



Agrivoltaics: a review of PV technologies and modelling methods

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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

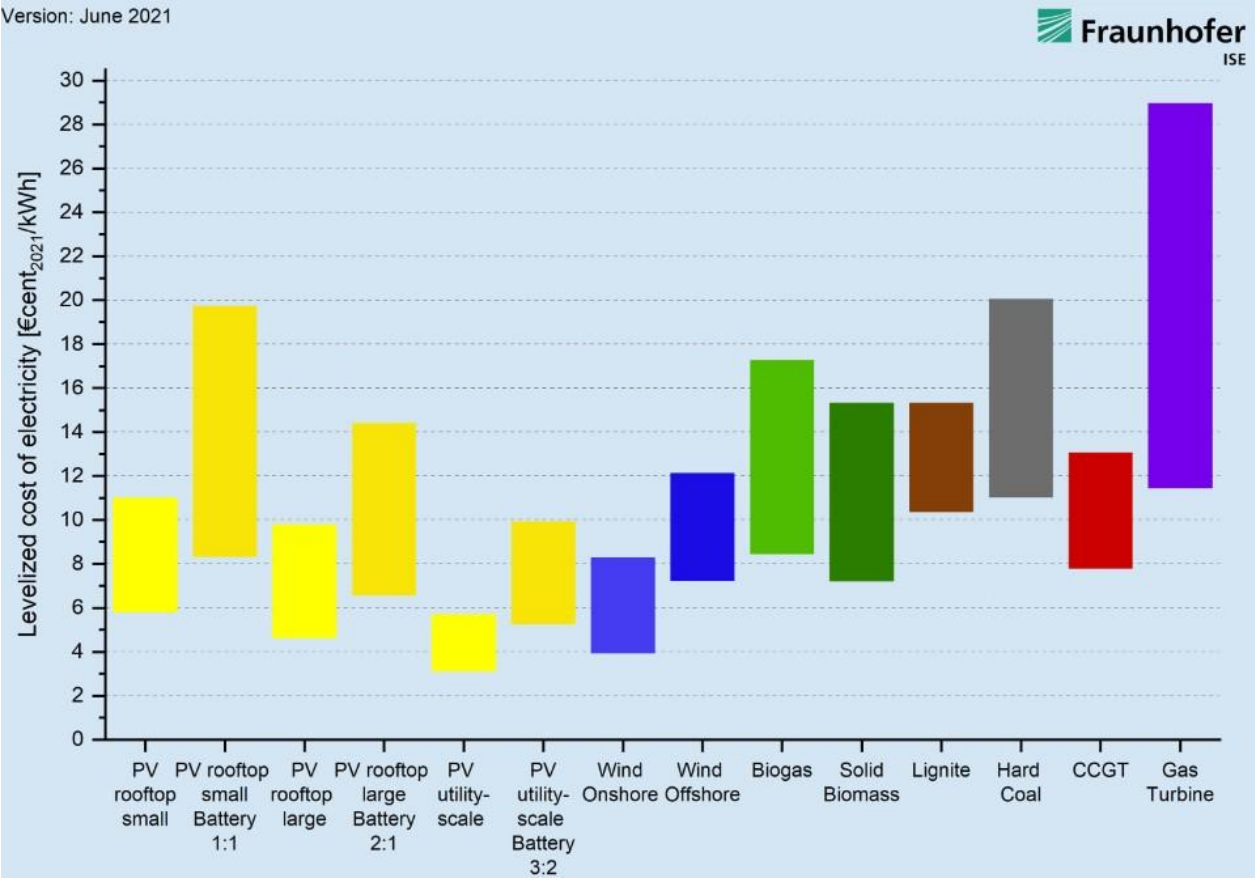
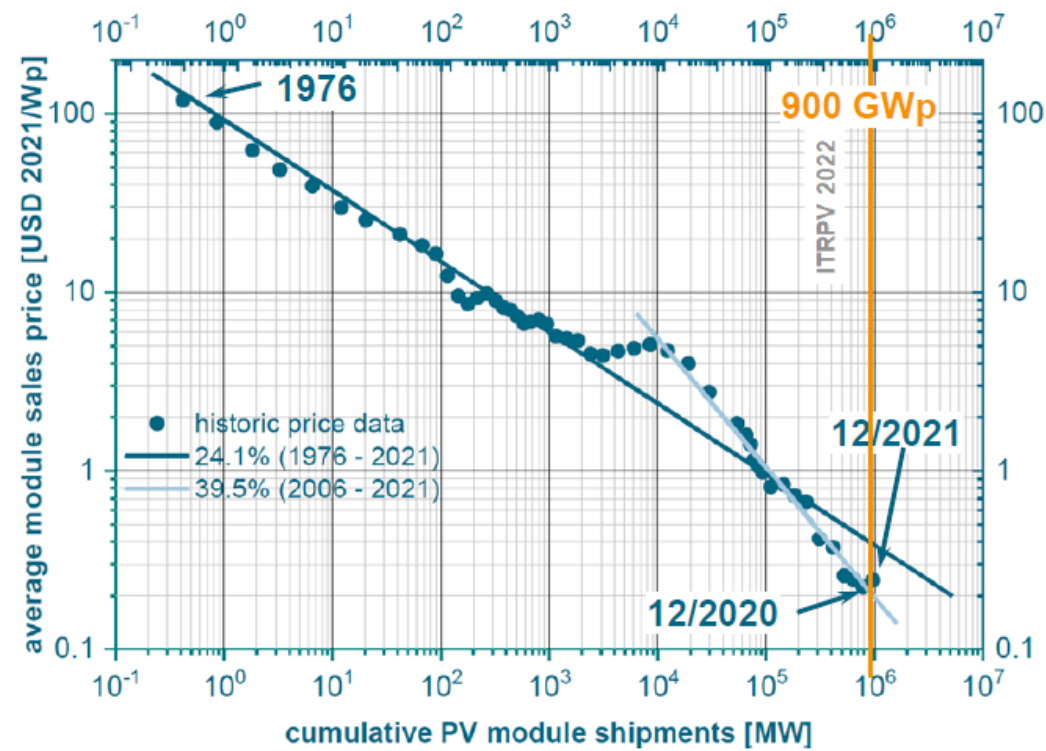
Grid integration | Diagnosis & Data | Energy management systems | Storage | Smart grids & Smart cities

