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# Agrivoltaics : a review of PV technologies and modelling methods

D. Munoz, H. Colin  
CEA-LITEN, INES






The INES campus: a research center covering the whole value chain of photovoltaics



**22 000 sqm**  
Equipment > **120 M€**  
~ **500 employees**  
Annual Budget~ **50 M€**



**Research, innovation**

**Education, capacity building**

11 labs  + 2 labs  

 Education & Evaluation Platform  


# OUR ACTIVITIES

Premium PV Cells and modules | Process & equipment | X-IPV | Power electronics | PV plants Architectures

Hardware



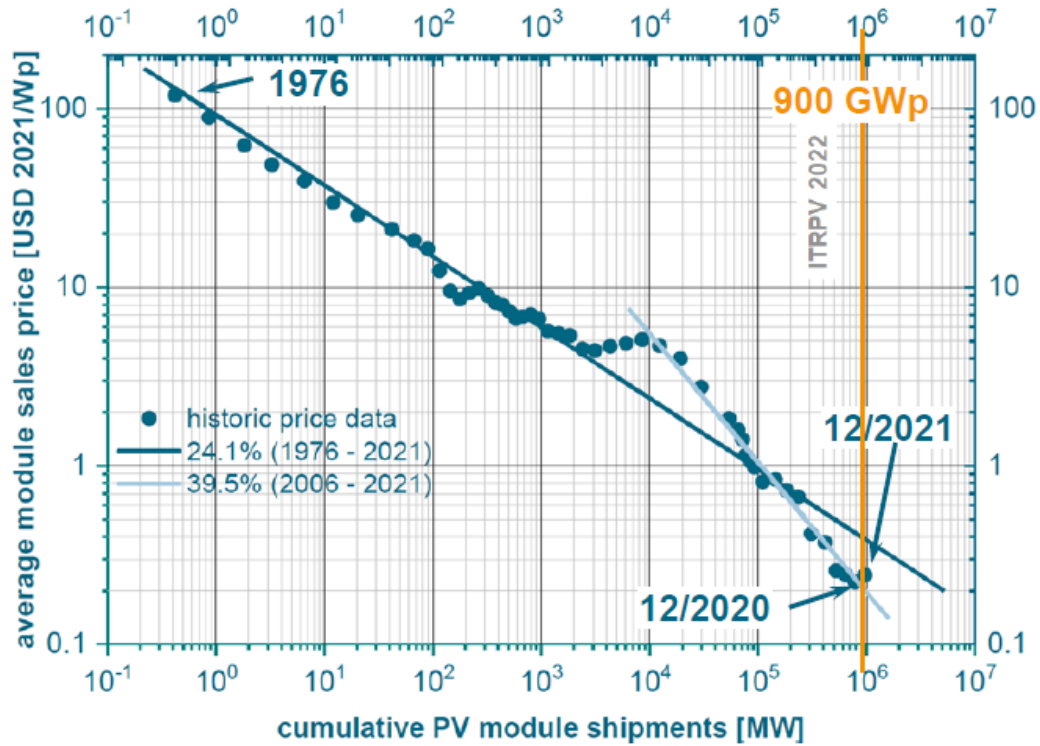
& software developments

Grid integration | Diagnosis & Data | Energy management systems | Storage | Smart grids & Smart cities

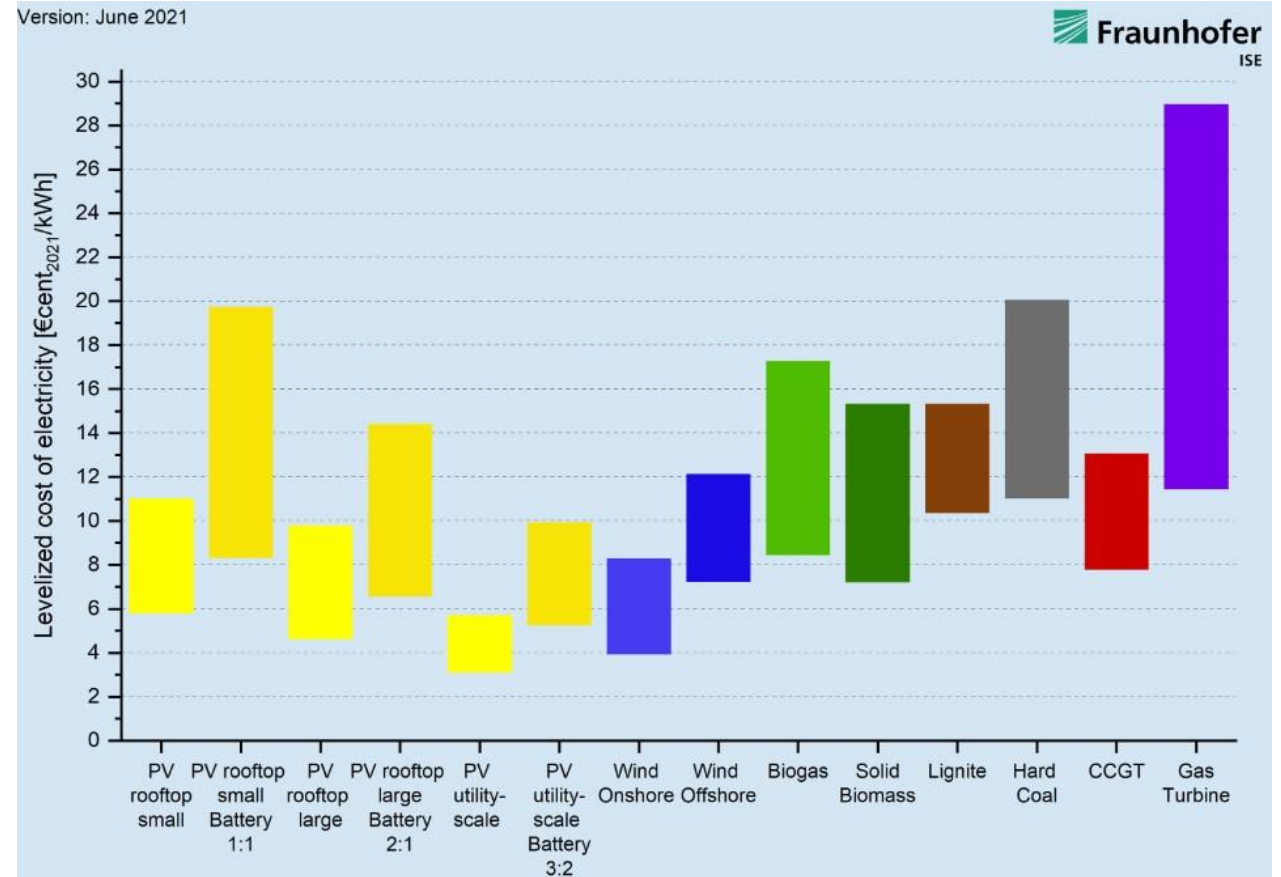
# PART 1 : REVIEW OF PV MODULES TECHNOLOGIES

