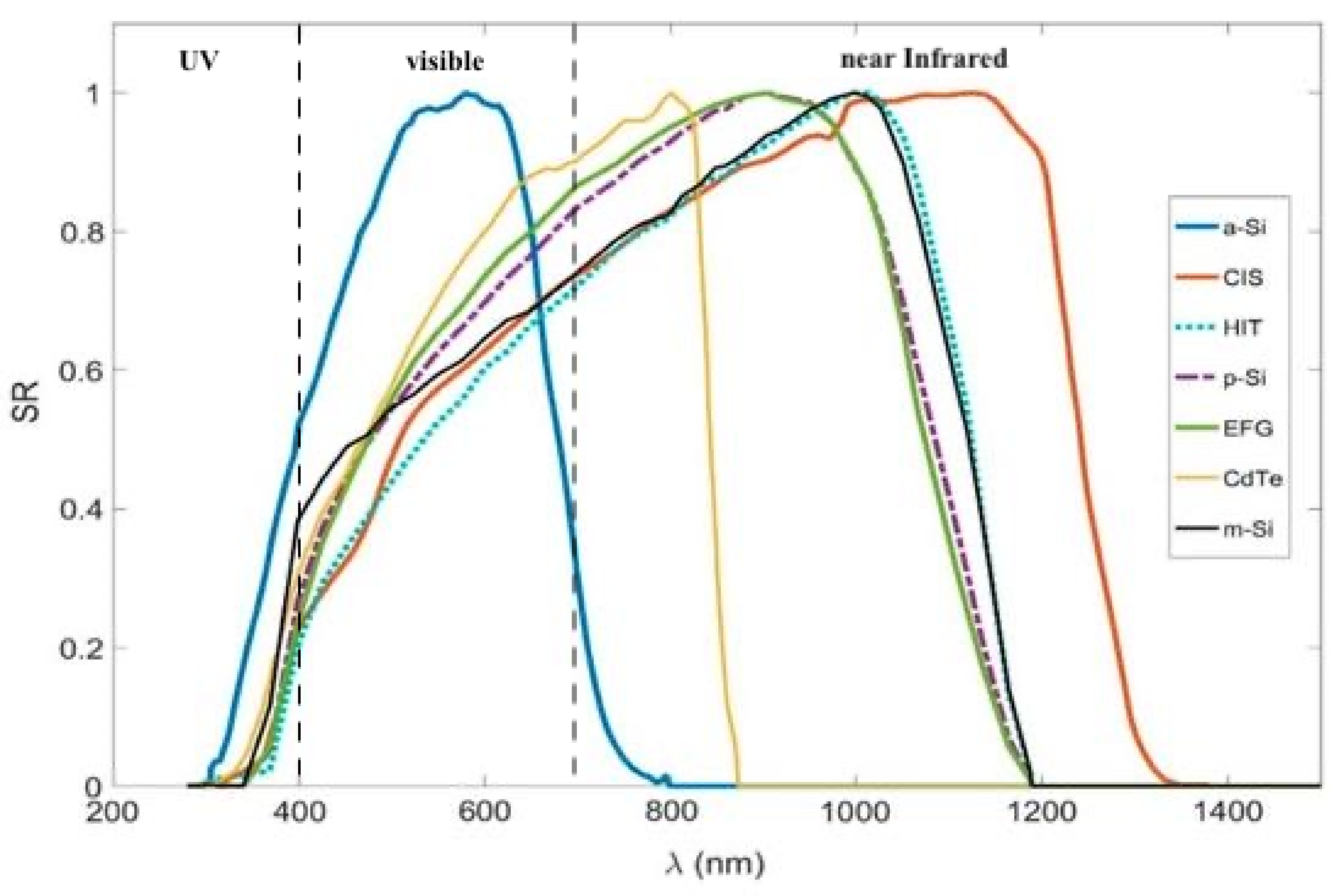
Lightweight, **Flexible**, **Suitable for curved surfaces**, **Semi-transparent**, **Useful for BIPV**, **Printable**, **Low material use**, **Tunable color/appearance**, **Useful for architectural integration**, **Good under diffuse or indoor light**, **Interesting for IoT sensors and low-power devices**


Sunlight
Glass
Transparent conductive oxide (TCO)
PEDOT:PSS
Active layer
Acceptor
Donor
Electrode

Technology	Efficiency	temperature coefficient (%/°C)	Module Cost (€ / kWp)
PERC Silicon (I)	21–23%	−0.30 to −0.35	80–130
TOPCon Silicon (I)	22–24.5%	−0.30 to −0.35	90–150
HJT Silicon (I)	23–25%	−0.24 to −0.28	120–220
IBC Silicon (I)	23–25%	−0.29	80–350
CdTe (II)	18–21%	−0.25	70-120
CIGS (II)	15–20%	−0.30	150–350
Amorphous Silicon (II)	6–10%	−0.25	700
Perovskite-Silicon Tandem (III)	26–30% (pilot)	−0.30 to −0.35	>300
Organic PV (III)	10–18%	−0.30	800

Efficiency decreases as temperature rises, HJT and CdTe often outperform conventional silicon despite similar nominal efficiencies.

Sensitivity toradiation wave-lengths:



For Residential Rooftops in France (2026)

1. TOPCon offers the best price/performance ratio.
2. HJT is attractive when roof area is limited and summer temperatures are high.
3. IBC is the premium solution when maximum energy production is desired.
4. Perovskite-silicon tandem modules are promising but not yet sufficiently mature for most residential installations.

For a typical house in Grenoble, a modern TOPCon module with 22–24% efficiency is currently the most economically attractive technology. A premium HJT or IBC installation generally yields only 3–8% more annual energy production but at a noticeably higher investment cost.

For residential installations, it is important to distinguish:

- Module cost (€/kWp of panels only)
- Turnkey installed system cost (€/kWp including inverter, mounting, wiring, labor, permits, VAT)

The installed system cost is usually what matters for homeowners because modules represent only 25–40% of the total project cost.

Typical Module Costs (2026)

Technology	Module Cost (€ / kWp)
PERC	80–130
TOPCon	90–160
HJT	120–220
IBC	180–350
CdTe	70–120 (utility scale)
CIGS	150–350
Perovskite-Si Tandem	>300 (pilot stage)

These prices are factory-level and fluctuate significantly with global silicon prices and Chinese manufacturing capacity.

Residential Rooftop Systems (France)

For a typical 3–9 kWp installation:

Technology	Installed Cost (€ / kWp)
PERC	1,300–2,000
TOPCon	1,400–2,100
HJT	1,600–2,500
IBC	1,900–3,000
CIGS	2,000–4,000
Perovskite-Si Tandem	Not yet mainstream

Size	TOPCon System
3 kWp	5,000–7,000 €
6 kWp	8,000–12,000 €
9 kWp	11,000–17,000 €

The €/kWp cost decreases as system size increases because fixed costs are spread over more panels.

Utility-Scale Solar Farms

Large ground-mounted systems benefit from economies of scale:

Technology	Installed Cost (€ / kWp)
TOPCon	500–800
HJT	650–900
CdTe	500–750
CIGS	700–1,200

Many large European solar farms now achieve total EPC costs below 700 €/kWp.