PART 1 : REVIEW OF PV MODULES TECHNOLOGIES

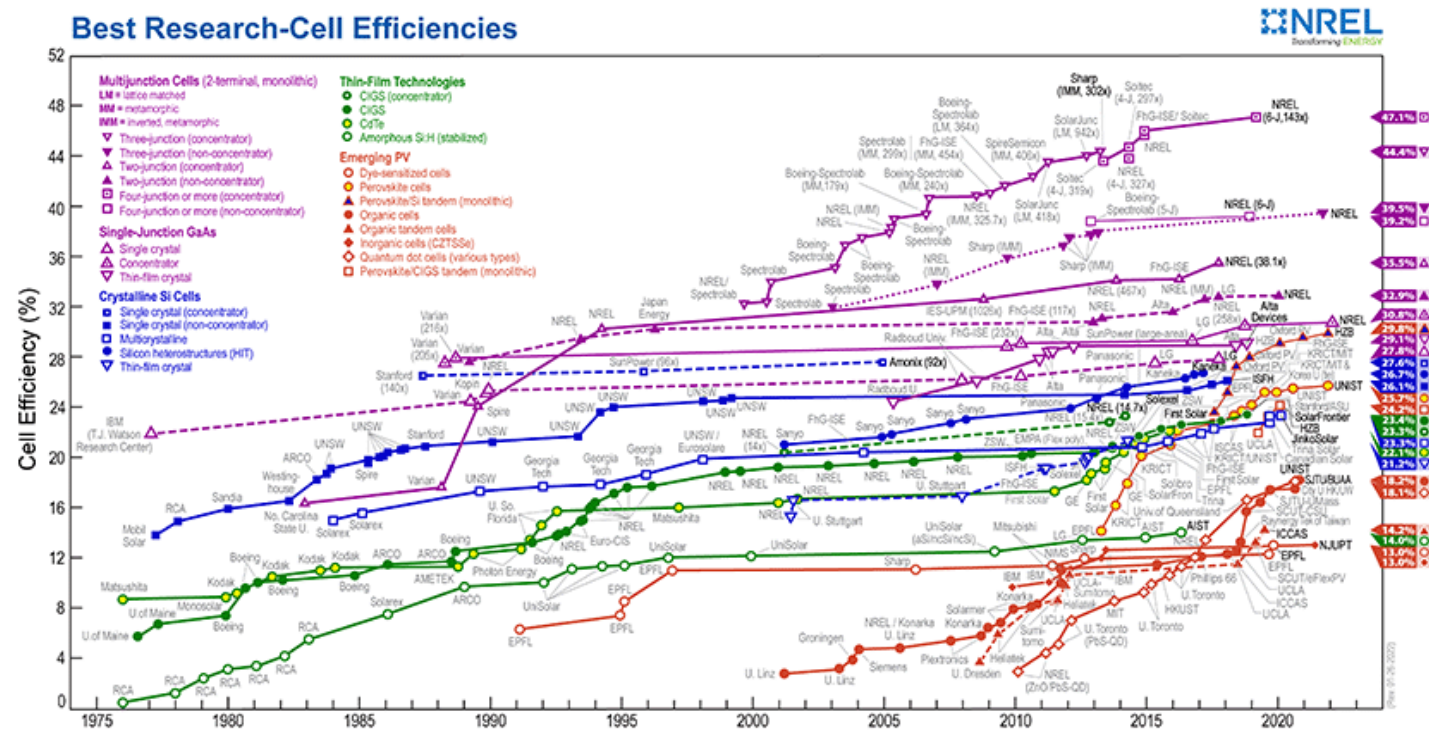
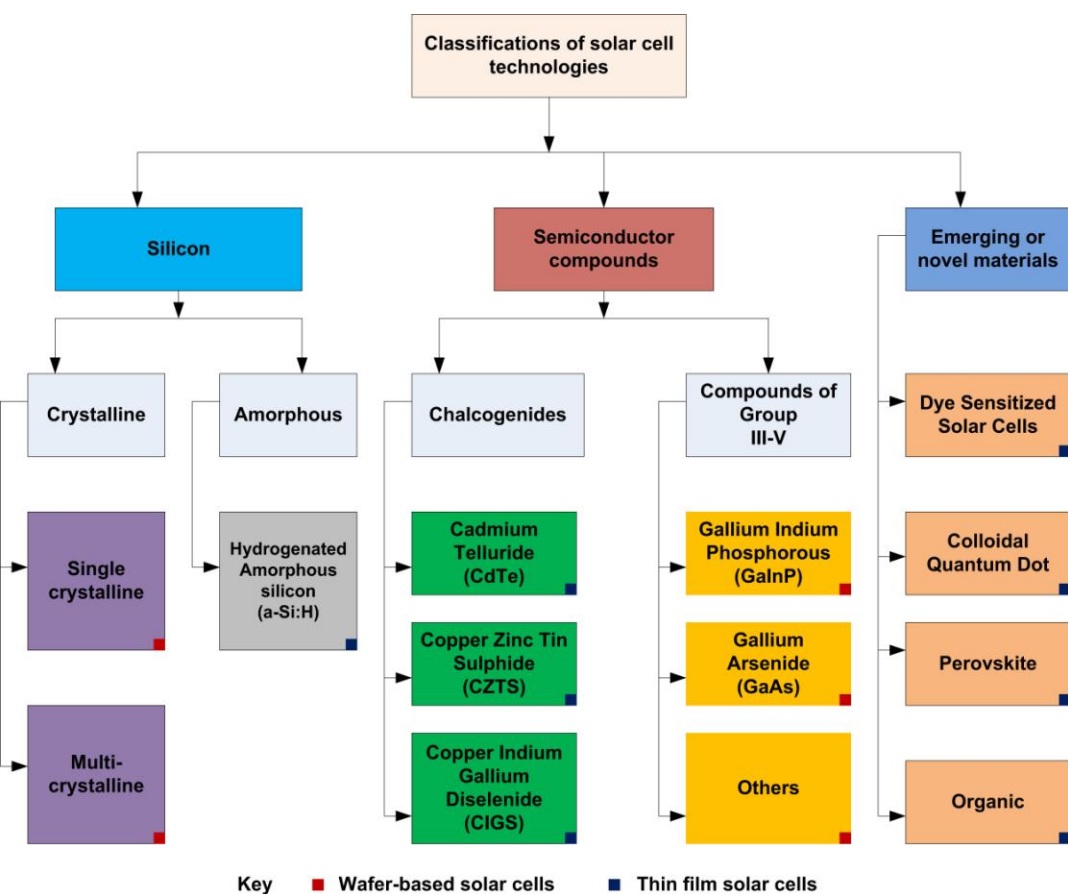
COST OF ENERGY