## COST OF ENERGY

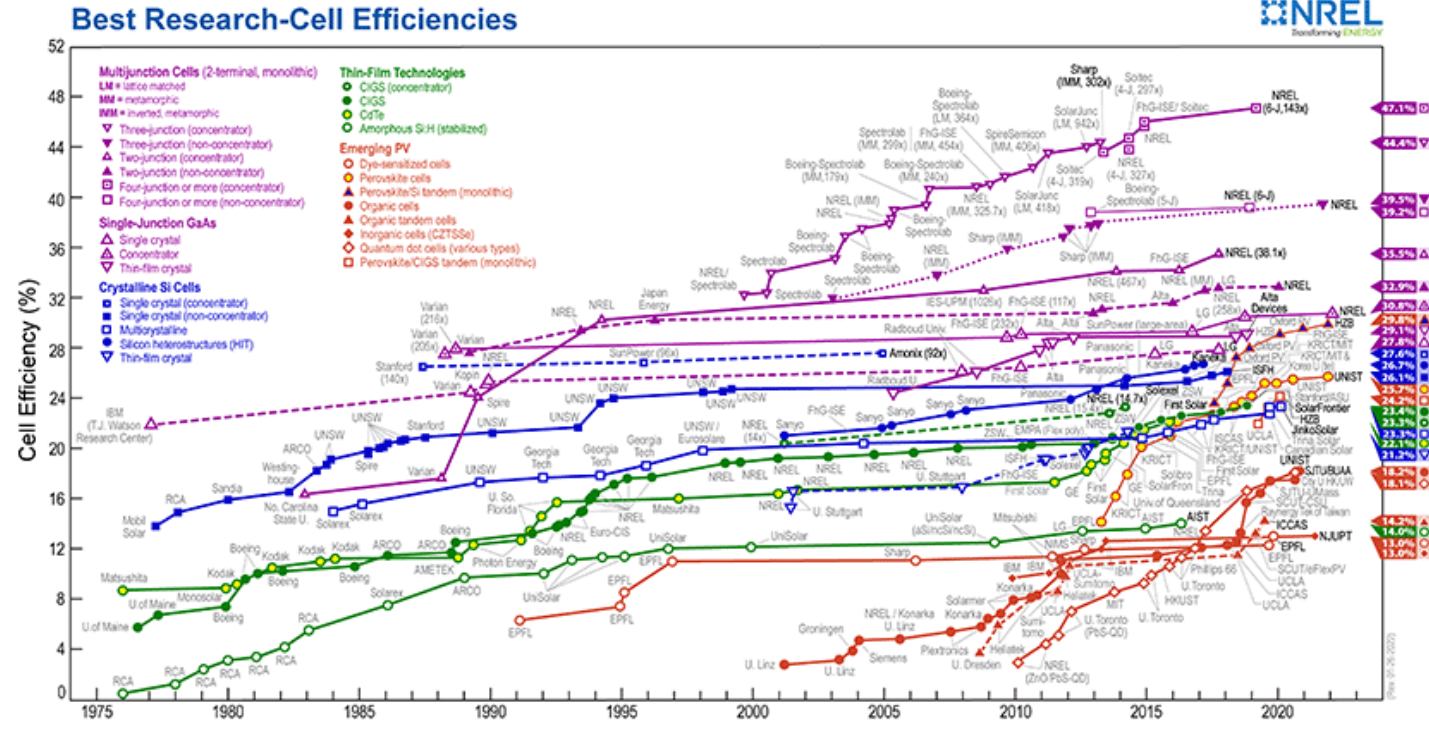
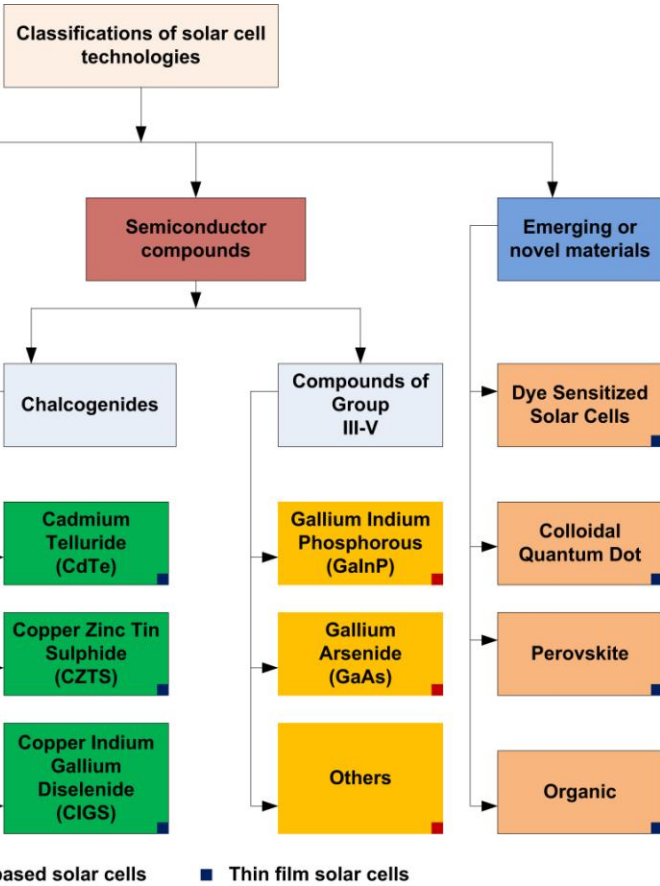
### PV learning curve



### Cost of Energy



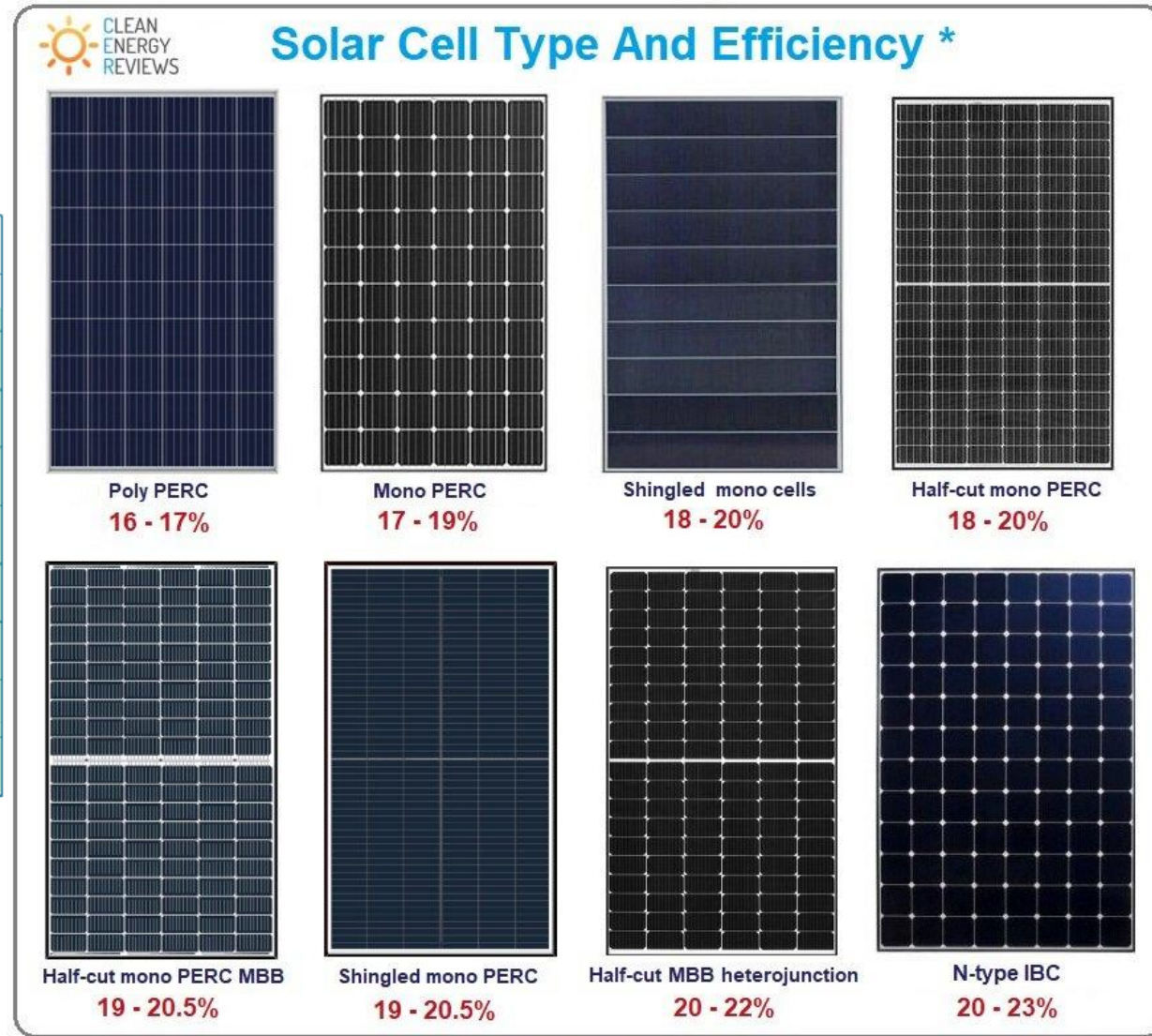
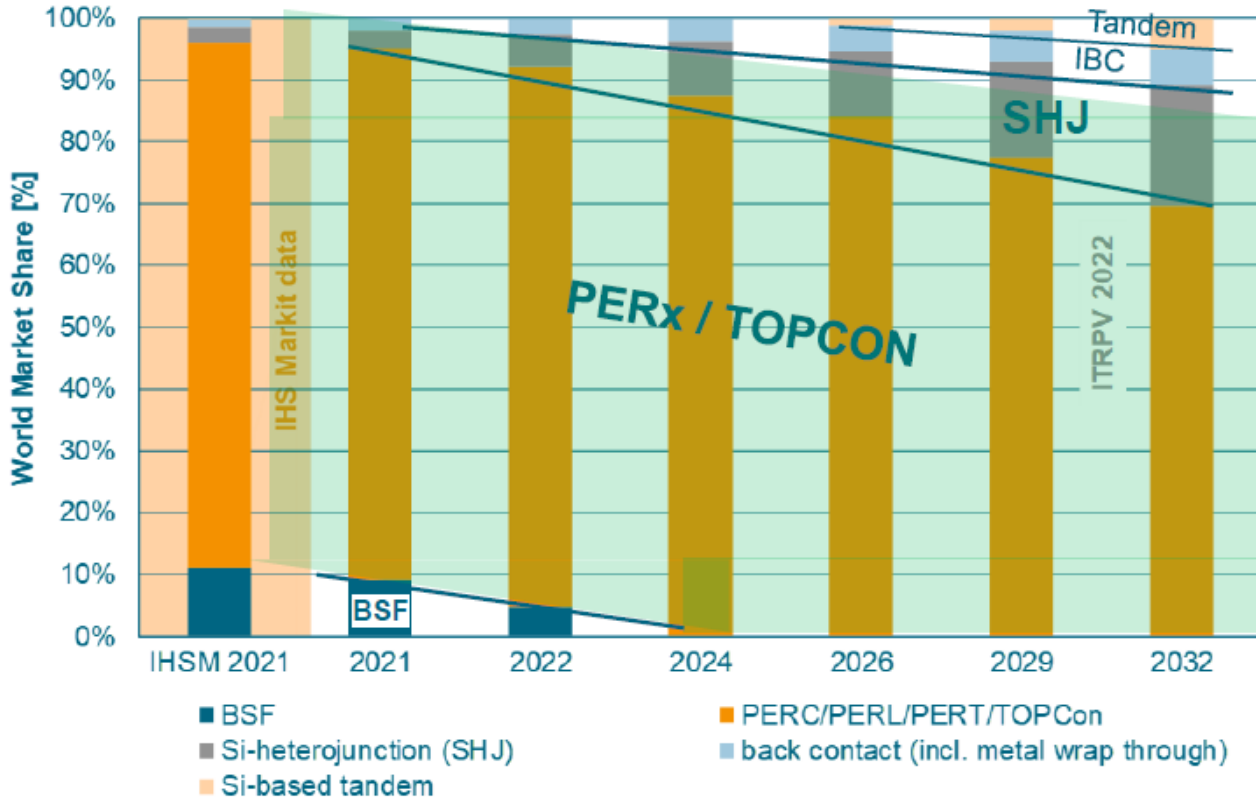
# PV FAMILIES