Cost per Unit of Roof Area

Because efficiencies differ, cost per square meter is also informative.

Technology	Typical Power Density
PERC	190–210 W/m^2
TOPCon	210–230 W/m^2
HJT	220–240 W/m^2
IBC	230–250 W/m^2

A 100 m² roof could typically host:

Technology	Installed Capacity
PERC	19–21 kWp
TOPCon	21–23 kWp
HJT	22–24 kWp
IBC	23–25 kWp

Cost of Additional Energy

Compared with a TOPCon system:

Technology	Extra Cost	Extra Annual Yield
HJT	+10–20%	+2–5%
IBC	+20–40%	+3–8%

HJT +10–20% +2–5%
IBC +20–40% +3–8%

This is why TOPCon currently dominates the market: the efficiency gain of HJT and IBC often does not fully compensate for their higher cost unless roof area is very limited, self-consumption value is high, aesthetics are important, or the project targets maximum production.

Dimensions of photovoltaic panels

Depend mainly on the cell format and the intended market (residential, commercial, utility-scale).

Residential Panels (Most Common)

Residential modules usually contain 108, 120, or 144 half-cells.

Power	Dimensions (approx.)	Area
400 W	1.72 × 1.13 m	1.94 m^2
430 W	1.76 × 1.13 m	1.99 m^2
450 W	1.76 × 1.13 m	1.99 m^2
500 W	1.95 × 1.13 m	2.20 m^2

Typical residential panel:

- Width: 1.10–1.15 m
- Height: 1.70–1.80 m
- Thickness: 30–35 mm
- Weight: 20–25 kg

Example:

A modern 430 W TOPCon module is often around:

- 1762 × 1134 mm
- 22–23 kg

Commercial / Industrial Panels

Used on warehouses, schools, supermarkets, etc.

Power	Dimensions
550 W	2.28 × 1.13 m
600 W	2.38 × 1.13 m
650 W	2.38 × 1.30 m

Typical characteristics:

- Area: 2.5–3.1 m^2
- Weight: 30–38 kg

Utility-Scale Panels

Large solar farms increasingly use very large modules.

Power	Dimensions
650 W	2.38 × 1.30 m
700 W	2.40 × 1.30 m
750 W	2.50 × 1.30 m

These modules may exceed:

- 3 m^2
- 40 kg

Relationship Between Size and Efficiency

Power is approximately:

$$P = G \times A \times \eta$$

where:

- P = panel power (W)
- G = irradiance (1000 W/m² under STC)
- A = panel area (m²)
- η = efficiency

For example:

$$430 = 1000 \times 1.95 \times 0.22$$

which corresponds to a 22% efficient panel.

Typical Power Density

Technology	Power Density
PERC	190–210 W/m^2
TOPCon	210–230 W/m^2
HJT	220–240 W/m^2
IBC	230–250 W/m^2

Thus a 2 m² module typically delivers:

Technology	Power
PERC	380–420 W
TOPCon	420–460 W
HJT	440–480 W
IBC	460–500 W

How Much Roof Area Is Needed?

For a modern TOPCon installation:

Installed Capacity	Required Roof Area
3 kWp	13–15 m^2
6 kWp	27–30 m^2
9 kWp	40–45 m^2
12 kWp	55–60 m^2

A useful rule of thumb is 1 kWp requires approximately 4.5–5 m^2 of roof area with current TOPCon modules.

Inverter and MPPT

The efficiency of a photovoltaic inverter depends on two different aspects that are often confused:

1. Power conversion efficiency (DC → AC)
2. Energy harvesting efficiency due to MPPT (Maximum Power Point Tracking)

An inverter can be very efficient electrically while still losing significant energy if it does not track the maximum power point properly.

Power Conversion Efficiency

Modern grid-connected inverters are extremely efficient.

Inverter Type	Peak Efficiency
Old inverter (2000s)	90–94%
Modern string inverter	97–99%
Premium string inverter	98–99%
Microinverter	96–97.5%
Hybrid inverter	96–98.5%

Typical examples:

Type	Typical European Efficiency
String inverter	97–98%
Hybrid inverter with battery	96–98%
Microinverter	96–97%

The "European efficiency" is more representative than peak efficiency because it accounts for operation under varying loads.

What MPPT Adds

The power-voltage curve of a PV panel has a unique operating point where power is maximal.

$$P(V) = V \cdot I(V)$$

The MPPT continuously adjusts the operating voltage to maximize power production.

Without MPPT, the panel often operates away from this optimum.

Energy Harvesting Efficiency

- **With MPPT**

Modern MPPT controllers achieve:

MPPT Technology	Tracking Efficiency
Basic MPPT	98–99%
Premium MPPT	99–99.9%

This means almost all available PV power is extracted.

- **Without MPPT**

If the operating voltage is fixed:

Conditions	Energy Captured
Ideal laboratory condition	90–95%
Real outdoor conditions	70–90%
Partial shading	50–80%

Losses vary strongly because: irradiance changes, temperature changes, panel aging changes the optimum voltage.

A fixed-voltage inverter can therefore lose 10–30% of annual production.

Typical Annual Energy Comparison

Consider a 6 kWp system producing 7,200 kWh/year under ideal MPPT control.

System	Annual Production
Modern MPPT inverter	7,000–7,200 kWh
Fixed-voltage inverter	5,500–6,500 kWh

The MPPT can therefore recover:

- 500–1,500 kWh/year
- often 10–20% more energy

Partial Shading

MPPT becomes even more important under:

- chimneys,
- trees,
- neighboring buildings,
- complex roof geometries.

Modern inverters often include:

- 2 MPPT inputs,
- 3–6 MPPT inputs (commercial systems),
- module-level MPPT (microinverters or optimizers).

Example:

Configuration	Additional Yield Under Shading
Single MPPT	Baseline
Dual MPPT	+2–8%
Module-level MPPT	+5–20%

Component	Efficiency
MPPT tracking	99–99.9%
DC wiring	98–99%
Inverter conversion	97–99%
AC wiring	99%

Typical Efficiencies of Real Systems

Component	Efficiency
MPPT tracking	99–99.9%
DC wiring	98–99%
Inverter conversion	97–99%
AC wiring	99%

Overall:

$$\eta_{system} \approx 0.99 \times 0.98 \times 0.99 \times 0.99 = 96\text{–}98\%$$

Power electronics in PV systems

A photovoltaic module delivers DC power, while most buildings and the grid use AC power.