Cost of Energy

PV learning curve



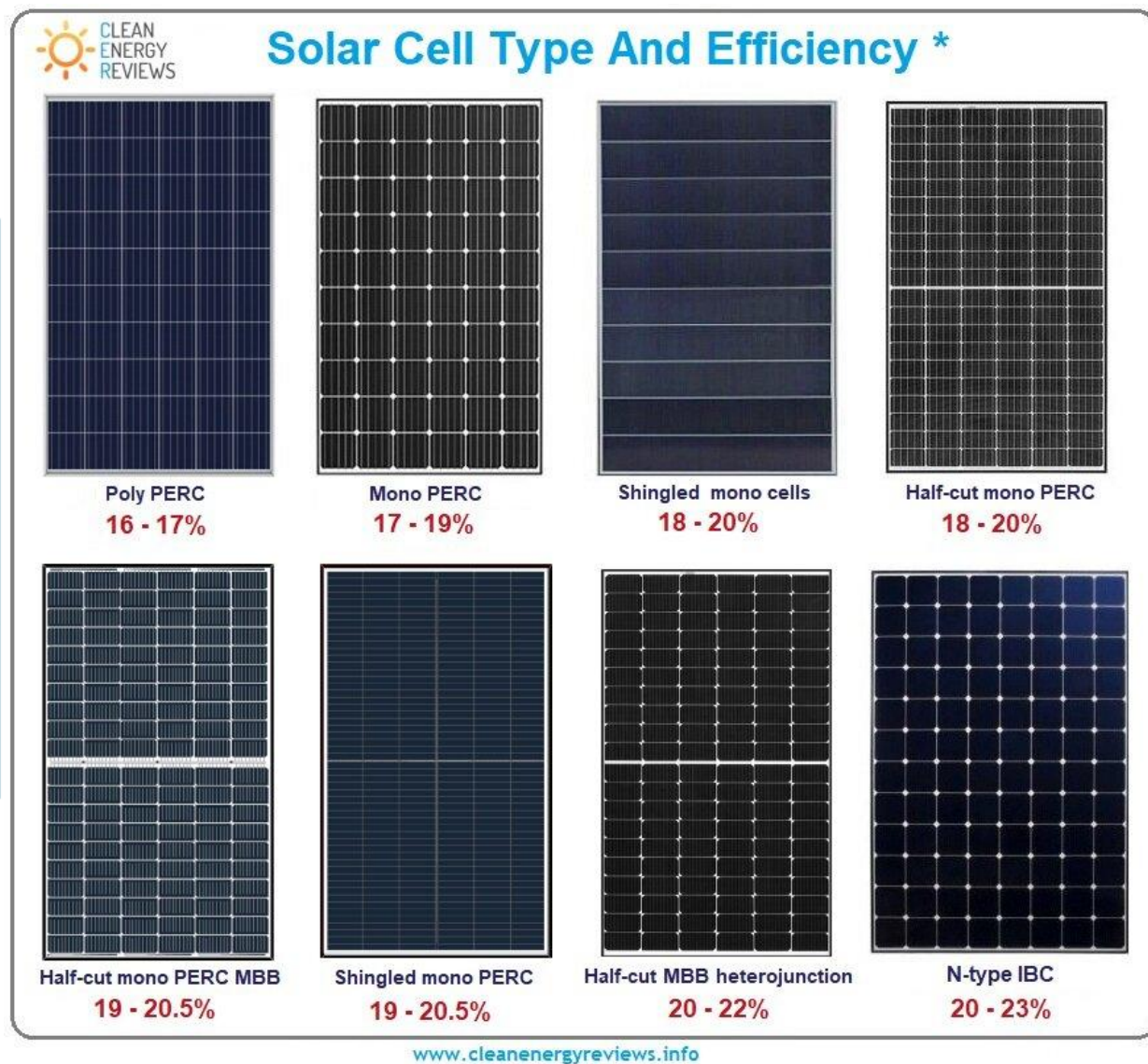
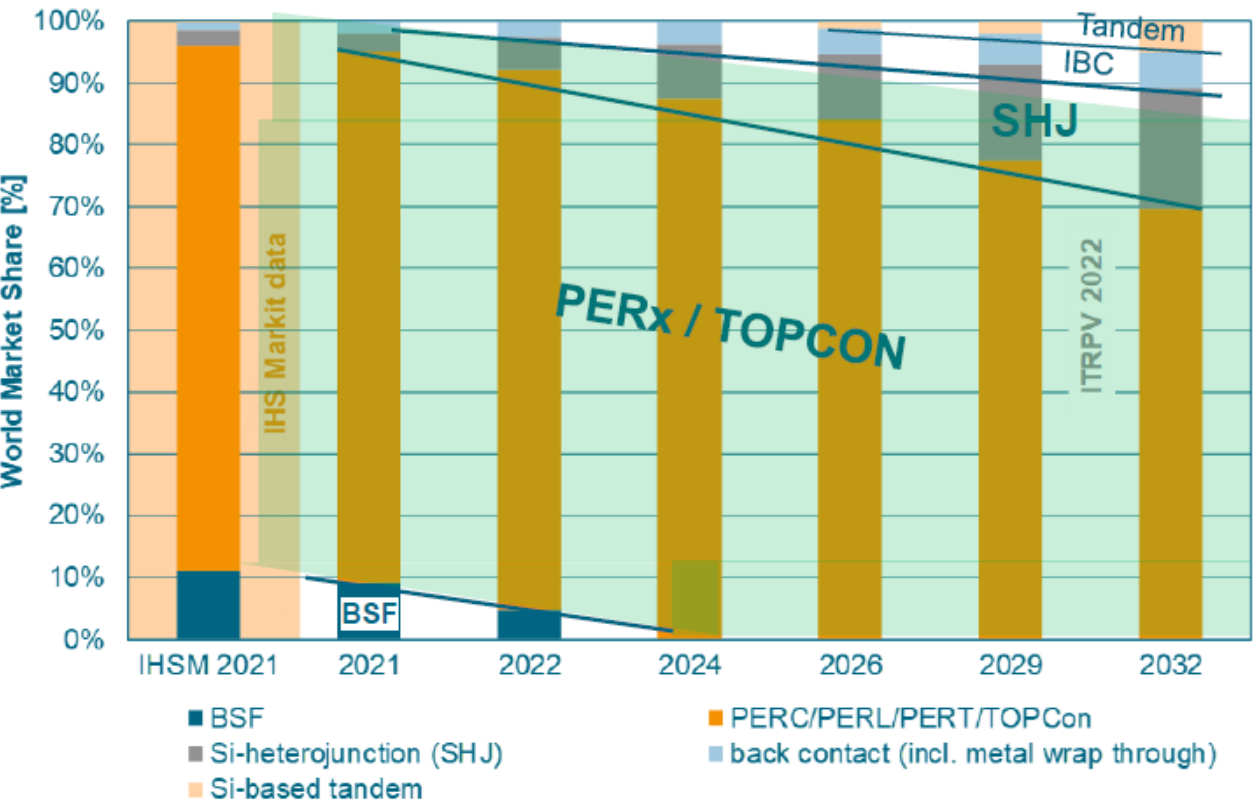
PV FAMILIES



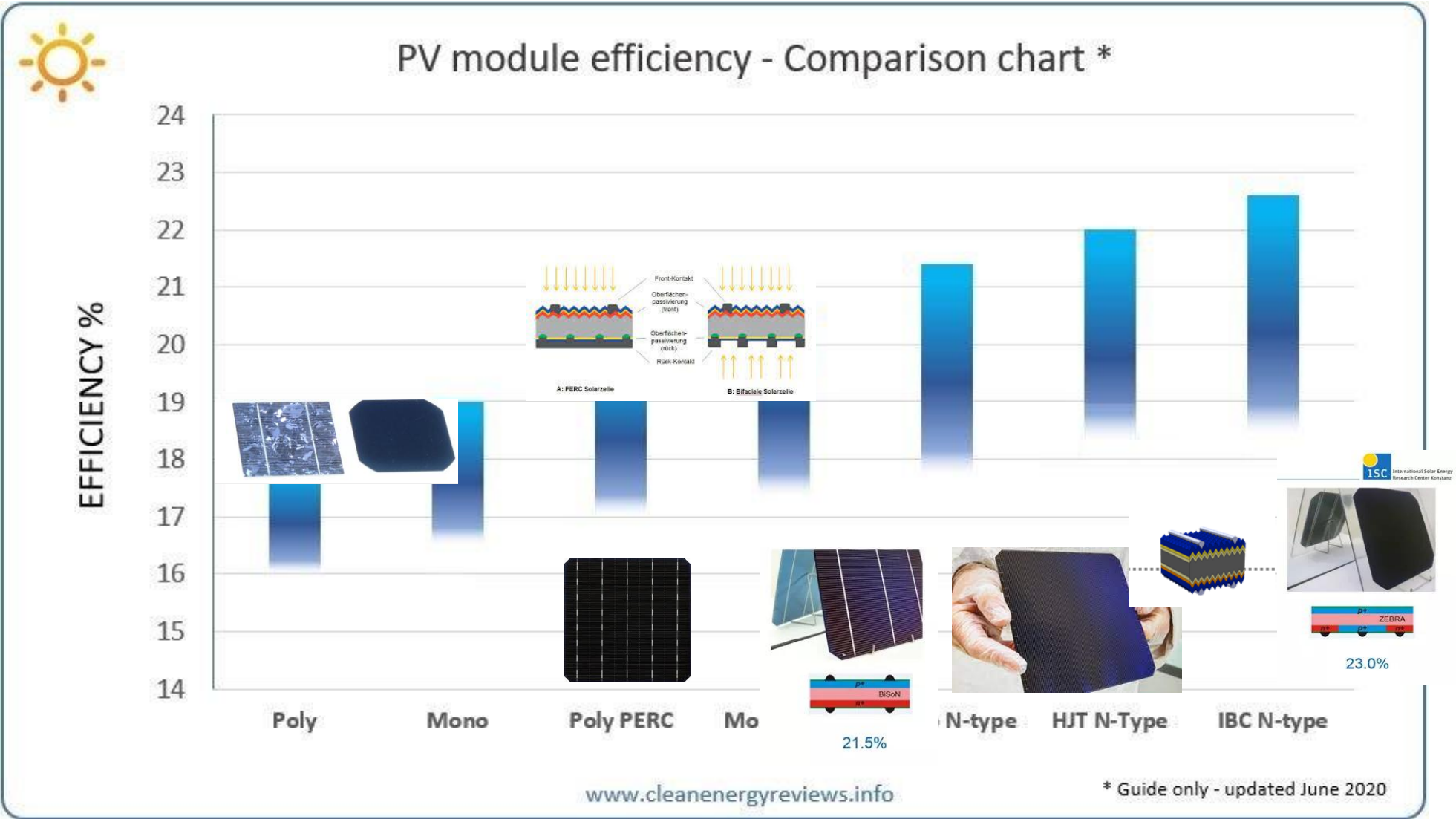
The final application will drive the technology selection