The final application will drive the technology selection

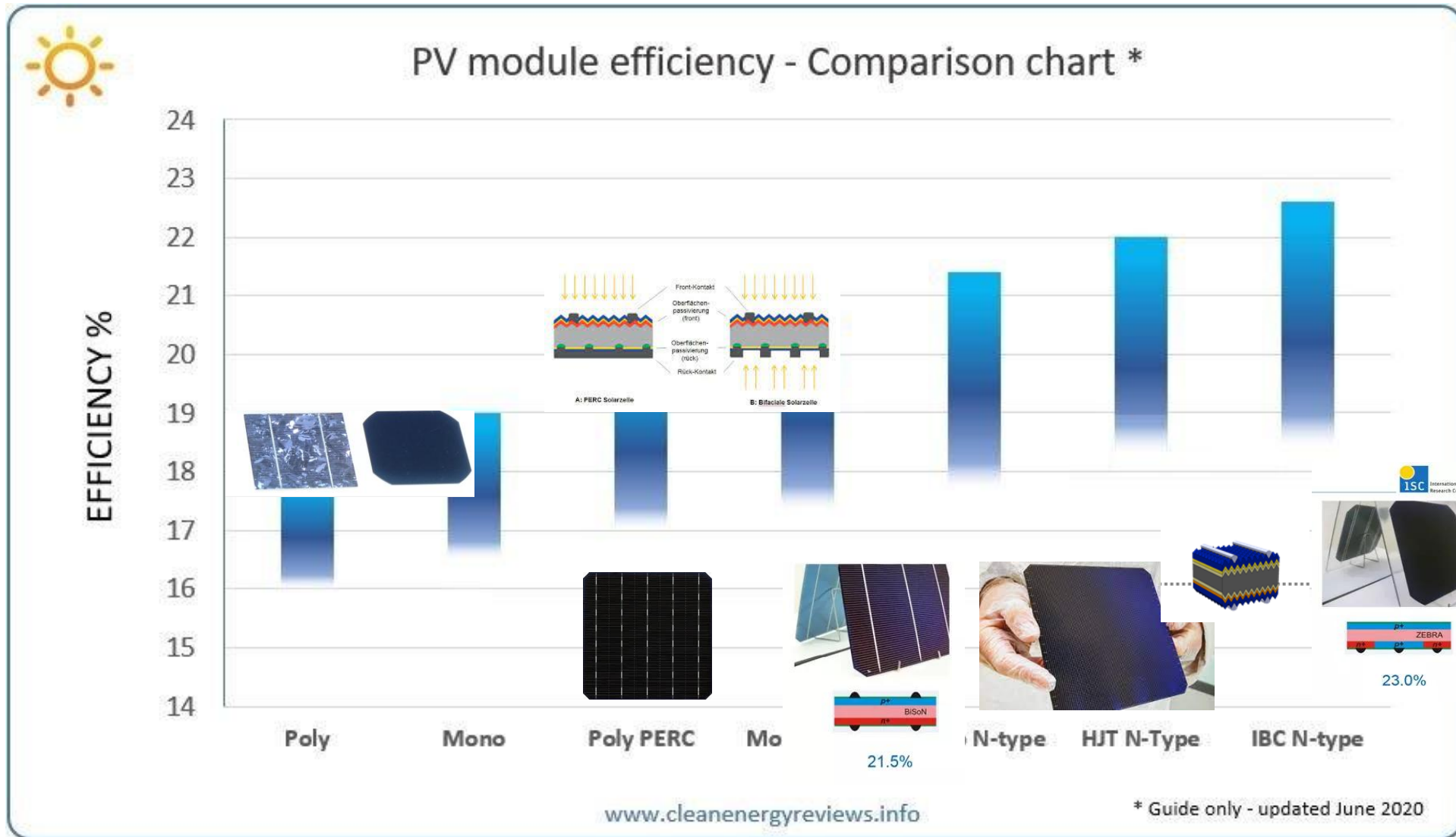
# VARIETY OF C-SI SOLAR CELLS & EFFICIENCY

## Trend: share of cell technologies



[www.cleanenergyreviews.info](http://www.cleanenergyreviews.info)