The power electronics interface has two main roles:

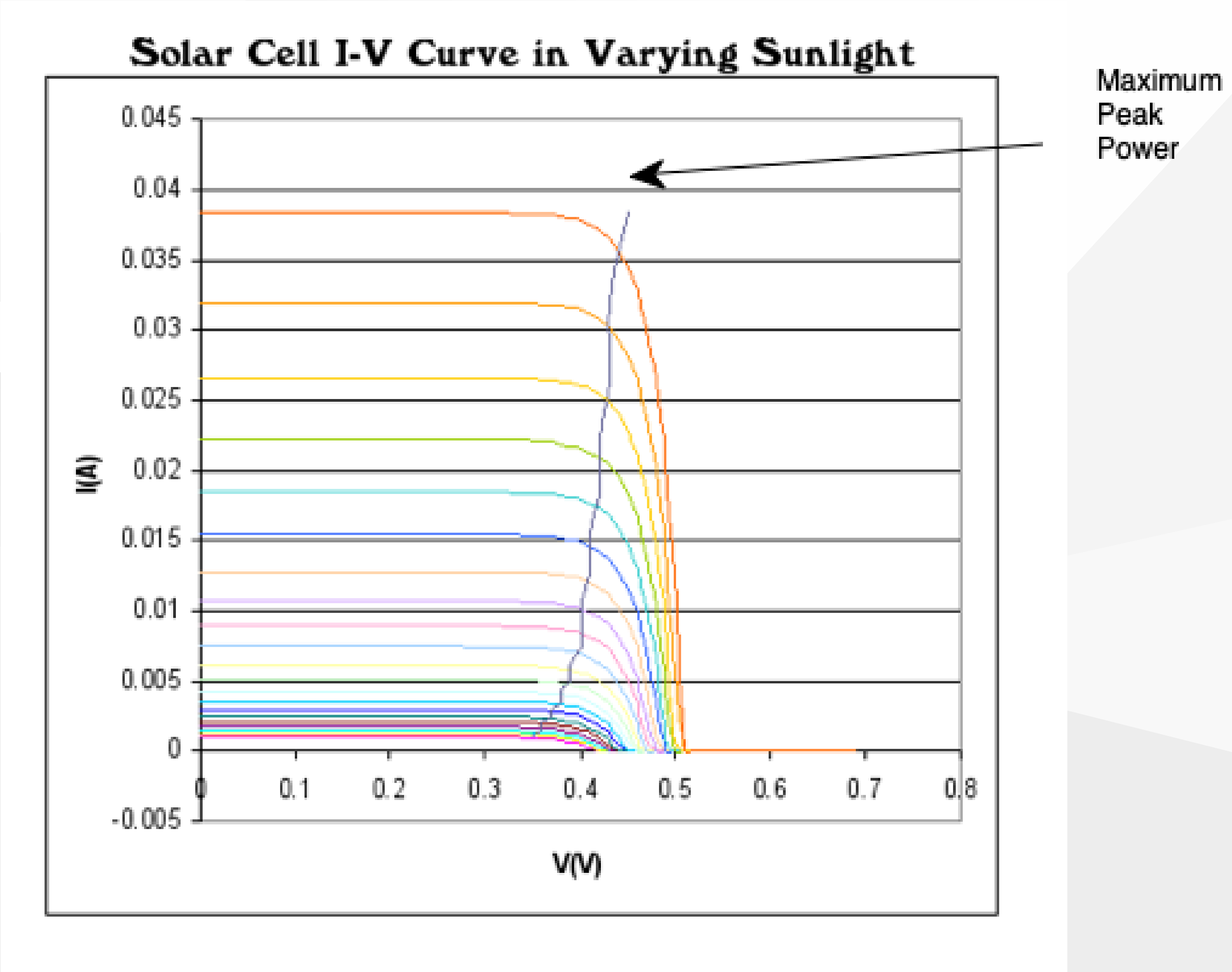
- convert DC electricity into AC electricity,
- operate the PV array close to its Maximum Power Point (MPP).

We have seen that a MPPT is needed to extract the maximum power from a PV panel. Indeed, the current-voltage curve of a PV cell is nonlinear.

The electrical power is:

$$P(V) = V\, I(V)$$

The maximum power is obtained near the "knee" of the I-V curve.



Solar Cell I-V Curve in Varying Sunlight
Maximum Peak Power
I(A)
V(V)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

PV cells are not ideal voltage sources

For most operating points, a PV cell behaves approximately as a current source.

However, near the knee of the I-V curve:

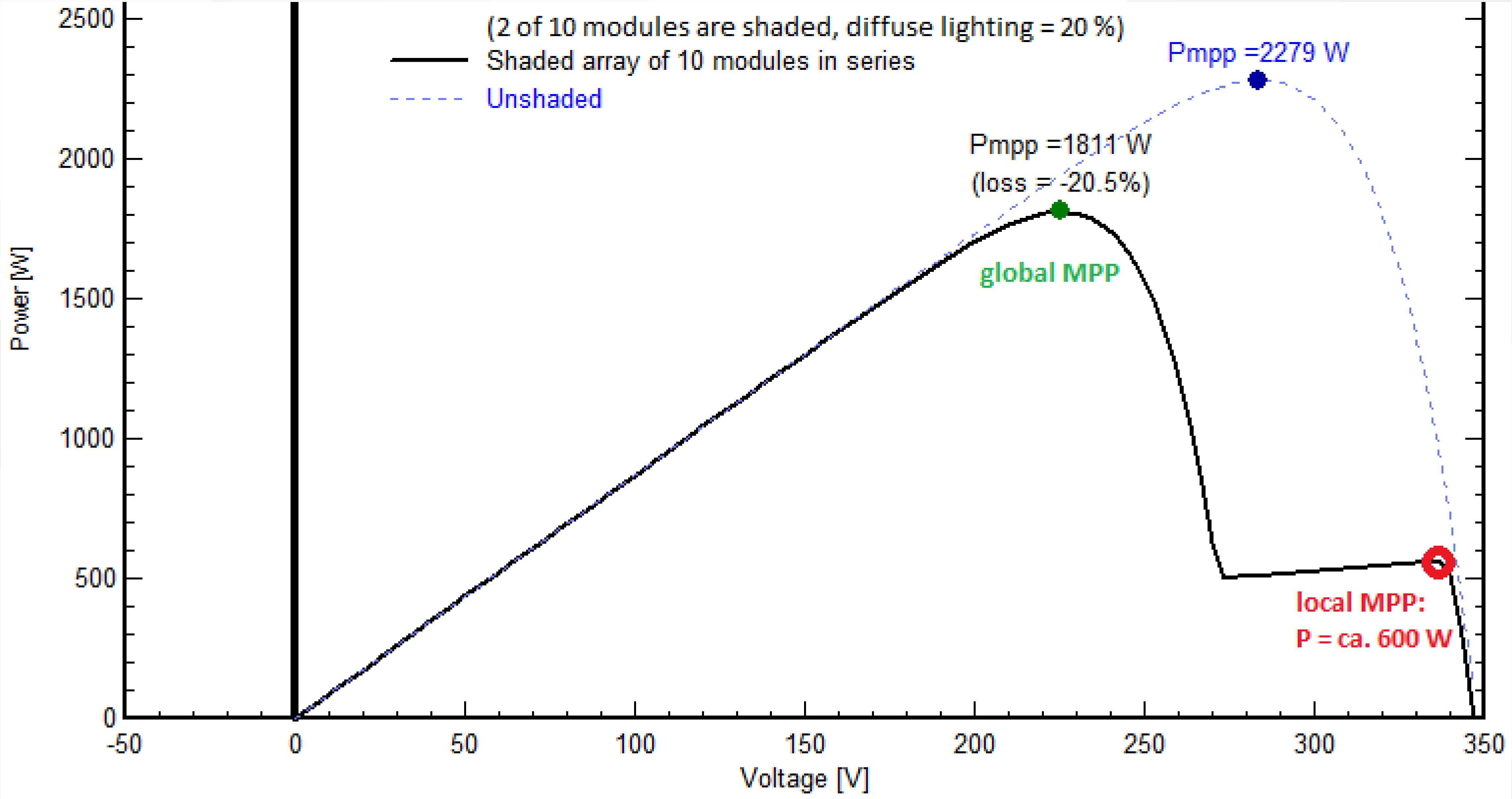
- voltage variations strongly affect current,
- the produced power reaches a maximum,
- beyond this region, voltage collapses and power falls rapidly.