VARIETY OF C-SI SOLAR CELLS & EFFICIENCY

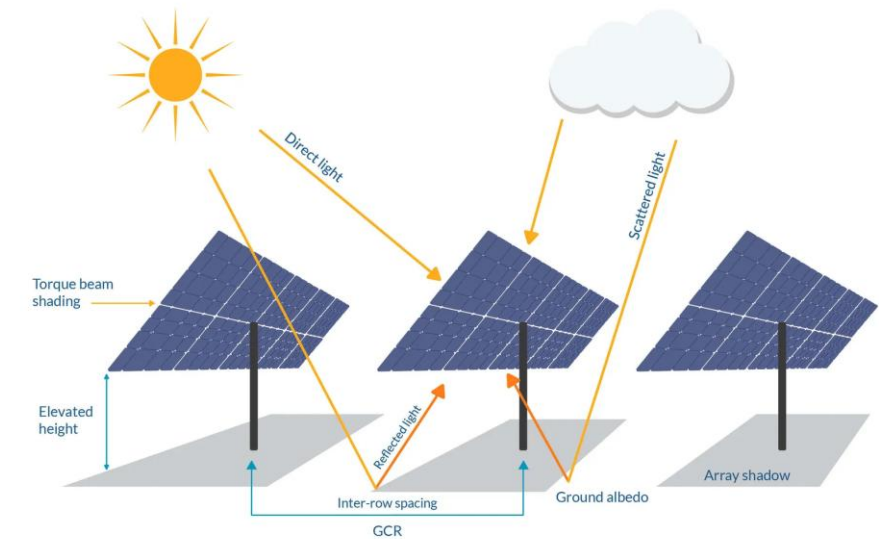
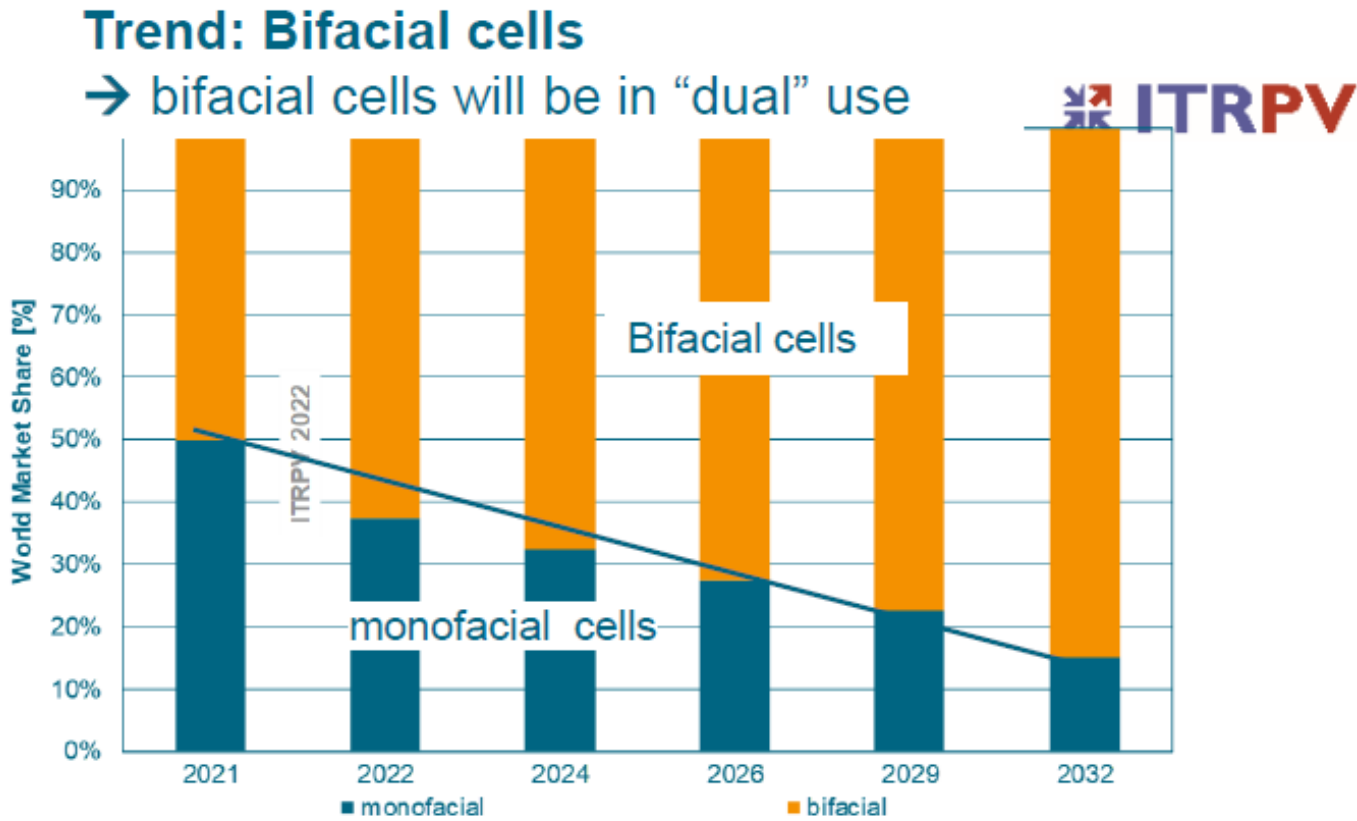
Trend: share of cell technologies



VARIETY OF C-SI SOLAR CELLS & EFFICIENCY



BIFACIALITY IS HERE AND IT IS THE MAINSTREAM FOR UTILITY SCALE



BIFACIALITY IS HERE AND IT IS THE MAINSTREAM FOR UTILITY SCALE

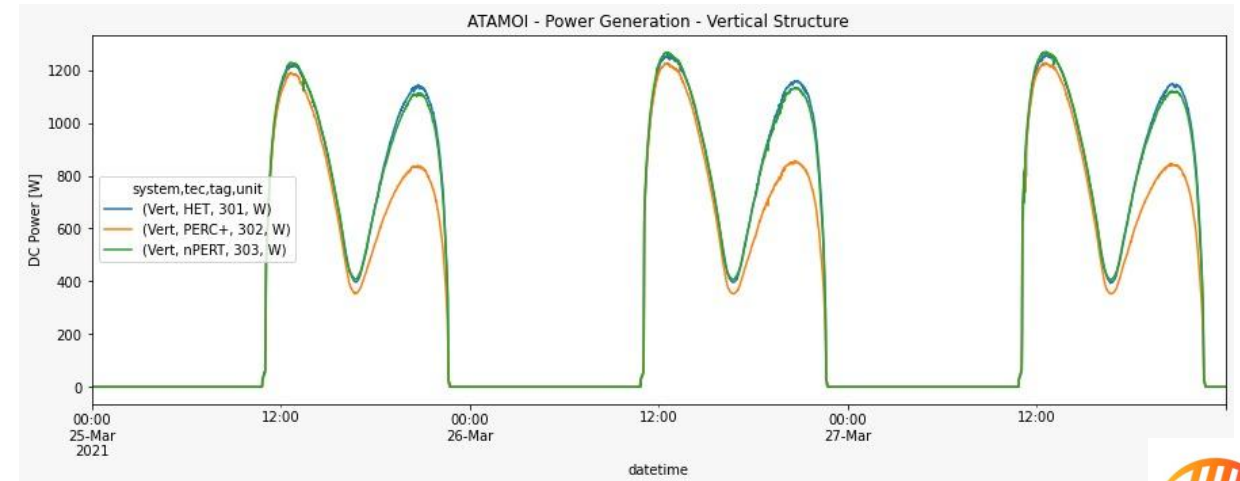
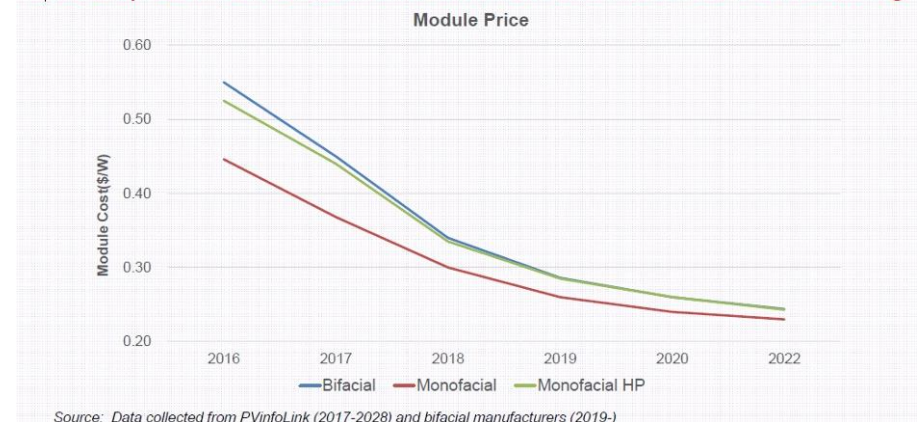
Solar generation capacity up to 25% depending on:

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

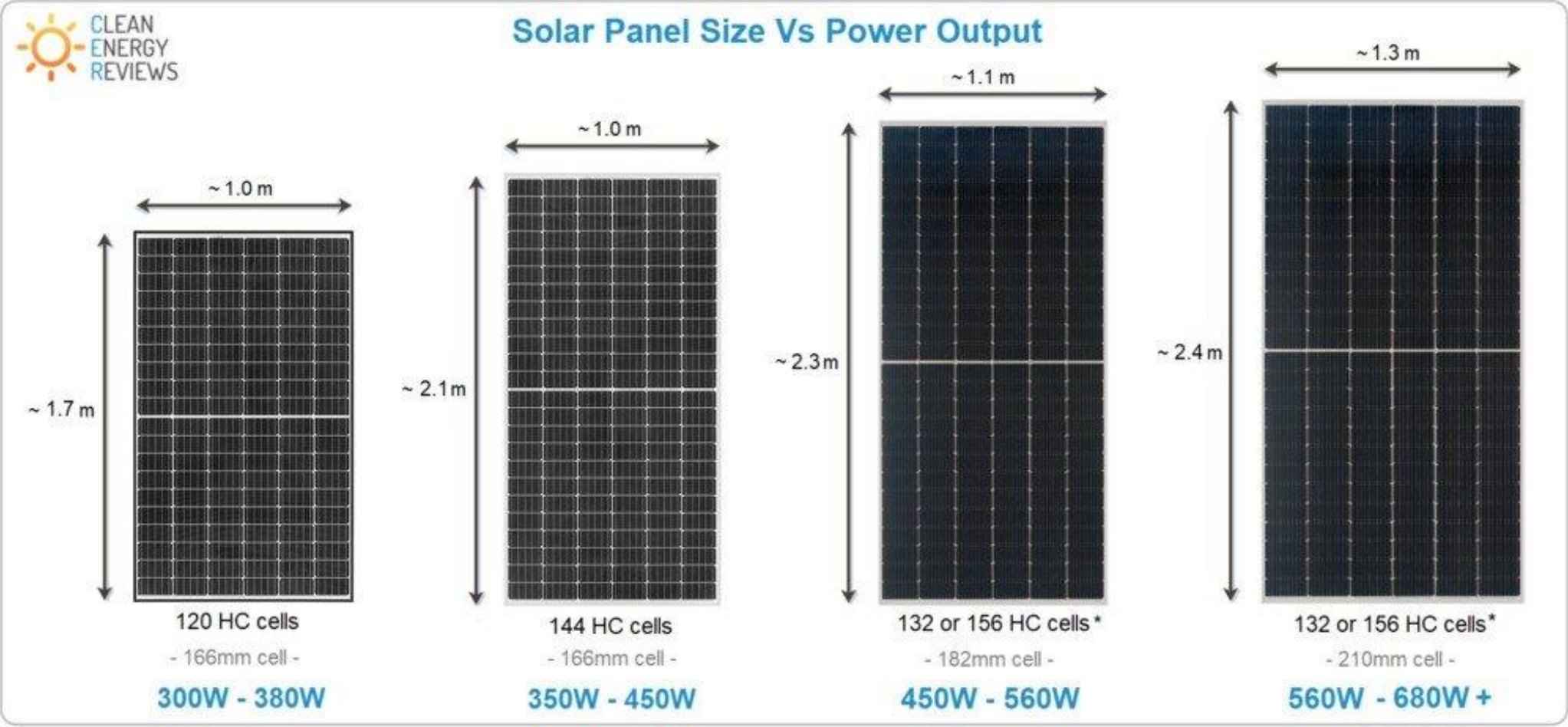
A bifacial, single axis tracking (1T) pv plant can cost approximately 15% more than a comparable monofacial non tracking PV plant.

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

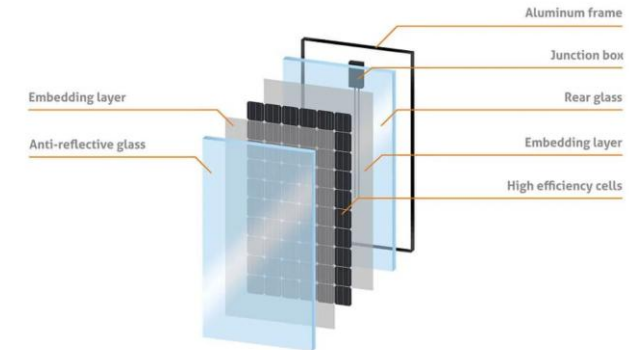
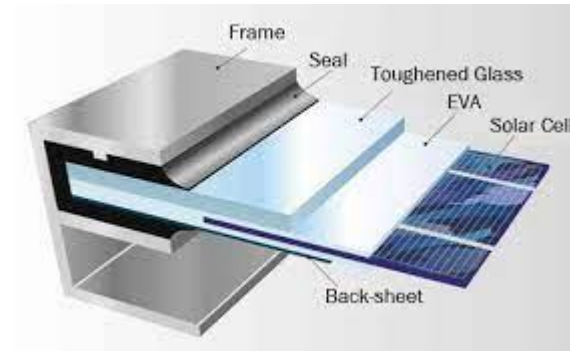
FRAME OR FRAMELESS?

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

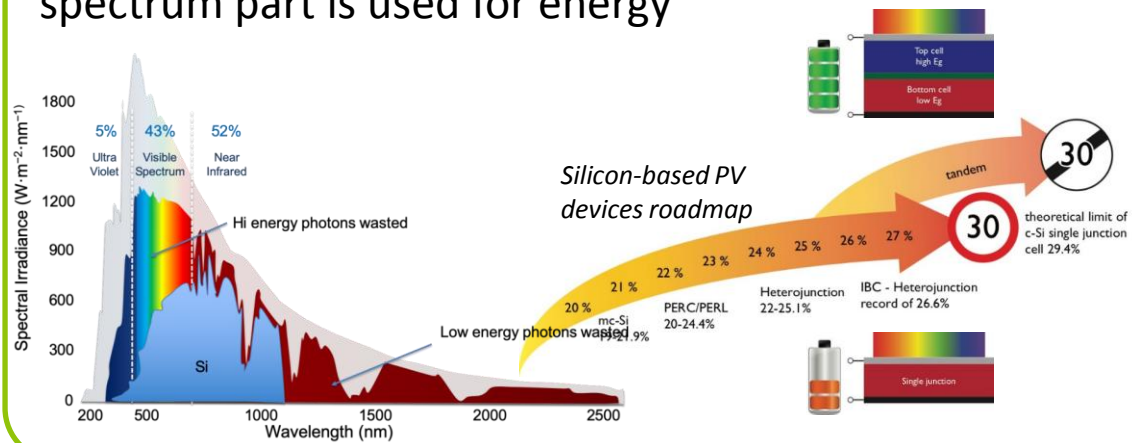
Drawbacks:

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



NEXT GENERATION OF PV MODULES

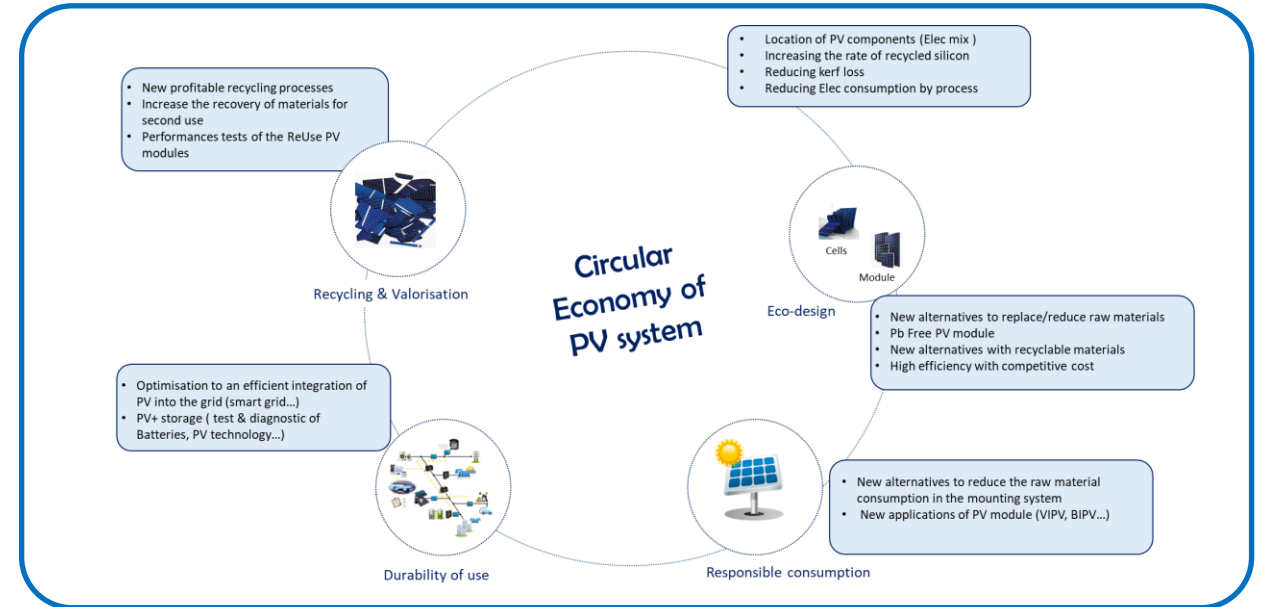
Tandem technologies > 30% efficiency
Maximizing solar spectrum use or varying which spectrum part is used for energy