# VARIETY OF C-SI SOLAR CELLS & EFFICIENCY



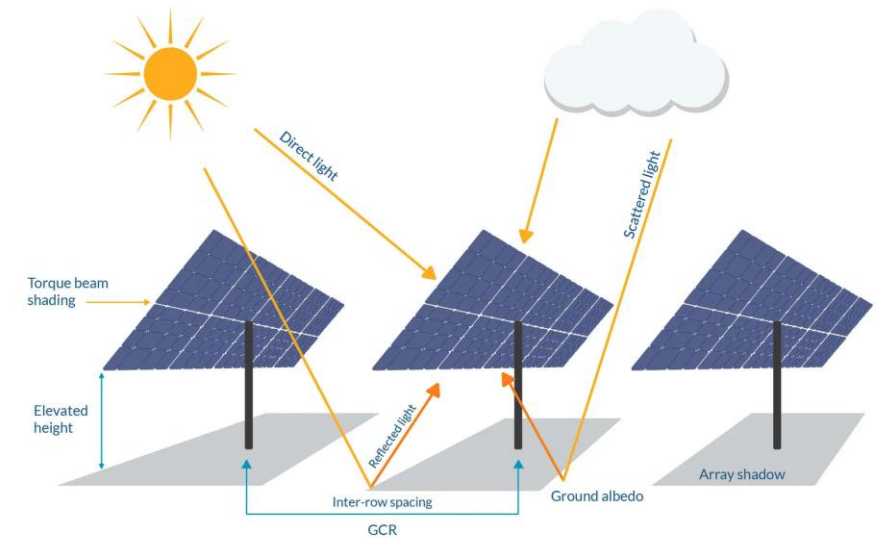
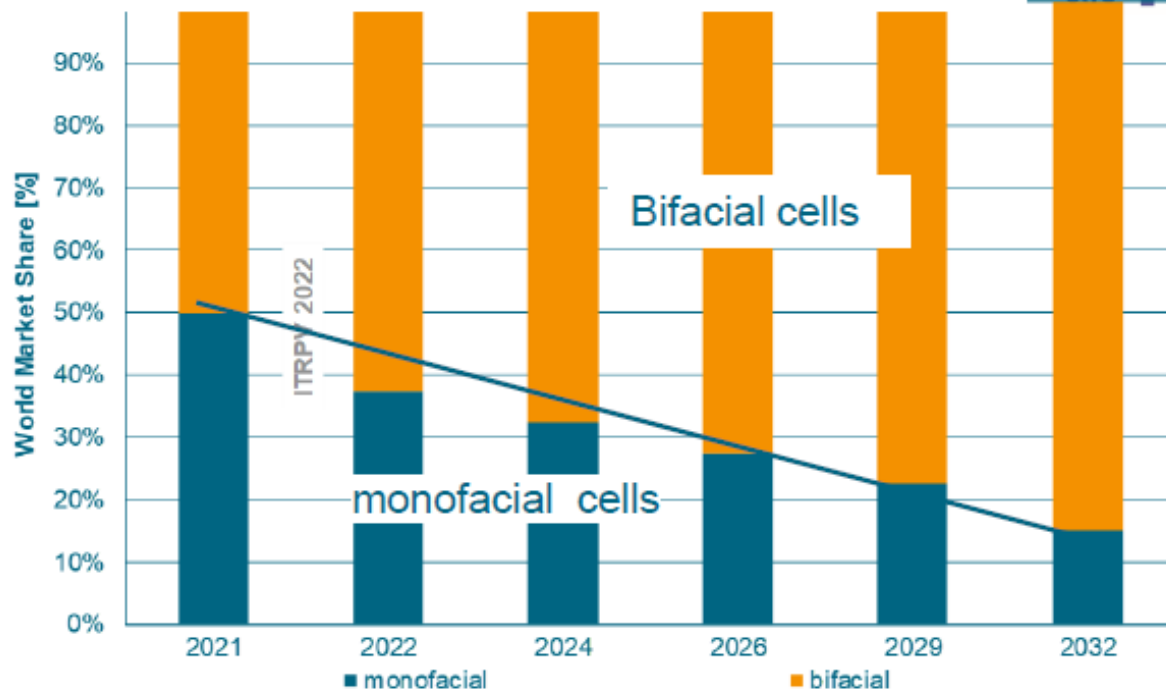


# BIFACIALITY IS HERE AND IT IS THE MAINSTREAM FOR UTILITY SCALE



## Trend: Bifacial cells

→ bifacial cells will be in “dual” use



# BIFACIALITY IS HERE AND IT IS THE MAINSTREAM FOR UTILITY SCALE

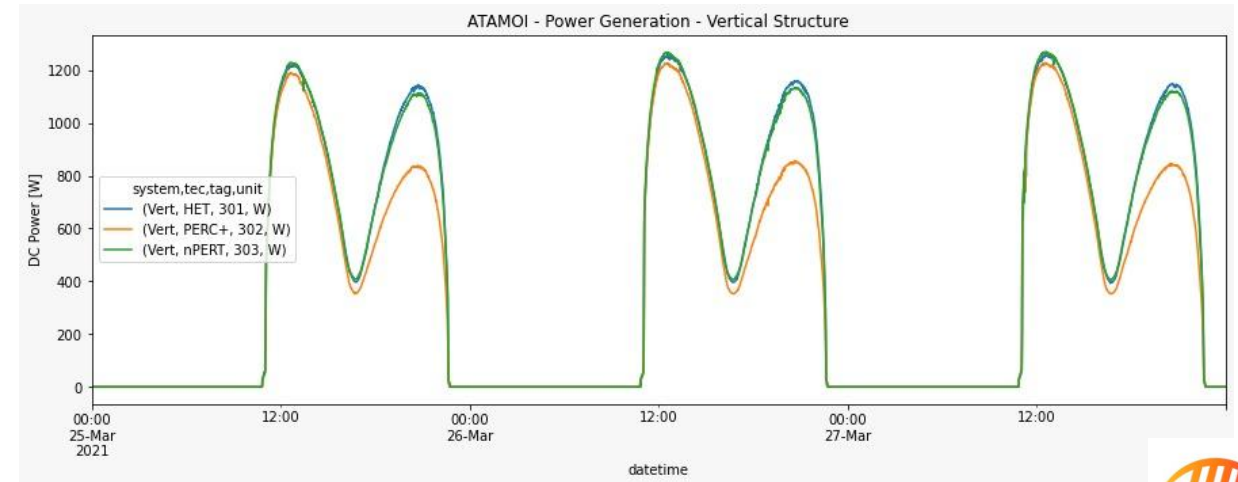
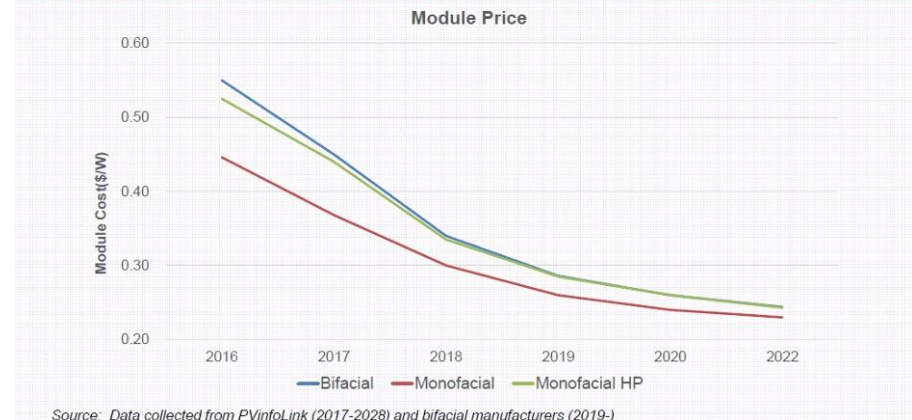
Solar generation capacity up to 25% depending on:

1. Solar cell and module technology
2. Site selection: Albedo, Land cost, latitude...
3. Height, row distance, tracker, tilt,
4. Meteorological conditions

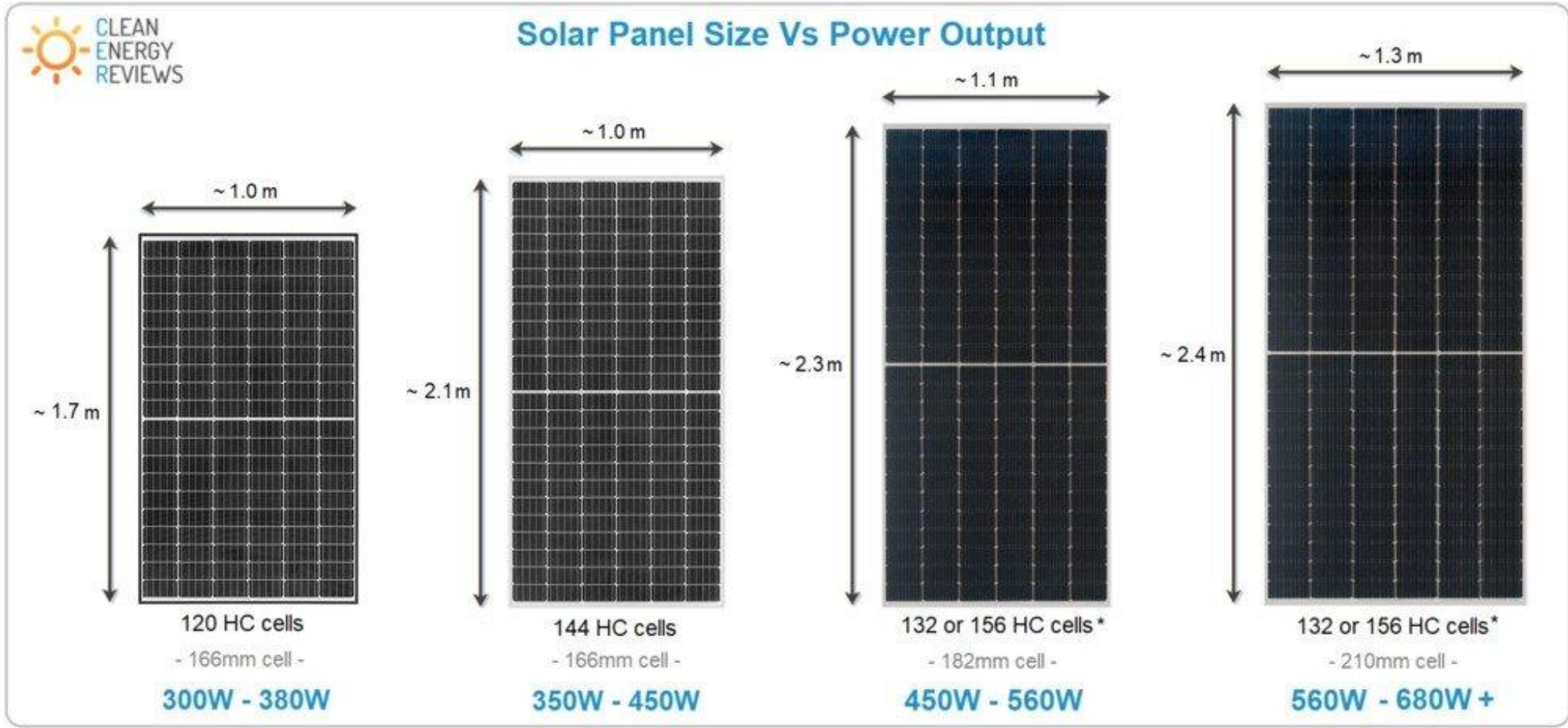
A bifacial, single axis tracking (1T) pv plant can cost approximately 15% more than a comparable monofacial non tracking PV plant.