The MPPT controller adjusts the operating voltage so that the PV array remains close to this maximum-power region.

Environmental conditions move the MPP

The voltage and current corresponding to maximum power cannot be fixed once and for all. They depend on:

- irradiance,
- cell temperature,
- aging,
- soiling,
- shading,
- electrical mismatch between modules.


(2 of 10 modules are shaded, diffuse lighting = 20 %)
Shaded array of 10 modules in series
Unshaded
Pmpp =2279 W
Pmpp =1811 W
(loss = -20.5%)
global MPP
local MPP:
P = ca. 600 W
Power [W]
Voltage [V]
2500
2000
1500
1000
500
0
-50
0
50
100
150
200
250
300
350

Maximum power point condition

For a given operating condition, the MPP is reached when:

$$\frac{dP}{dV} = 0$$

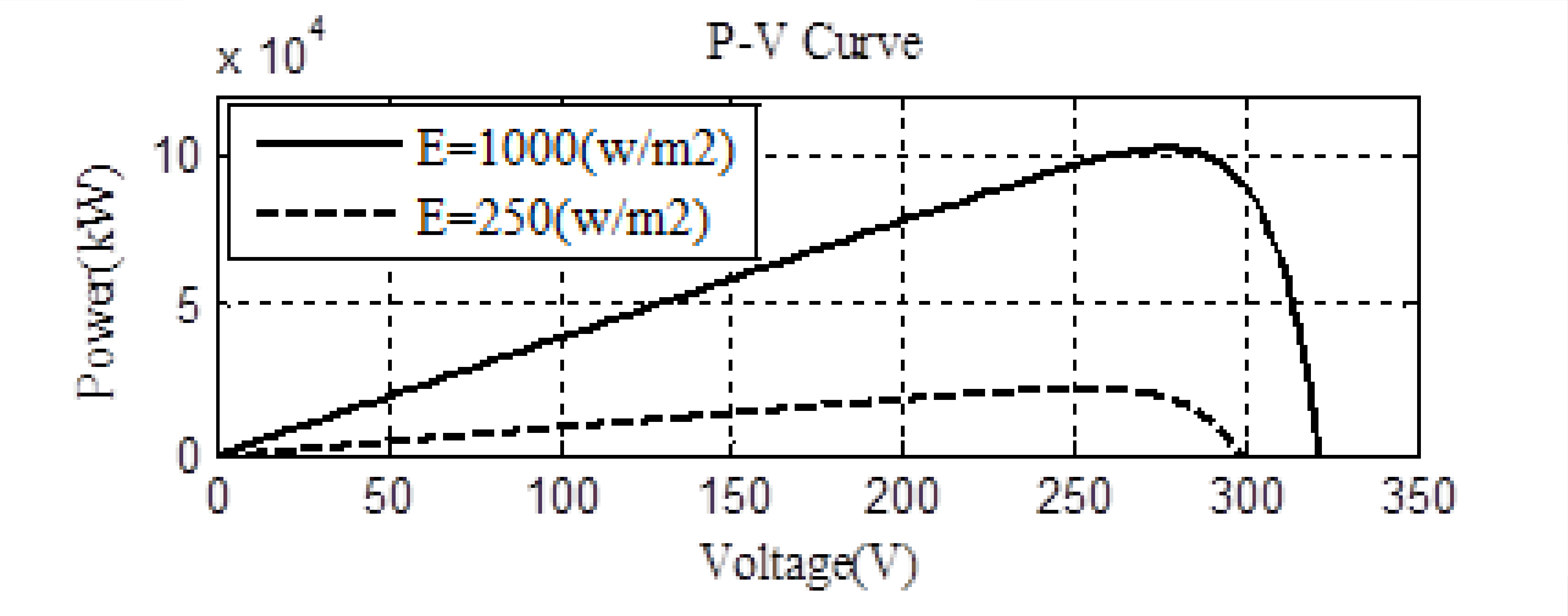
Since $P(V) = V\,I(V)$, we have:

$$\frac{dP}{dV} = I(V) + V\frac{dI}{dV}$$

And, at MPP $\frac{dI}{dV} = -\frac{I}{V}$

Power-voltage curve

The MPP is easier to visualize on the power-voltage curve.



Interpretation:

- left of MPP: increasing voltage increases power,
- at MPP: power is maximal,
- right of MPP: increasing voltage decreases power.

Load resistance and operating point

For a given PV operating point, the equivalent load resistance is $R = \frac{V}{I}$.

At MPP, this resistance is sometimes called the characteristic resistance of the PV cell or array.

This resistance is not constant. It changes with irradiance, temperature, shading and module condition.

A direct connection between a PV panel and a load rarely gives the correct resistance for maximum power extraction.

Role of the DC-DC converter

A DC-DC converter can modify the impedance seen by the PV array.

Its duty ratio changes the apparent load resistance.

Therefore, MPPT is usually implemented as a control loop:

1. measure PV voltage and current,
2. compute the electrical power,
3. adjust the converter duty ratio,
4. move the operating point toward maximum power.

Main MPPT algorithms

Several MPPT algorithms are used in practice.

Algorithm	Principle	Main advantage	Main limitation
Perturb & Observe	Perturb voltage and compare power	Simple and robust	Oscillates around MPP
Incremental conductance	Use $dI/dV = -I/V$	Better under changing irradiance	More computation
Current sweep	Reconstruct I-V curve periodically	Direct curve-based estimation	Temporary perturbation
Open-voltage ratio	Use $V_{ref} = kV_{OC}$	Simple and cheap	Approximate and interruptive
Temperature method	Estimate $V_{mpp}(T)$	Low-cost and stable	Poor under low irradiance

Perturb and Observe (P&O)

P&O is the simplest hill-climbing MPPT method. At each step, we impose an operating voltage V_1, measure the power P_1, perturb voltage by ΔV, measure the new power P_2, and keep moving in the direction that increases power.

1. impose an operating voltage V_1,
2. measure the power P_1,
3. perturb voltage by ΔV,
4. measure the new power P_2,
5. keep moving in the direction that increases power.

Incremental conductance

Incremental conductance uses the MPP condition:

$$\frac{dI}{dV} = -\frac{I}{V}$$

The controller compares:

- incremental conductance: $\Delta I / \Delta V$,
- instantaneous conductance: I/V.

Decision rule:

- if $dP/dV > 0$, increase voltage,
- if $dP/dV < 0$, decrease voltage,
- if $dP/dV = 0$, stay at MPP.

It can track fast irradiance changes better than P&O, but requires more computation and careful sampling.

Open-voltage ratio method

The open-voltage method uses the empirical approximation:

$$V_{mpp} \approx kV_{OC}$$

where k is often around 0.7–0.8 for silicon PV modules.