Efficiency, Cost, Reliability

Sustainability, Eco-design, Recyclable

Integrated, adapted



CONCLUSION ON PV MODULES TECHNOLOGIES

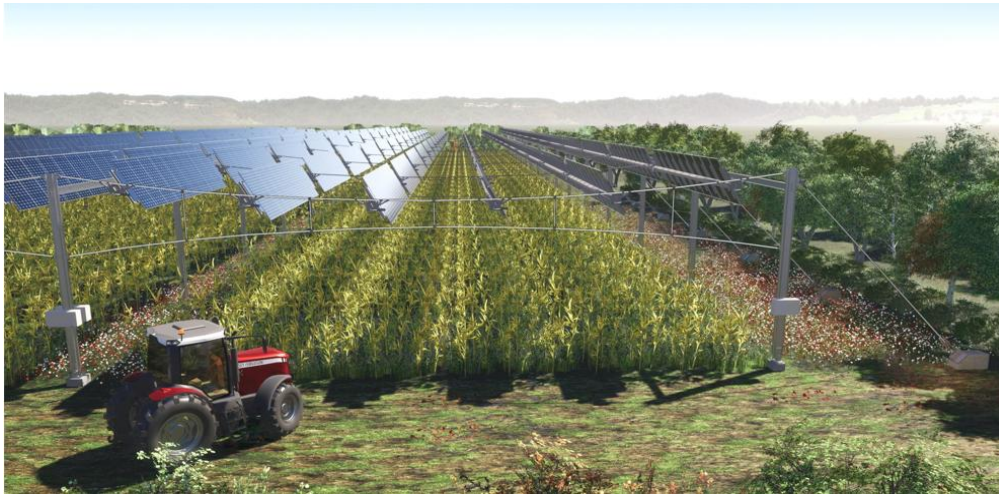
- New paradigm for PV modules
- Not more a standard for everything
- Module has to be adapted to the application
- The total cost of the system is calculated not only with LCOE basis (other KPI needed)
- Reliability is a must
- The system and O&M costs will depend on the module technology chosen
- Modelling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

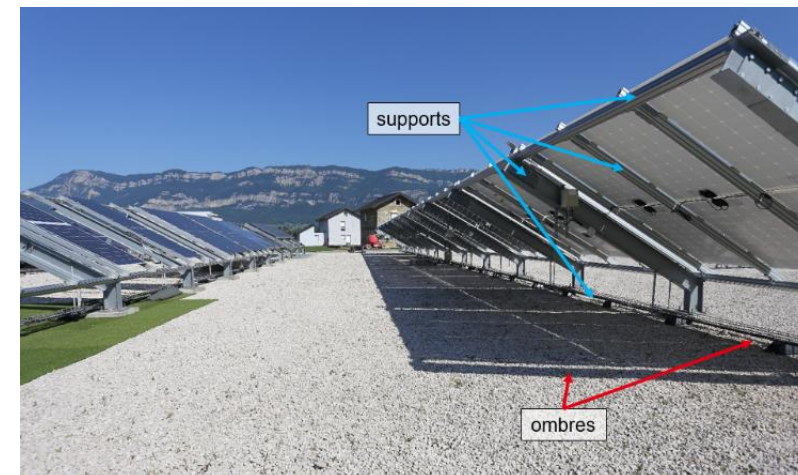
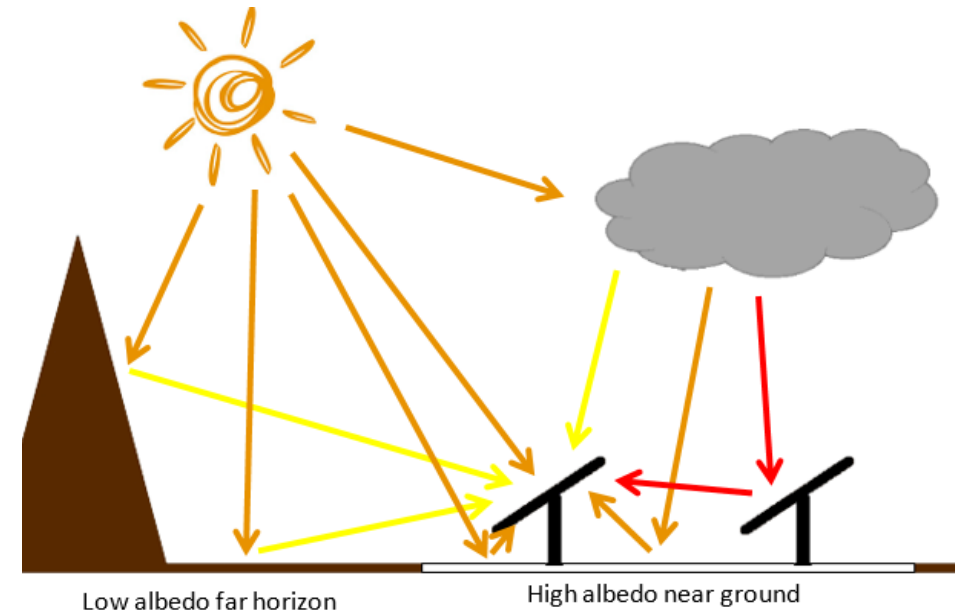
- Production estimations
- System optimization
- Operation monitoring

Three kinds of models are needed:

- Thermal model
- Electrical model
- Optical model

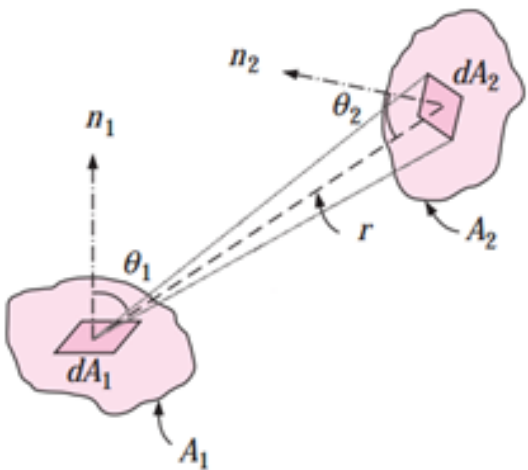
Calculation of the irradiance on the module backside is a key issue:

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



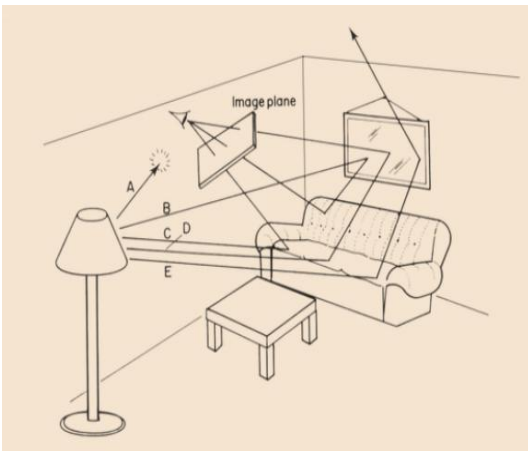
PART 2 : MODELLING METHODS OF THE PV PRODUCTION