**YIELD: a bifacial 1T plant can be well above 20%, up to 35 to 39% in some cases if conditions can be optimized.**

Cost Gap Between Bifacial and Conventional Modules is Decreasing



# LARGE AREA MODULES: MORE POWER / MODULE



HC = Half-Cut cells

HC\* = Half-Cut or 1/3 Cut cells

[www.cleanenergyreviews.info](http://www.cleanenergyreviews.info)

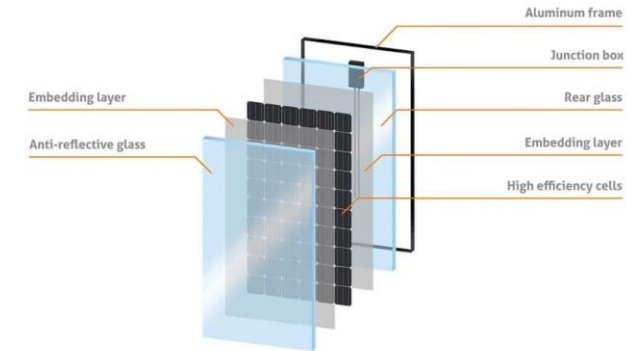
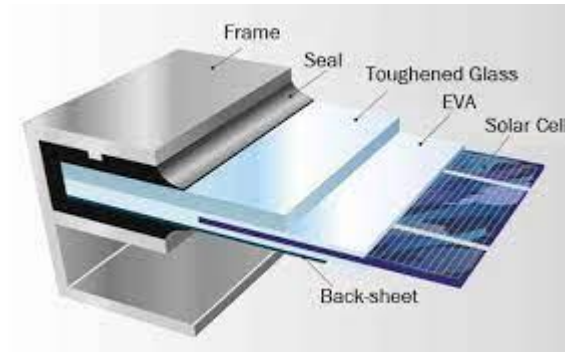
## FRAME OR FRAMELESS?

### Advantages :

1. Reduces impact of potential-induced degradation (PID) – enabling longer lifespan.
2. No corrosion, no Aluminum
3. Easy to recycle
4. Less soiling and snow issues
5. increases the aesthetic appeal

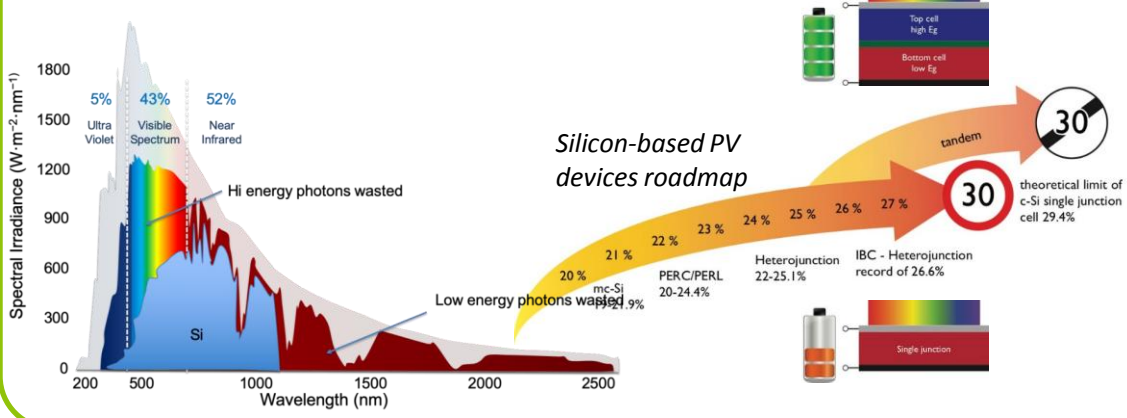
### Drawbacks:

1. Specific structures
2. Cost higher / 2 glasses, high weight
3. edges of the panels can be little weak

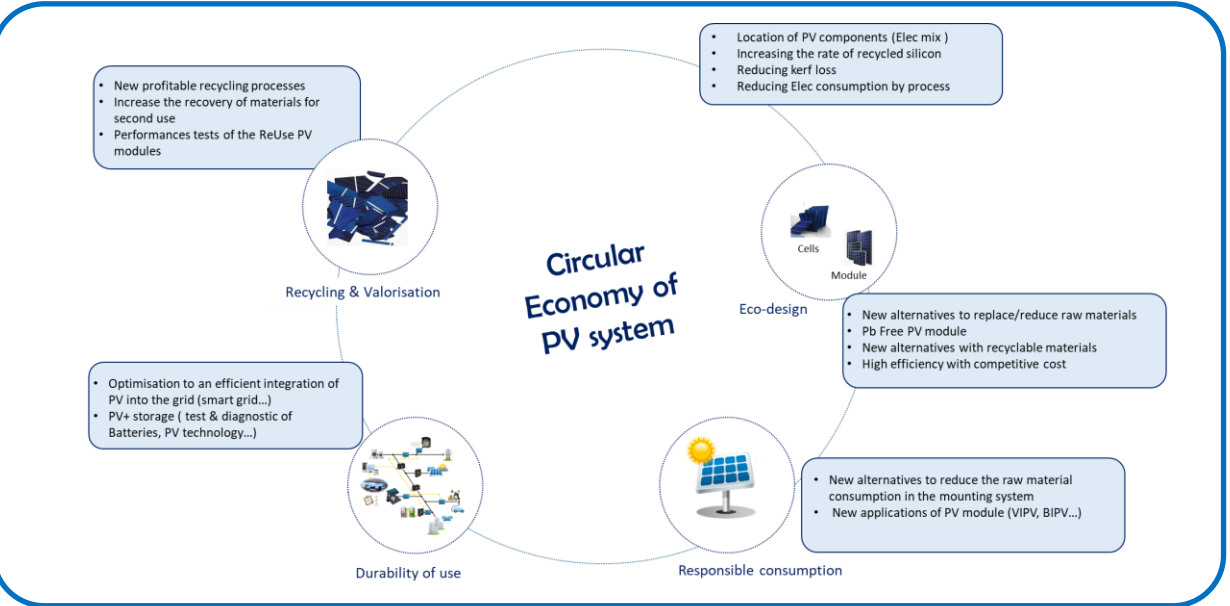


# NEXT GENERATION OF PV MODULES

Tandem technologies > 30% efficiency  
 Maximizing solar spectrum use or varying which spectrum part is used for energy