Procedure:

1. momentarily disconnect the array,
2. measure the open-circuit voltage V_{OC},
3. set the operating voltage to $V_{ref} = kV_{OC}$.

This method is simple, but it interrupts production and does not guarantee the true MPP.

Temperature-based MPPT

The MPP voltage varies with cell temperature.

A simple estimate is:

$$V_{mpp}(T) = V_{mpp}(T_{ref}) + u_{V_{mpp}}(T - T_{ref})$$

where:

- T is the measured module temperature,
- T_{ref} is a reference temperature,
- $u_{V_{mpp}}$ is the temperature coefficient of V_{mpp}.

This approach is simple and stable, but it may be inaccurate under low irradiance or partial shading.

String-level versus module-level MPPT

Traditional string inverters perform MPPT for a whole series string.

In a string, the same current flows through all modules. If one module is shaded or degraded, the whole string can be affected.

Module-level MPPT uses:

- power optimizers,
- microinverters,
- dedicated DC-DC converters.

Each module can then operate closer to its own MPP.

When is module-level MPPT useful?

Module-level MPPT is most valuable when modules have different operating conditions:

- partial shading,
- different orientations,
- different tilts,
- soiling,
- module mismatch,
- aging heterogeneity.

When all modules are identical and similarly illuminated, a single MPPT input may be sufficient.

Key messages

- A PV module has a nonlinear I-V curve.
- The maximum-power point depends on irradiance, temperature and module condition.
- MPPT adjusts the operating voltage through power electronics.
- The mathematical MPP condition is $dI/dV = -I/V$.
- P&O is simple but oscillatory.
- Incremental conductance is more informative but more complex.
- Module-level MPPT improves production under mismatch and partial shading.

The way cells are interconnected inside a photovoltaic module has a major impact on production under partial shading.

Basic Cell Connection: Series

A silicon solar cell typically produces:

- Voltage: ≈ 0.5–0.6 V
- Current: ≈ 10–20 A (modern cells)

To obtain a useful voltage, manufacturers connect cells in series.

Example:

- 72 cells × 0.55 V ≈ 40 V
- Current remains unchanged
- ---- Cell ---- Cell ---- Cell ---- Cell ---- -

In a series connection:

$$V_{total} = \sum_i V_i$$

$$I_{total} = I_1 = I_2 = \cdots$$

The current is therefore limited by the weakest cell.

Why Shading Is Dangerous

Suppose all cells produce 10A except one shaded cell producing only 2A.

10A → 10A → 10A → 2A → 10A → 10A

Since the cells are in series: $I_{string} = 2A$

The entire string is forced to operate at 2 A.

A shadow on 5% of the surface may reduce power by much more than 5%.

This is one of the most counter-intuitive aspects of photovoltaics.

Current Trends

Most premium panels in 2026 combine:

- TOPCon or HJT cells,
- Half-cell architecture,
- Multiple bypass diodes,
- Multi-busbar connections,
- Sometimes shingled layouts.

These improvements have dramatically reduced shading sensitivity compared with panels manufactured 10–15 years ago, but a shadow from a chimney, tree, antenna, or neighboring building can still reduce annual production by 5–30% if the electrical architecture is not carefully designed.

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Hot Spot Effect

A shaded cell can become reverse biased.

Instead of generating power, it dissipates power:

$$P = V \times I$$

The cell heats up and may exceed 100°C.

This is called a hot spot.

Hot spots can:

- damage encapsulation,
- crack cells,
- shorten module life.

Bypass Diodes

To prevent hot spots, modules are divided into several sections protected by bypass diodes.

Typical Modern Panel

A residential panel usually contains:

- 108 half-cells
- 120 half-cells
- 144 half-cells

organized into 3 substrings.

Example:

Substring 1 ----|
|-- Diode
Substring 2 ----|
|-- Diode
Substring 3 ----|

[36 cells]--D1
[36 cells]--D2
[36 cells]--D3

where D1, D2, D3 are bypass diodes.

Example: Shadow on One Substring

Consider a 450 W panel.

Without shading:

150 W + 150 W + 150 W = 450 W

One substring shaded:

150 W + 0 W + 150 W = 300 W

The bypass diode activates and the module continues producing.

Instead of losing 100% of production, only about one third is lost.

Example:

Upper half

Lower half

Advantages:

- Lower resistive losses
- Better shade tolerance
- Higher efficiency

What Happens With a Shadow?

Classical Full-Cell Panel

Shadow on one cell:

Power loss ≈ large

Half-Cell Panel

Shadow on one lower corner:

Only one section affected

Power loss becomes significantly smaller.

Multi-Busbar and Shingled Cells

Multi-Busbar

Modern cells have many conductors:

|||||||||||

instead of

|||

This reduces resistive losses and improves current collection around small shadows.

Shingled Cells

Cells overlap like roof tiles.

//////////
//////////
//////////

Benefits:

- More parallel current paths
- Better partial shading behavior
- Higher module efficiency

Effect at the String Level

The module is only one level.

Several modules are then connected in series to form a string.

Example:

Panel1 -- Panel2 -- Panel3 -- Panel4 -- Panel5

If one panel is strongly shaded:

450W -- 100W -- 450W -- 450W -- 450W

the entire string may suffer unless:

- the MPPT finds a new optimum,
- bypass diodes activate.

Microinverters and Optimizers

Power Optimizers

Examples:

- SolarEdge

Panel + Optimizer

Each module is individually controlled.

Typical gain under shading:

- 5–25%

Microinverters

Examples:

- Enphase Energy

Panel --> Microinverter
Panel --> Microinverter
Panel --> Microinverter

Each panel operates independently.

Advantages:

- Excellent shading performance
- Per-panel monitoring
- Improved safety

Disadvantages:

- Higher cost
- More electronics on the roof

Typical Production Losses

Shadow Situation	Production Loss
10% of one cell shaded	20–80% on a substring
One bypass section shaded	≈ 33% of panel
One panel shaded in a string	10–50% string loss
Same system with optimizers	2–15% system loss
Same system with microinverters	Mostly limited to shaded panel

Current Trends

Most premium panels in 2026 combine:

PV mounting systems

The mounting system affects installation cost, maintenance, module temperature, wind resistance, and energy production.

1. Roof-parallel mounting (most common)

The panels follow the roof slope (it is called "plane roof mounting" in BATEM).

```
Roof
///////////////////
PV
///////////////////
```

Typical use: residential houses, small commercial buildings.