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 ⇔ modules
- Sky ⇔ ground
- Ground ⇔ 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

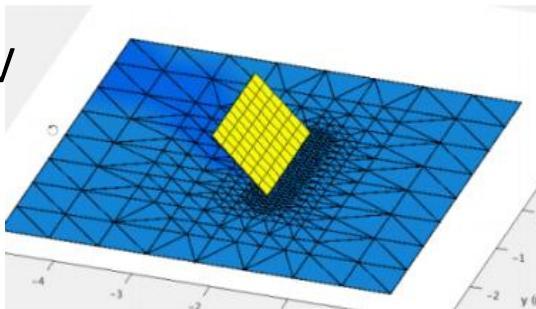
Among open source tools (Bifacial_Radiance (RT), PVfactors, Bifacial_vf (2D VF)), commercial tools (PVsyst (2D VF), PVcase (RT)) and in-house tools (BigEye, MoBiDiG (3D VF), PVNOV (RT)), **CEA is developing its own 3D VF tool: Trifactors**

A simulation with Trifactors is run in few steps:

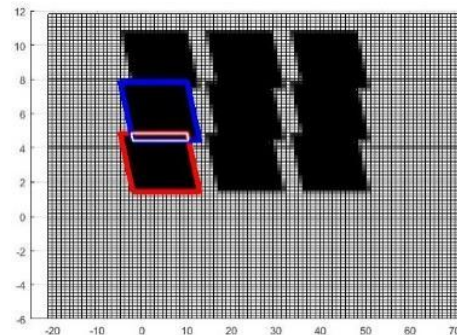
1st: collection of PV system, meteo, simulation data