Efficiency, Cost, Reliability



Sustainability, Eco-design, Recyclable

Integrated, adapted

## CONCLUSION ON PV MODULES TECHNOLOGIES

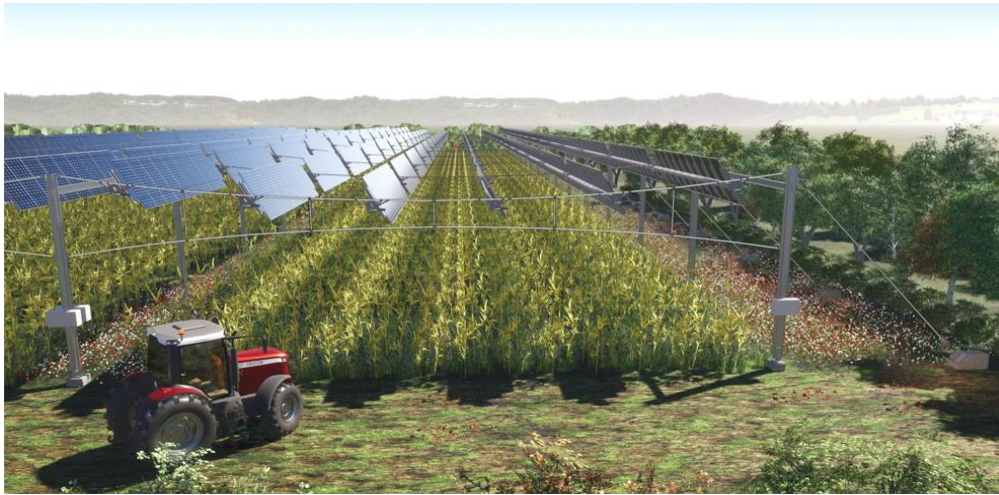
- New paradigm for PV modules
- Not more a standard for everything
- Module has to be adapted to the application
- The total cost of the system is calculated not only with LCOE basis (other KPI needed)
- Reliability is a must
- The system and O&M costs will depend on the module technology chosen
- Modelling is mandatory to select the best technology



Each agrivoltaic installation can adapt PV module technology

## PART 2 : MODELLING METHODS OF THE PV PRODUCTION

### An application favourable to the development of bifacial technologies



(source TSE)



(source Next2Sun)

- High clearance of modules above the ground (up to several meters to give way to agricultural machinery)
  - Space between modules rows (to limit the shadow projected on the ground)
  - Use of glass-glass modules for higher resistance (mist, agricultural chemicals, ...)
- ➔ Bifacial modules are appropriate and may operate in good conditions to provide an energy gain.

## PART 2 : MODELLING METHODS OF THE PV PRODUCTION

System modelling is required for:

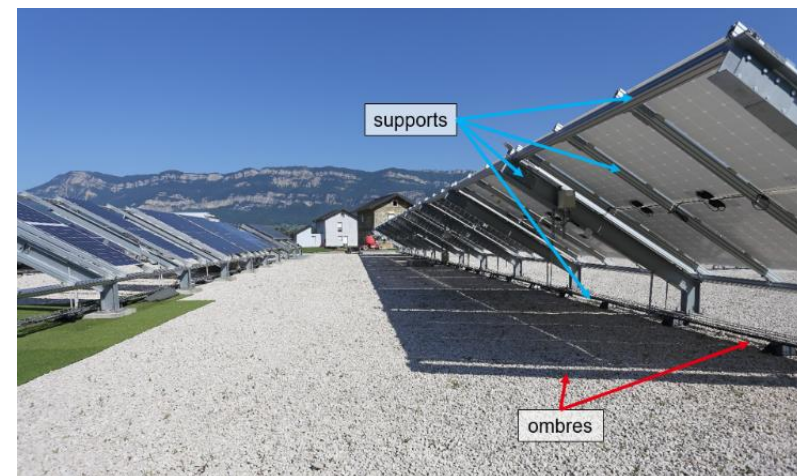
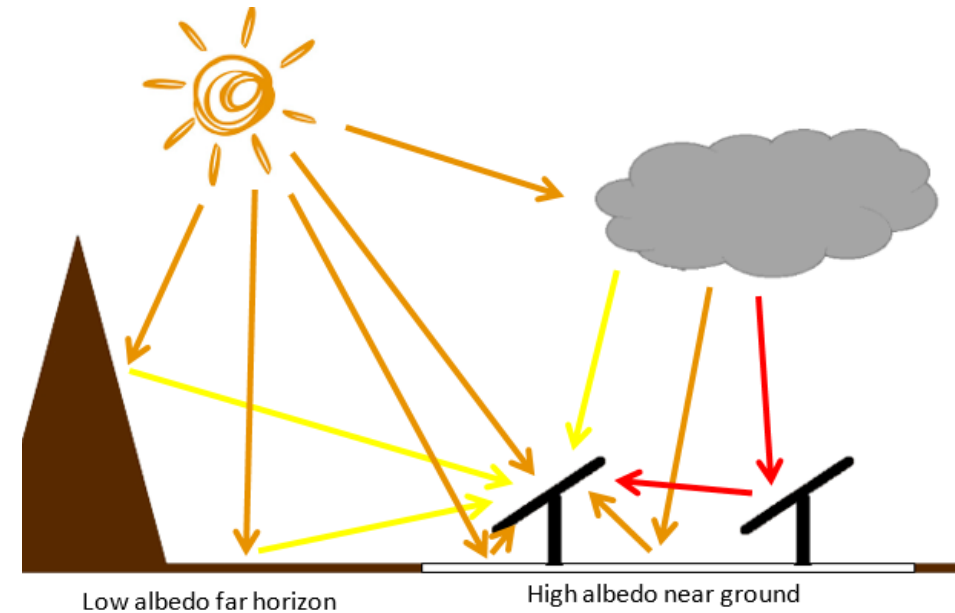
- Production estimations
- System optimization
- Operation monitoring

Three kinds of models are needed:

- Thermal model
- Electrical model
- Optical model

Calculation of the irradiance on the module backside is a key issue:

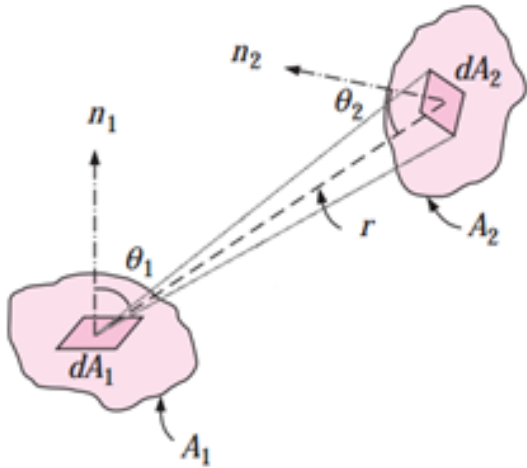
- Mainly diffusion irradiance
- Impact of neighbouring obstacles
- Projected shadow on the ground
- Irradiance mismatch





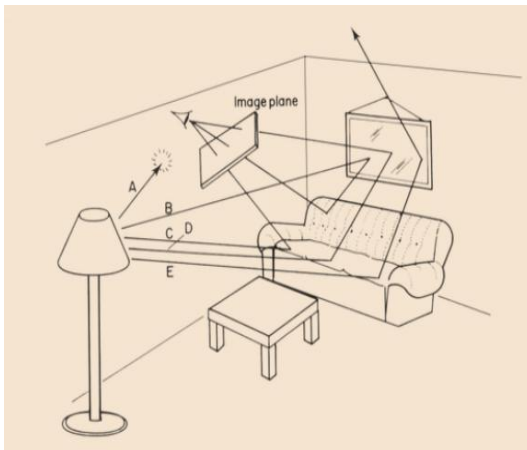
## PART 2 : MODELLING METHODS OF THE PV PRODUCTION

Optical methods are mainly divided in two families : view factors (2D and 3D VF) and ray tracing (RT)



VF:

- Depend on geometry
- Calculated once
- Sky  $\Leftrightarrow$  modules
- Sky  $\Leftrightarrow$  ground
- Ground  $\Leftrightarrow$  modules



RT:

- Traces rays of light backwards to the sources
- Calculated for each position of the sun

	View-Factor (VF)		Ray-Tracing (RT)
Origin	from heat transfer studies		rendering image method
PV System definition (the modules)	2D (infinite row hypothesis)	3D	3D
Modelling rear side inhomogeneity (edge effect)	No	Yes	Yes
Precise structure shading (racking)	No (at best a global shading factor)		Yes
Reflection nature (scattering)	isotropic only		all types of reflection (isotropic, specular, etc.)
unconventional configurations: BIPV, curved surfaces, .....	No		Yes
Computation time to simulate yearly irradiance on a standard CPU laptop	seconds to minutes	hours	days
When to use?	Rules of thumb Trends Yield calculation	Yield calculation Diagnosis and prevision	diagnosis and prevision