Advantages

- Lowest cost, simple installation
- Good aesthetics, low wind loads
- Minimal structural impact

Disadvantages

- Orientation imposed by the roof
- Limited ventilation behind the modules

2. Tilted rack on pitched roof

Panels are mounted at a different angle from the roof to improve orientation, tilt, and winter production (can be simulated by several "plane roof mountings" in BATEM).

```
Roof
////////////////
PV
///////////
```

Advantages

- Better solar exposure

Disadvantages

- Higher wind loads, more visible structure
- Additional hardware

3. Flat roof — ballasted mounting

Very common on commercial buildings. **No roof penetration** — concrete blocks provide weight (it is called "flat mounting" in BATEM).

```
       PV
      /
____/_______
Roof
```

Advantages

- No waterproofing perforation
- Easy installation, removable

4. Flat roof — anchored mounting

The structure is mechanically attached to the building (plane roof mount).

```
PV
 /
/____ Anchor
```

Advantages

- Lower weight than ballast
- Better resistance to strong winds

Disadvantages

- Roof penetrations
- More complex waterproofing

5. East–west flat roof configuration

Panels face opposite directions (typical on large commercial roofs) (it is called "back2back mounting" in BATEM).

```
\  /  \  /  \  /
 V     V     V
```

Advantages

- More panels per square metre
- Smoother production during the day
- Lower wind loads

Disadvantages

- Slightly lower annual yield per panel

6. Ground-mounted fixed structure

Panels on driven piles or concrete foundations (flat mount).

```
     PV
    /
__/______
Ground
```

Advantages

- Easy maintenance, optimal orientation, good ventilation

Disadvantages

- Requires available land

7. Pole-mounted systems

Panels on a single pole — remote sites, small off-grid systems.

```
  PV
-----
   |
   |
   |
```

Advantages

- Adjustable orientation

Disadvantages

- Limited array size

8. Single-axis tracker

Structure rotates on one axis during the day (utility-scale farms).

```
Morning   /
Noon      –
Evening   \
```

Typical energy gain: +15 to +30% vs fixed tilt.

9. Dual-axis tracker

Tracks daily azimuth and seasonal elevation.

```
     Sun
      ☀️
      |
    [PV]
   ↔️    ↕️
```

Typical energy gain: +25 to +40% vs fixed tilt.

Disadvantages

- Moving parts, higher maintenance

10. Carport mounting

PV panels form the roof of a parking structure.

Advantages

- Dual use of land
- Vehicle protection
- EV charging integration

11. Agrivoltaic mounting

Panels elevated above agricultural land (typically **2–6 m** above ground).

Applications: vineyards, orchards, pasture.

12. Facade mounting

Panels installed vertically on building façades.

Advantages

- Useful when roof area is limited
- Higher winter production, less snow accumulation

Disadvantages

- Lower annual production than an optimally tilted roof

For Grenoble, a south-facing vertical façade may produce about **65–80%** of a south-facing roof, often with better winter performance.

13. Building-integrated photovoltaics (BIPV)

PV replaces construction materials (roof tiles, façade cladding, skylights, glass façades).

Advantages

- Architectural integration, dual functionality

Disadvantages

- Higher installation cost, more complex maintenance

14. Bifacial modules

A bifacial photovoltaic module is a solar panel that can produce electricity from both its front and rear sides.

Unlike a conventional (“monofacial”) panel, which only converts sunlight arriving on the front surface, a bifacial panel also captures:

- light reflected by the ground,
- light reflected by nearby surfaces,
- diffuse sky radiation,
- light reflected by snow, water, or white roofs.

Monofacial Module

Sun
↓

```
┌────────────────────────┐
│  PV Cell  │
└────────────────────────┘
```

Only the front side contributes to production.

Bifacial Module

Sun
↓

| PV Cells |

↑
Reflected light

Both sides generate electricity.

The rear side typically contributes an additional 5–30% of energy.

The rear side is usually slightly less efficient than the front side.

The bifaciality factor is:

$$B = \frac{\eta_{\text{rear}}}{\eta_{\text{front}}}$$

Typical values:

Technology	Bifaciality
PERC	65–75%
TOPCon	80–90%
HJT	90–98%

For a typical tiled roof in Grenoble:

- A 450 W monofacial TOPCon module and a 450 W bifacial TOPCon module will usually produce very similar energy if mounted close to the roof.
- If mounted with good rear ventilation and clearance, the bifacial module may provide roughly 2–8% additional annual production.
- The greater benefit may actually be the glass-glass construction, which often offers better durability and lower long-term degradation than the bifacial energy gain itself.

Comparison of typical mounting types

Mounting type	Cost	Yield	Maintenance
Roof-parallel	Low	Good	Low
Tilted roof rack	Medium	Good–very good	Low
Flat roof ballast	Medium	Good	Low
Ground-mounted fixed	Medium	Very good	Easy
Single-axis tracker	High	Excellent	Medium
Dual-axis tracker	Very high	Excellent	High
Carport	High	Very good	Easy
Façade	High	Moderate	Easy
BIPV	Very high	Moderate–good	Complex

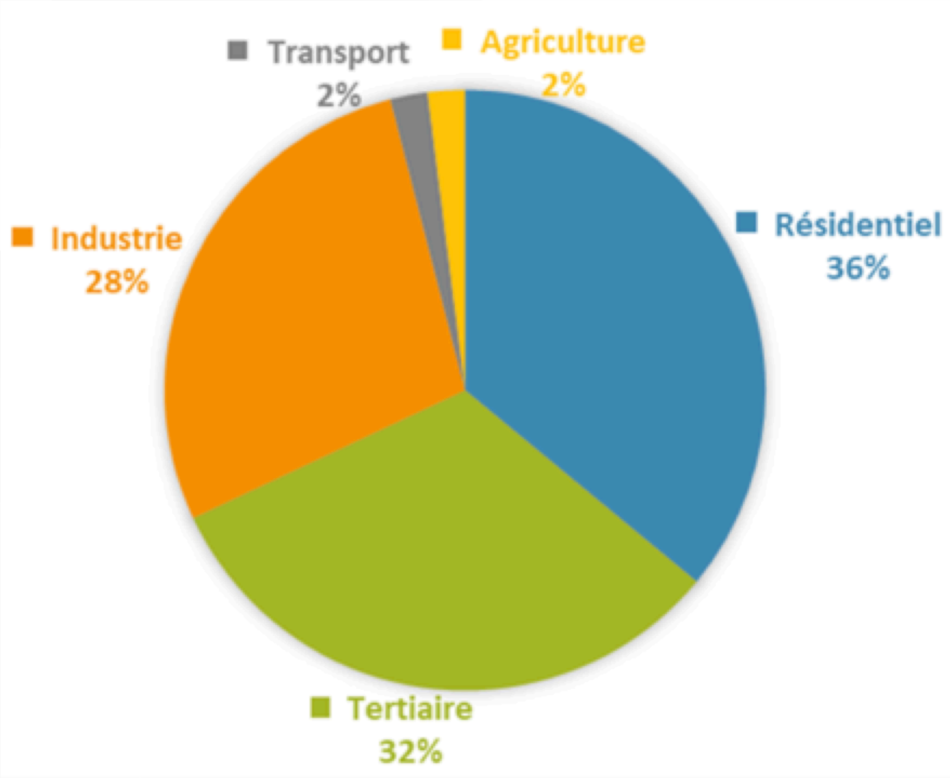
For a house in Grenoble (~100 m^2 roof)

Most economically attractive options:

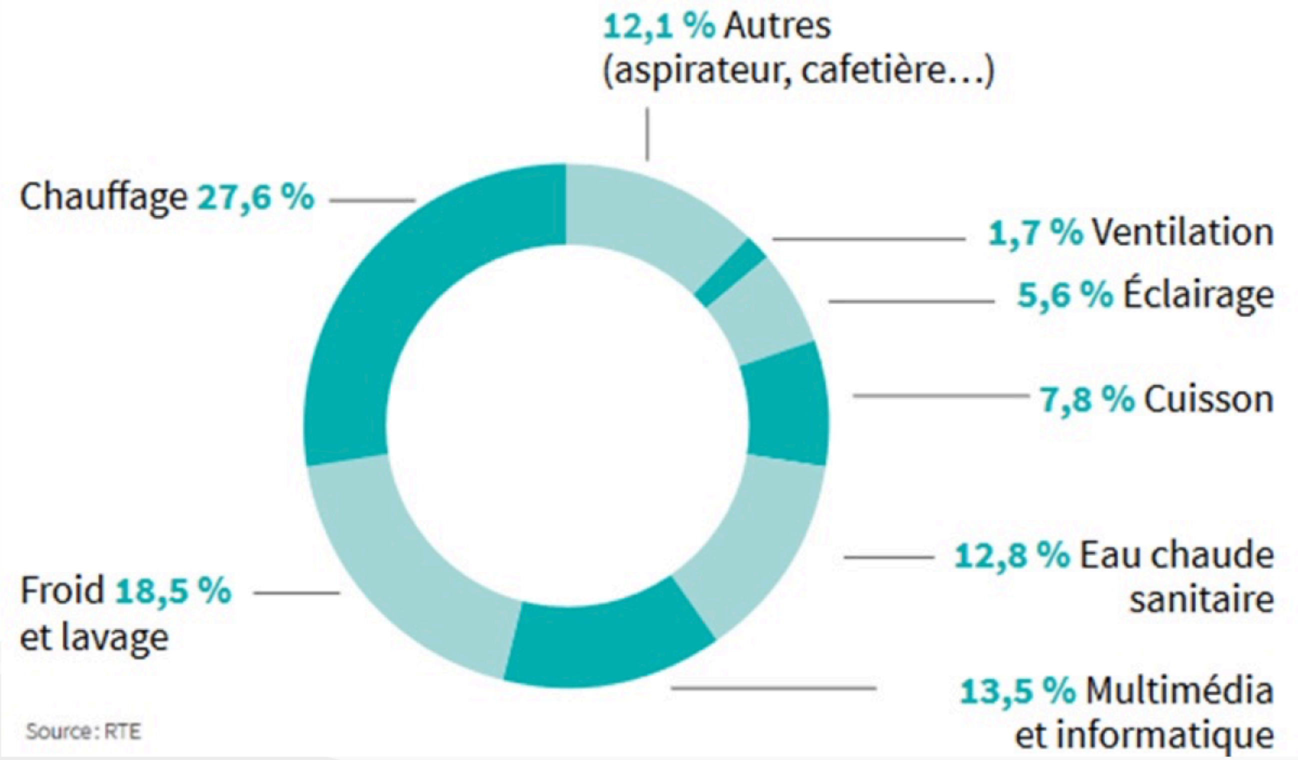
1. Roof-parallel mounting with TOPCon modules
2. Slightly elevated mounting to improve rear ventilation
3. Bifacial modules only if clearance **> 10–15 cm** exists behind the panels

A well-ventilated roof-mounted system can run **5–15 °C** cooler than a poorly ventilated one, increasing annual production by roughly **2–5%** (technology and climate dependent).

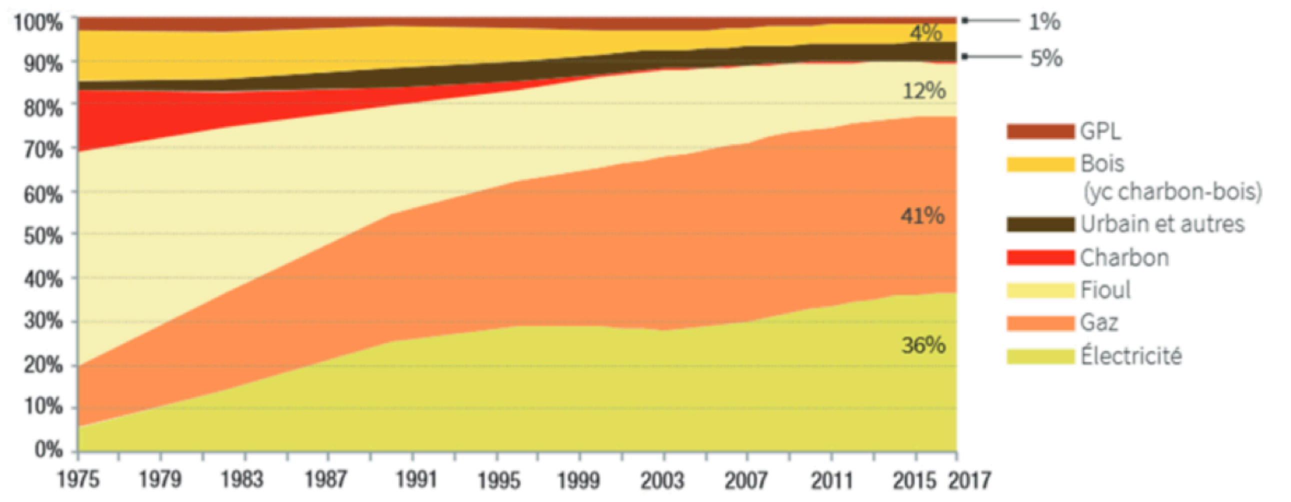
Energy consumption (France)



Consommation finale d'électricité par secteurs en 2018, source Insee



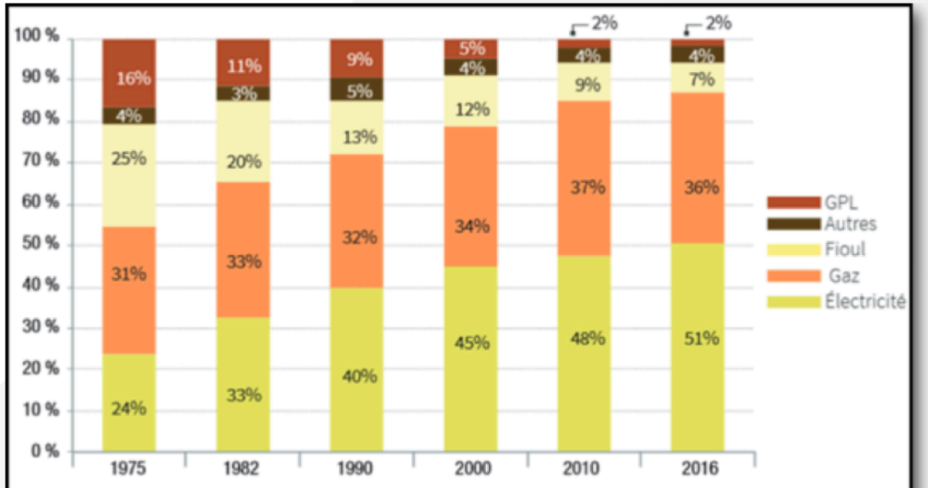
Répartition des usages de l'électricité domestique en 2018 source ADEME



Évolution du parc de résidences principales selon l'énergie de chauffage principal de 1975 à 2017

(Source : Climat, Air et Energie, chiffres clés, édition 2018[6])

source ADEME



Évolution du parc de résidences principales selon l'énergie production d'ECS de 1975 à 2016

(Source : Climat, Air et Energie, chiffres clés, édition 2018[6])

Consommation finale d'électricité par secteurs en 2018, source Insee

Répartition des usages de l'électricité domestique en 2018

Indicators for electricity user

Suppose during one year:

1. PV production: E_{PV}
2. Household consumption: E_{load}
3. PV electricity directly consumed on-site: E_{self}

The following indicators are used:

- self-consumption: $SC = \frac{E_{self}}{E_{PV}}$
- self-sufficiency (or self-production): $SS = \frac{E_{self}}{E_{load}}$
- net energy exchanged with the grid: $NEEG = E_{PV} - E_{load}$
- self-consumption: Of all the PV electricity produced, how much is consumed locally?
- self-sufficiency: Of all the electricity consumed by the building, how much comes from the PV system?