3rd: calculation of view factors

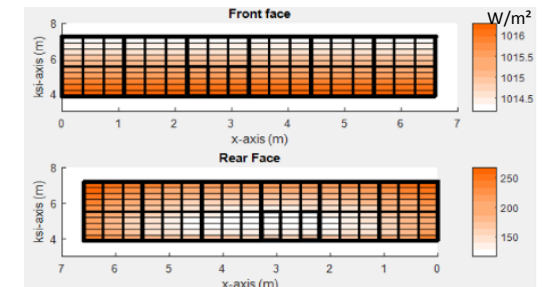
2nd: meshing of the ground and PV array



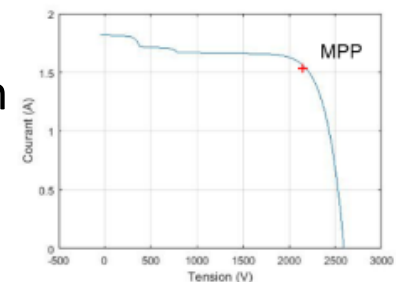
4th: calculation of projected shadows



5th: calculation of front and back irradiances

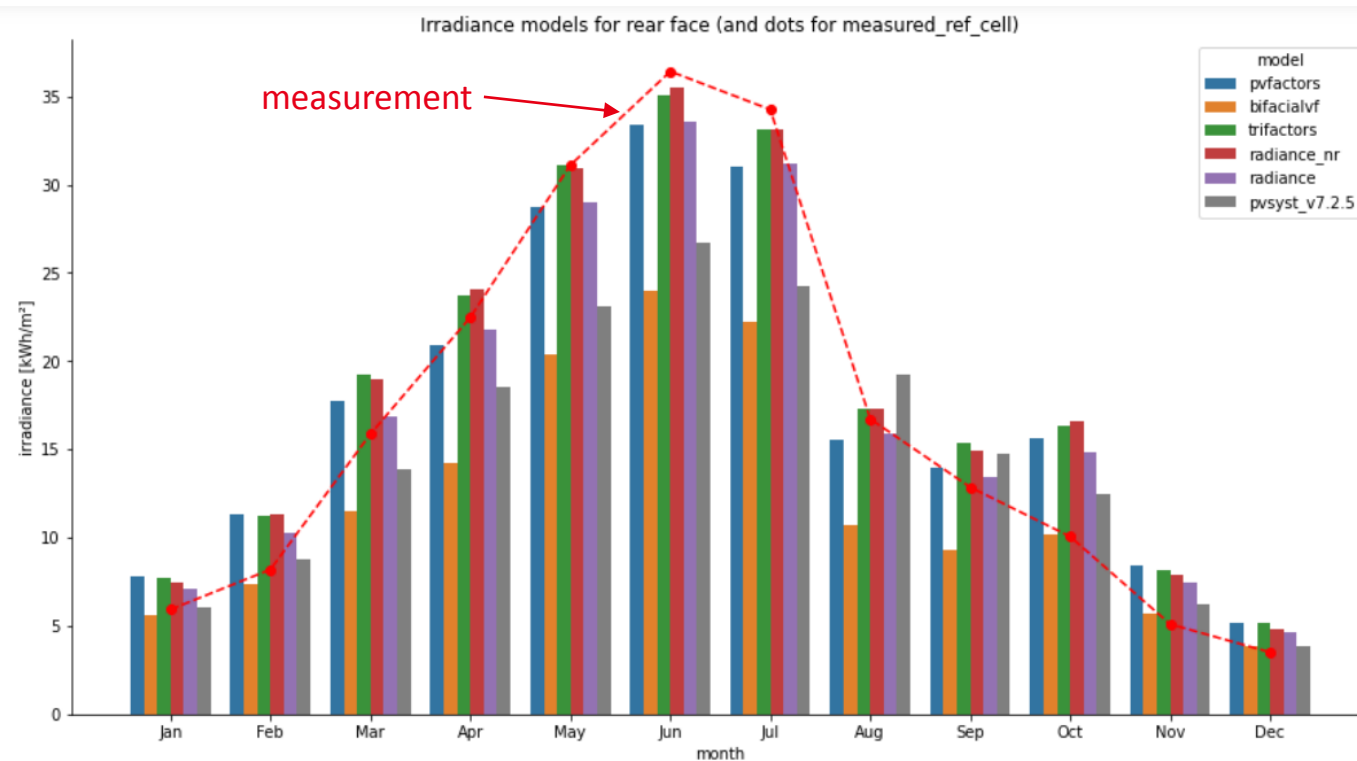


6th: calculation of electrical power at mesh level, then at system level

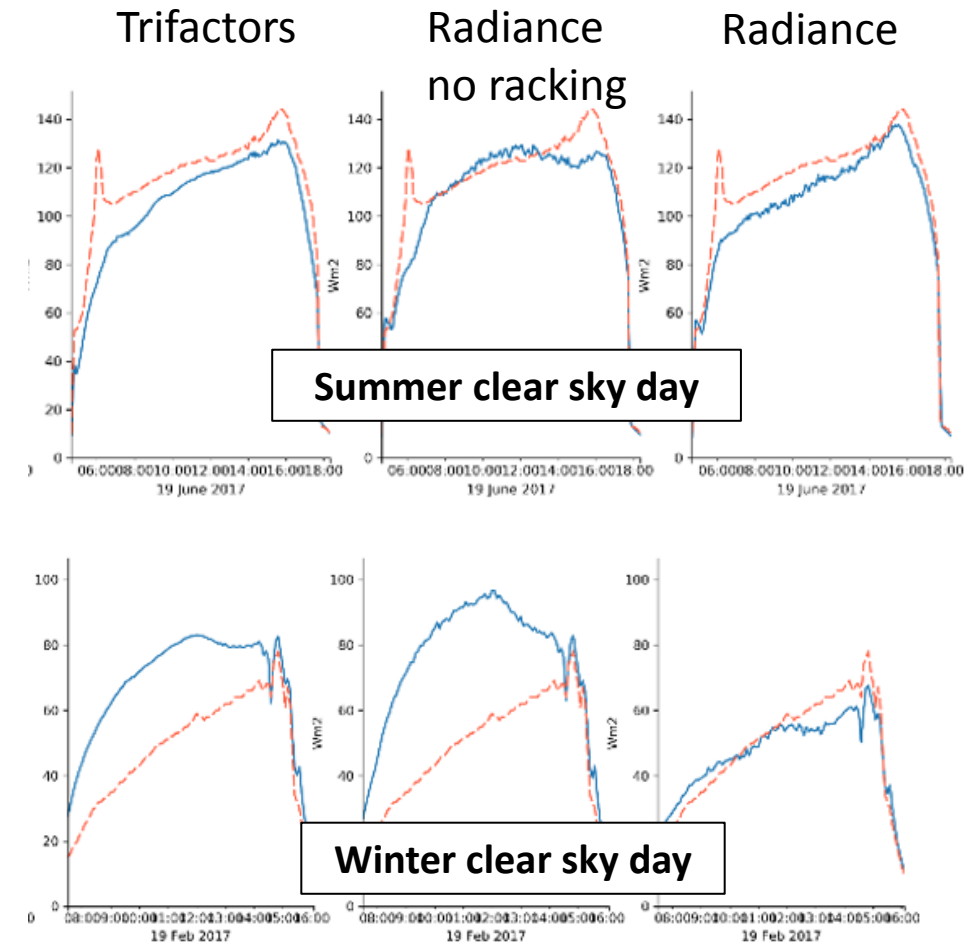


PART 2 : MODELLING METHODS OF THE PV PRODUCTION

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

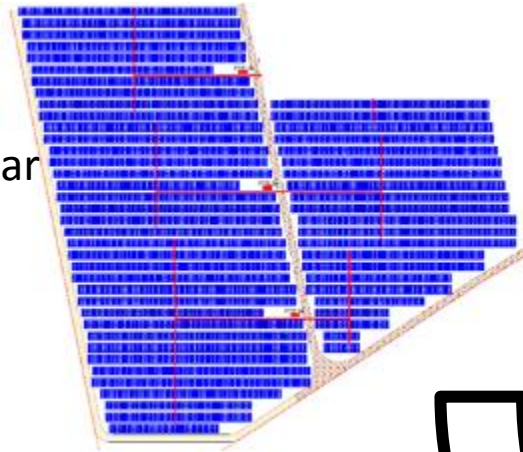


The impact of the supporting structure on backside irradiance is an area of improvement of VF tools



PART 2 : MODELLING METHODS OF THE PV PRODUCTION

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

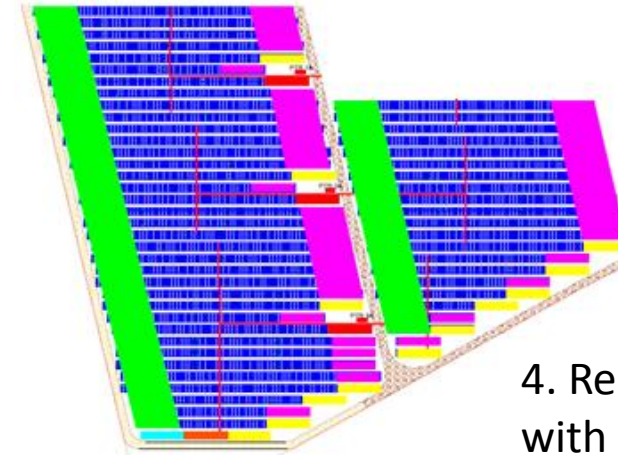
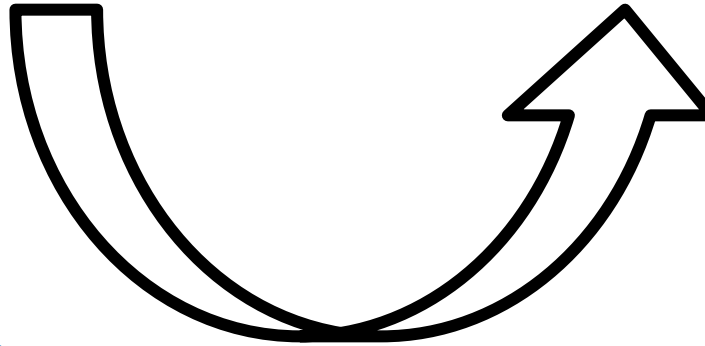
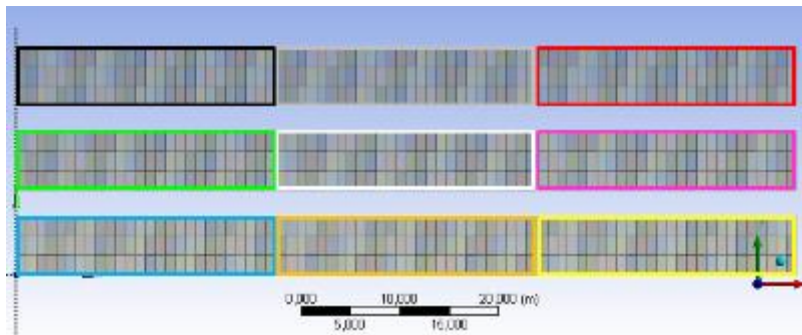


Real plant

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



Simulated pattern



Simulated plant



Conversion Table

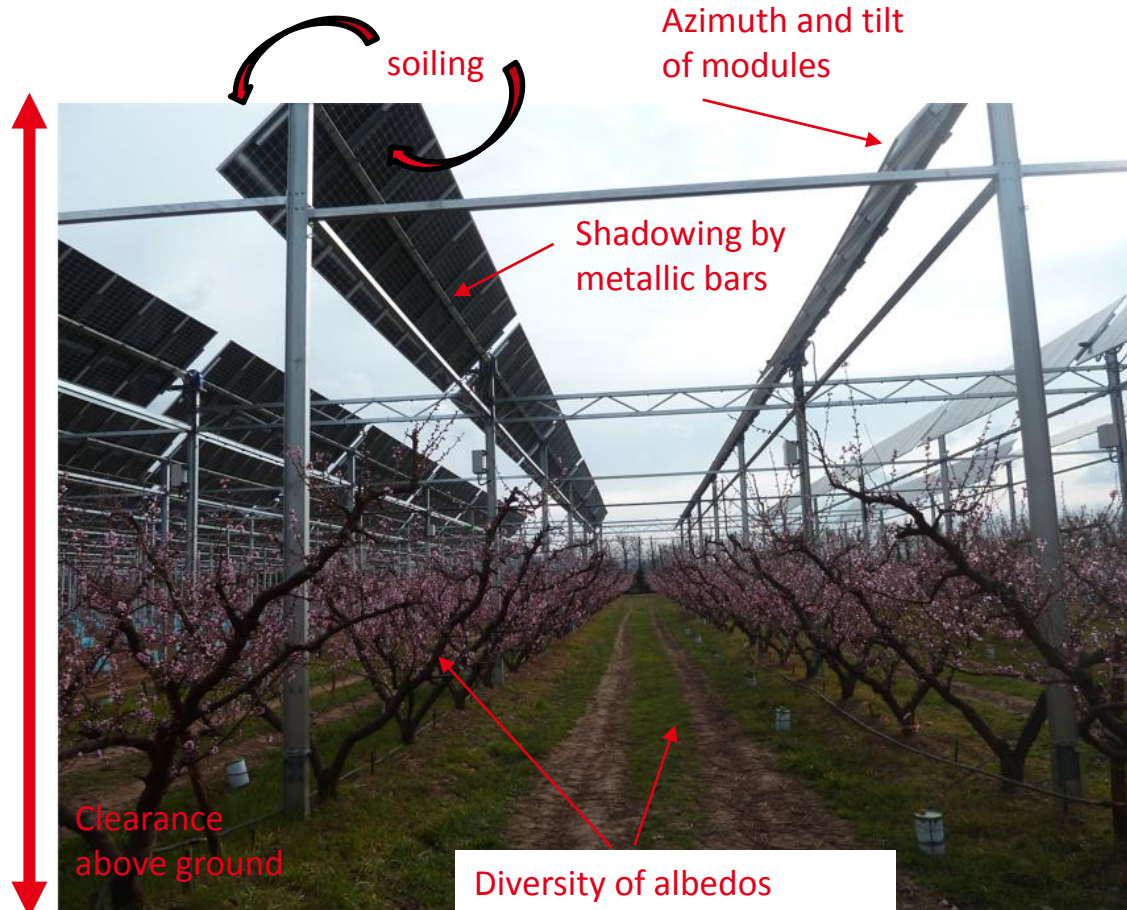
4. Rebuilding the plant with the different types of zones

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% | | |
| | | | Totaux | 316 | 24648 | 100,0% | | |

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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