## PART 2 : MODELLING METHODS OF THE PV PRODUCTION

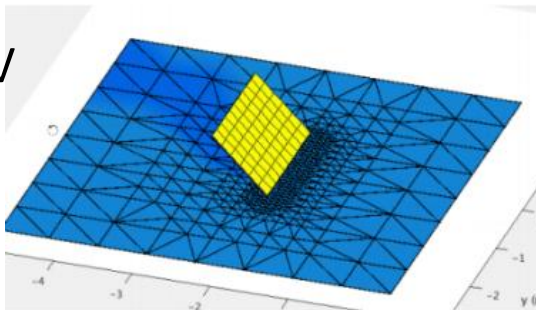
Among open source tools (Bifacial\_Radiance (RT), PVfactors, Bifacial\_vf (2D VF)), commercial tools (PVsyst (2D VF), PVcase (RT)) and in-house tools (BigEye, MoBiDiG (3D VF), PVNOV (RT)), **CEA is developing its own 3D VF tool: Trifactors**

A simulation with Trifactors is run in few steps:

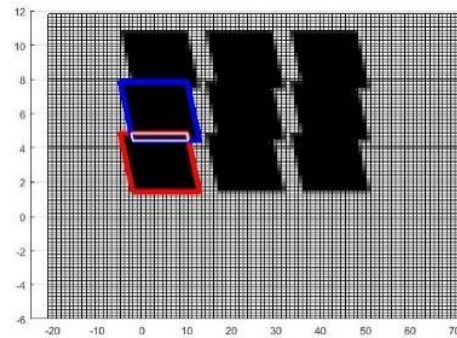
**1st:** collection of PV system, meteo, simulation data

**3rd:** calculation of view factors

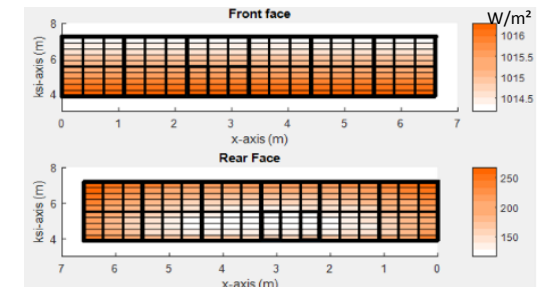
**2nd:** meshing of the ground and PV array



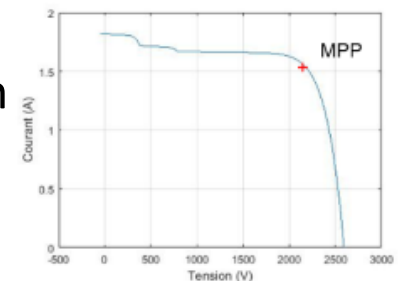
**4th:** calculation of projected shadows



**5th:** calculation of front and back irradiances

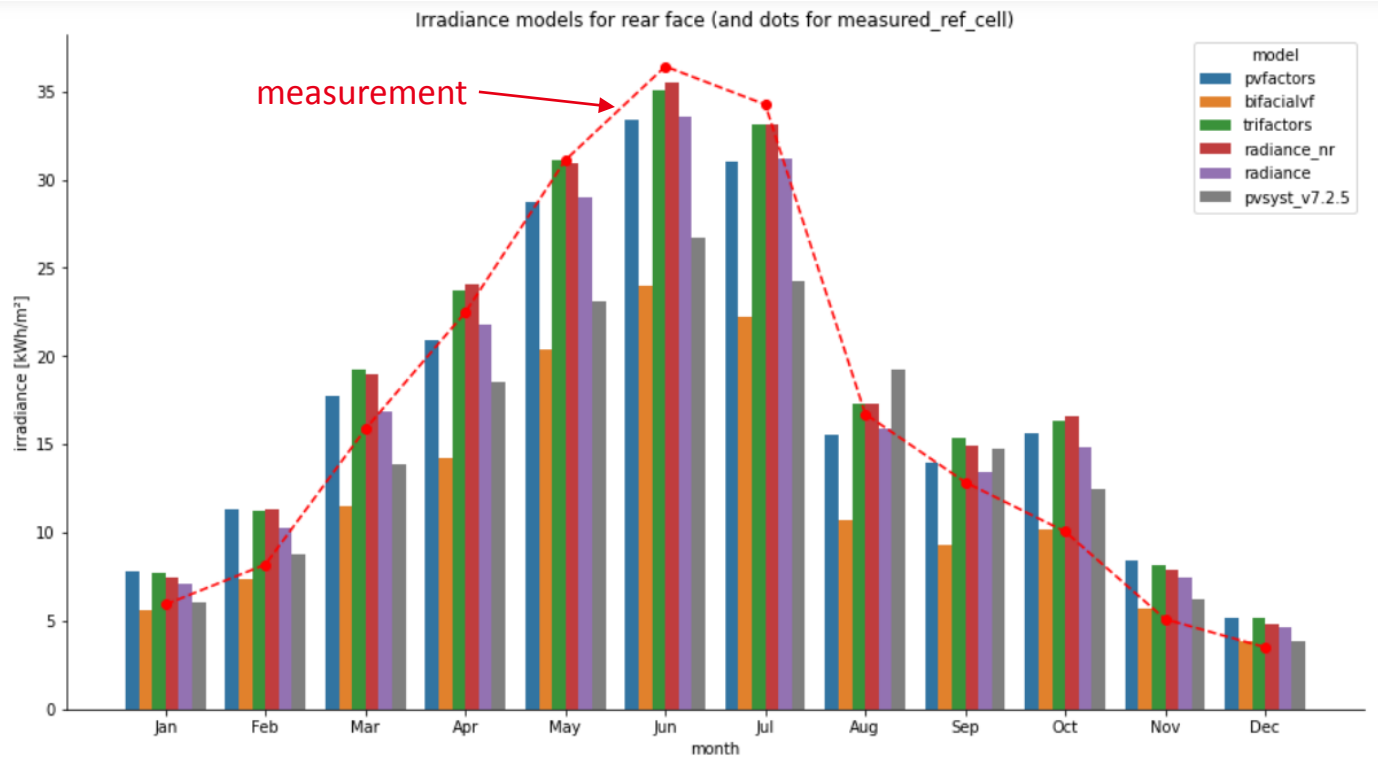


**6th:** calculation of electrical power at mesh level, then at system level

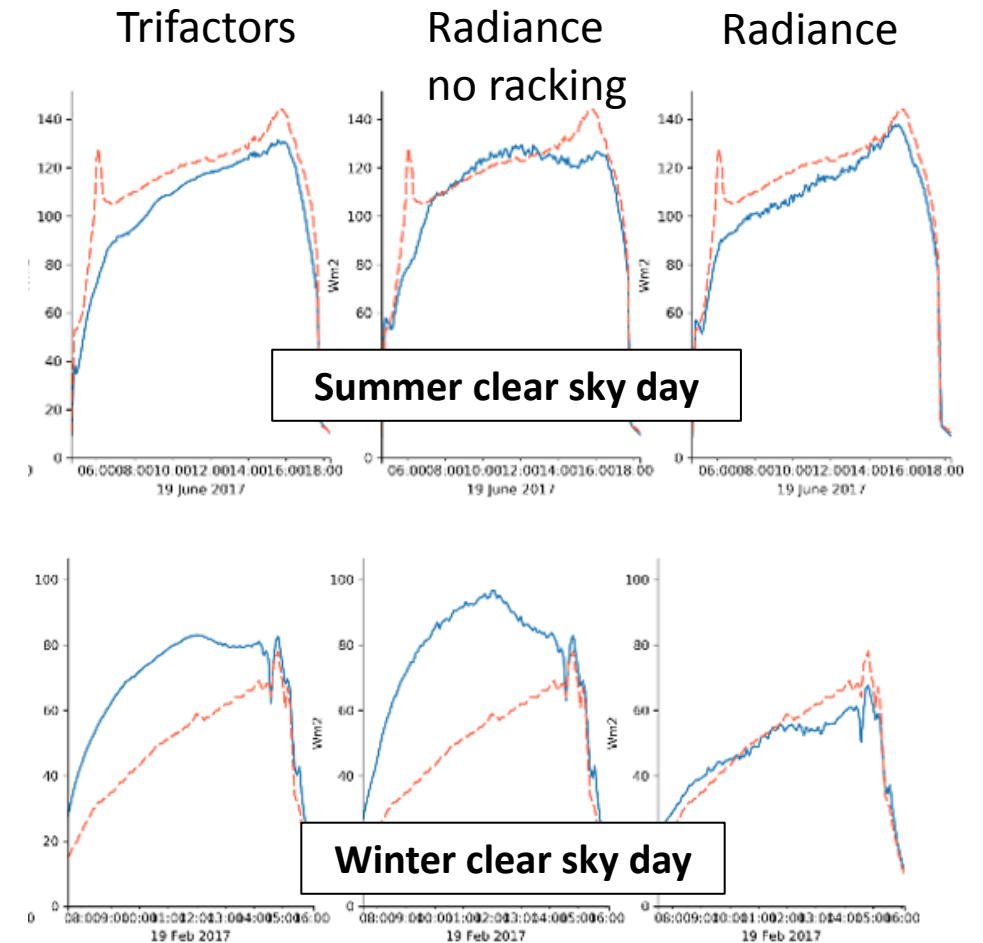


## PART 2 : MODELLING METHODS OF THE PV PRODUCTION

A benchmark with several tools shows that Trifactors is close to RT Radiance “no racking”