Typical residential values without battery:

- $SC \approx 20 - 50\%$
- $SS \approx 15 - 45\%$
- $NEEG \approx 1000 - 7000kWh/year$

Typical residential values with battery:

- $SC \approx 50 - 90\%$
- $SS \approx 30 - 80\%$
- $NEEG \approx 0 - 1500kWh/year$

Electricity and PV tariffs for most consumers

Tariffs apply since March–June 2025: Self-consumption with surplus sale

Installed power surplus purchase tariff
≤ 9 kWp ≈ 0.04 €/kWh
9–100 kWp ≈ 0.047 €/kWh

Installed Power Premium support:
≤ 9 kWp → 80 €/kWp
9–36 kWp → 140 €/kWp
36–100 kWp → 70 €/kWp

Since June 2026

Reducetion of the surplus purchase tariff to 0.011 €/kWh

No more self-consumption premium for new installations

For a residential customer in France:

Item	Typical Value
Purchased electricity	0.20–0.28€/kWh (about 0.25€/kWh)
Surplus sold (obefore 2026)	0.04€/kWh
Surplus sold (from June 2026 regime)	0.011€/kWh

The French policy has clearly shifted from:

“Install PV and sell electricity”

to:

“Install PV and consume it yourself.”

Economically, the key parameter is now no longer the annual production, but rather the self-consumption ratio

Self-check questionnaire

12 questions — photovoltaic power and MPPT

Choose the best answer each time.

(In class: discuss in pairs; answers on the following slides.)

Q1 — Primary vs final electricity

On the slides, 1 unit of final electricity corresponds to about:

- A. 2.58 units of primary energy (conversion losses upstream)
- B. 0.38 units of primary energy
- C. 1 unit of primary energy with no losses
- D. 10 units of thermal energy only

Q2 — Fatal energy

Fatal energy in the lecture is energy that is:

- A. Lost when it is not consumed at the time it is available (e.g. must-curtail renewables)
- B. Stored in pumped hydro only
- C. Always converted to useful heat in buildings
- D. The MPPT voltage reference V_{ref}

Q3 — Fatal energy in France (order of magnitude)

Using the figures on the slides, the total fatal-energy share cited for France is about:

- A. ~3% of the relevant mix (with run-of-river, wind, PV, solar thermal contributions listed)
- B. ~50% of all primary energy
- C. 0% because the grid is always balanced
- D. 100% for gravity dams only

Q4 — Grid balance

Production and consumption on the electrical grid must be balanced:

- A. At all times (power balance in real time; storage/grid help)
- B. Only once per year on average, with no hourly constraint
- C. Only for fossil plants, not for renewables
- D. Only inside a single PV module

Q5 — PV chain efficiencies (typical)

Typical orders of magnitude on the slides are:

- A. Cell collects ~20% of incident radiative power (with MPPT); inverter efficiency ~95%
- B. Cell 95%; inverter 20%
- C. Both near 100% with no MPPT
- D. Inverter converts sunlight directly without a DC panel

Q6 — Why MPPT?

Maximum Power Point Tracking is needed because:

- A. The I–V curve is nonlinear; the operating point must be adjusted so $P = VI$ is maximized for current irradiance/temperature
- B. Panel voltage is always constant regardless of sun
- C. dP/dV is always positive on the whole curve
- D. MPPT replaces the need for a DC–DC converter

Q7 — MPP condition (calculus)

At the maximum power point (MPP), the slides use the condition:

- A. $dP/dV = 0$, equivalent to $dI/dV = -I/V$ for $P = I(V)\,V$
- B. $I = 0$ always
- C. $V = 0$ is always optimal
- D. $dI/dV = I/V$ at MPP

Q8 — Characteristic resistance

The characteristic resistance at MPP is:

- A. $R = V/I$ at the operating point where power is maximum (changes with irradiance and temperature)
- B. Fixed at 50 Ω for all panels forever
- C. U_{bat} in W/m²·K
- D. HDD divided by CDD

Q9 — Perturb & Observe

The Perturb & Observe MPPT algorithm:

- A. Steps voltage by Δv, compares power, and moves toward higher P; can oscillate around MPP in steady sun
- B. Never changes voltage once started
- C. Measures only temperature with no current
- D. Is identical to open-circuit voltage with zero interruption

Q10 — Incremental conductance

Incremental conductance tracking reaches MPP when:

- A. $I_\Delta / V_\Delta = -I/V$ (incremental conductance equals negative of instantaneous conductance)
- B. $I = V$ always
- C. Duty ratio is fixed at 50% with no sampling
- D. $V_{\text{mpp}} = 0.76\, V_{\text{OC}}$ with no measurement of current

Q11 — Open-voltage method

The open-voltage / constant-ratio approach:

- A. Briefly measures V_{OC}, then operates near $V_{\mathrm{ref}} \approx k\, V_{\mathrm{OC}}$ (e.g. $k \approx 0.76$); simple but approximate and can interrupt production
- B. Guarantees exact MPP with no approximation under all irradiance
- C. Requires no DC–DC converter
- D. Maximizes CO_2 concentration indoors

Q12 — Module-level MPPT

Module-level MPPT (vs one MPPT for a whole string) mainly helps when:

- A. Modules see different irradiance (shading, soiling, mismatch) so each can run at its own MPP
- B. All modules are identical and uniformly illuminated
- C. Only AC loads are connected
- D. Temperature is constant everywhere on Earth

Answer key (1/2)

Q	Answer	Short rationale
1	A	1 kWh final el. ≈ 2.58 kWh primary (slide).
2	A	Energy lost if not used when available.
3	A	Total fatal share ~3% (listed breakdown).
4	A	Real-time balance on the grid.
5	A	~20% cell + MPPT; ~95% inverter typ.
6	A	Nonlinear I–V; adjust V for max P.

Answer key (2/2)

Q	Answer	Short rationale
7	A	MPP: $dP/dV = 0$ ↔ $dI/dV = -I/V$.
8	A	$R = V/I$ at MPP; weather-dependent.
9	A	P&O: perturb Δv; oscillations possible.
10	A	At MPP: $I_\Delta/V_\Delta = -I/V$.
11	A	$V_{\mathrm{ref}} = kV_{\mathrm{OC}}$; interruptions/approx.
12	A	Per-module MPP under mismatch/shading.