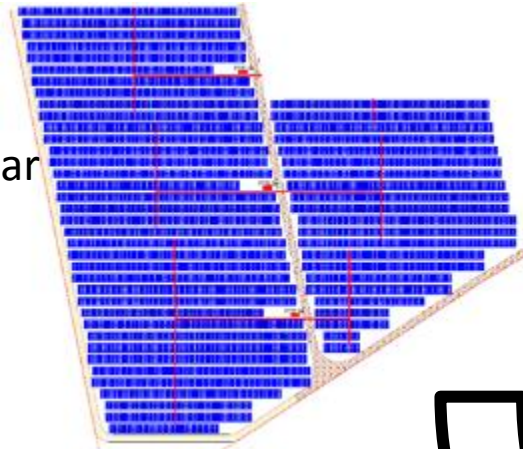


The impact of the supporting structure on backside irradiance is an area of improvement of VF tools



## PART 2 : MODELLING METHODS OF THE PV PRODUCTION

1. Large plants usually do not have rectangular shapes and show singularities (paths, missing arrays ...)

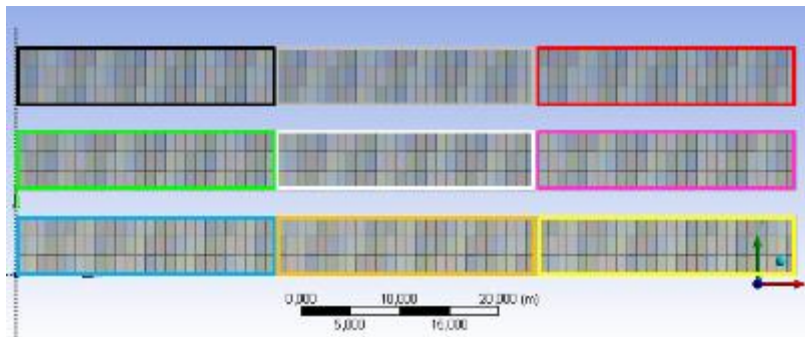


Real plant

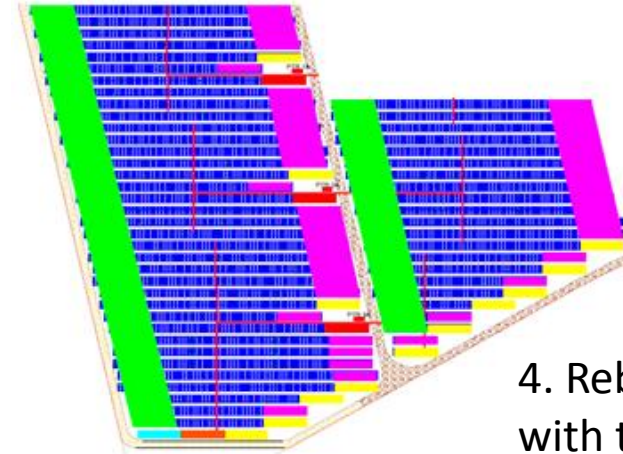
2. Simulation of only a small elementary pattern with all edge effect possibilities:



Simulated pattern



9 zones



Simulated plant

4. Rebuilding the plant with the different types of zones



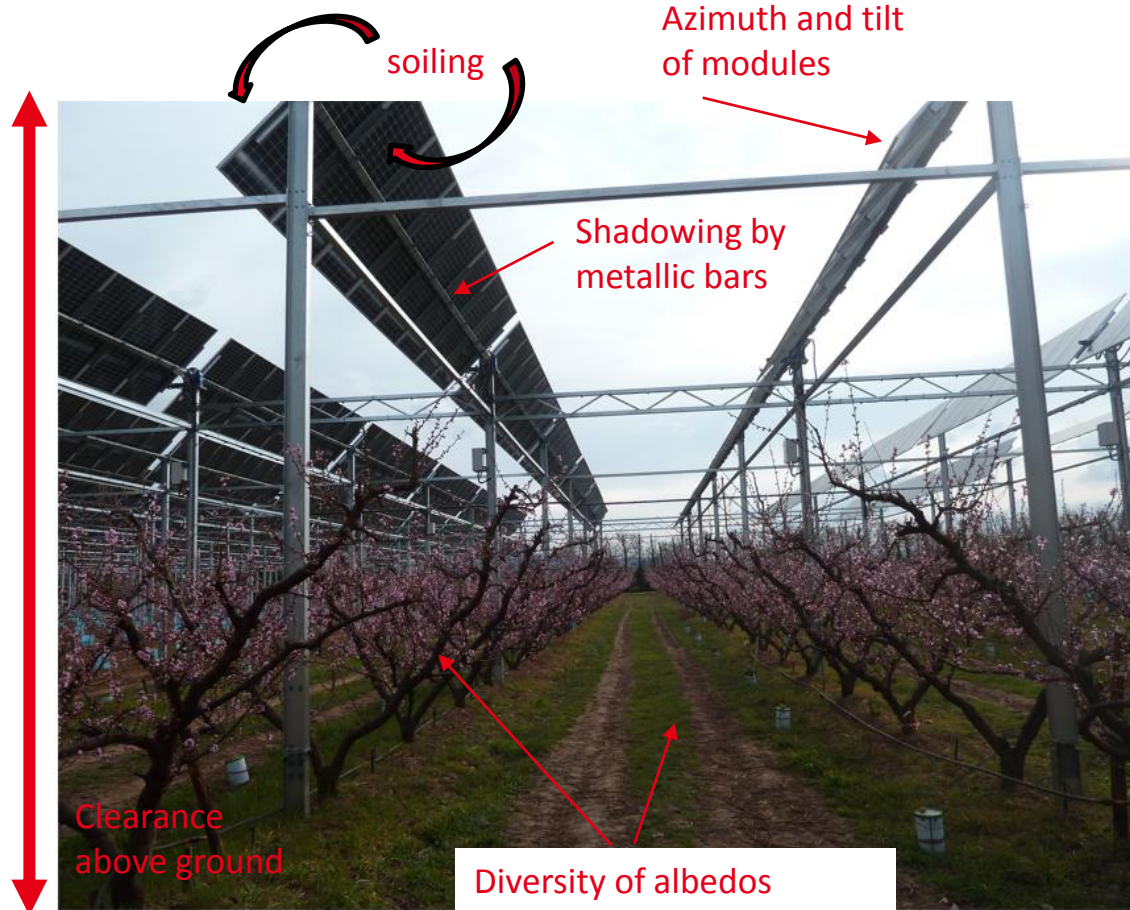
Conversion Table

3. Counting the different types of zones

Code couleur blocs 3V26				Nombre de blocs 3V26	Nombre de modules	% des tables
G	H	I	A	1	78	0,3%
D	E	F	B	1	78	0,3%
A	B	C	C	13	1014	4,1%
			D	56	4368	17,7%
			F	43	3354	13,6%
			G	0	0	0,0%
			H	0	0	0,0%
			I	3	234	0,9%
Totaux blocs bords				117	9126	37,0%
E				199	15522	63,0%
<b>Totaux</b>				<b>316</b>	<b>24648</b>	<b>100,0%</b>

## PART 2 : MODELLING METHODS OF THE PV PRODUCTION

Impacts of the agricultural environment on the PV system operation:



Color, height and shape of crops depending on type, season ...

Artificial albedo to boost reflection



Moving modules impacting electrical architecture



## CONCLUSIONS

**Crop growth remains the first goal of an AgriVoltaic system**

**And there are ways to optimize the PV production:**

- **Selection of appropriate PV module (glass-glass, high bifacial factor...)**
- **Sun tracking control when not required for crops**

**But rear face irradiation is highly depending on ground albedo**

**Main issues for PV production estimation are:**

- **The optical modelling (in progress)**
- **A near real-time and a 2D/3D spatial breakdown of the albedo (to be done)**

**THANK YOU FOR YOUR ATTENTION!**

Thanks to the CEA-INES team!

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