08 June 2023

Photovoltaic: a general overview

And a hypothetical case study

William Colombini - 892235
w.colombini@campus.unimib.it

Content overview

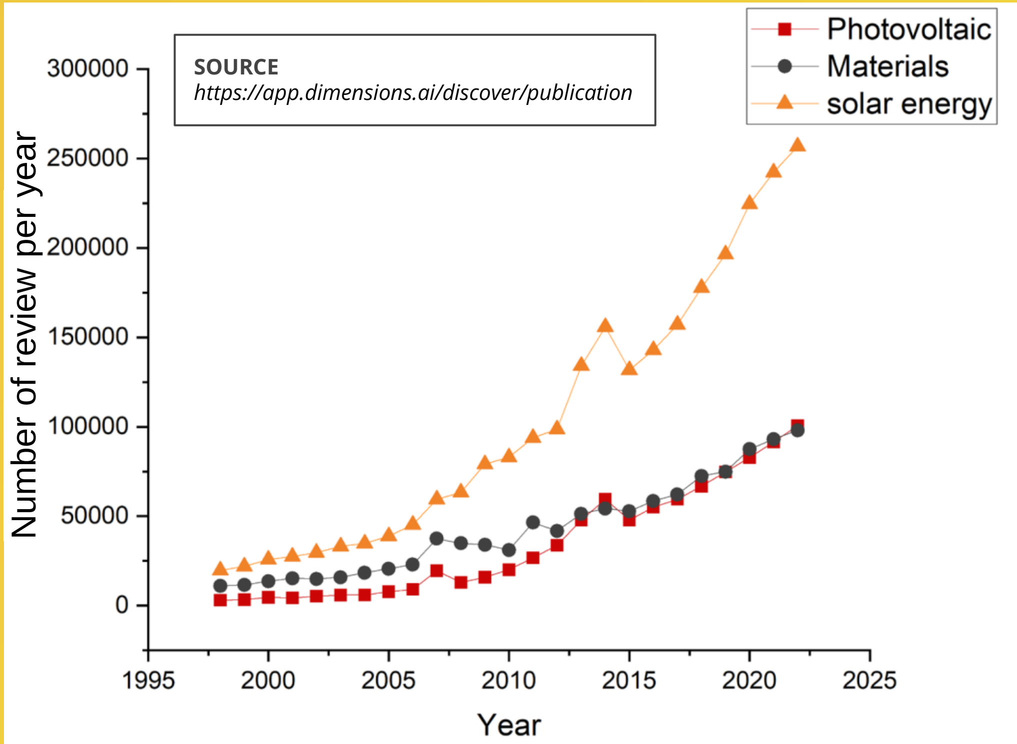
01
Introduction
Brief presentation of the PV linking back to Acciari's lesson

02
Materials
A brief description of main materials used in PV

03
Common issues & Solutions
Insight into the main problems of PV technologies

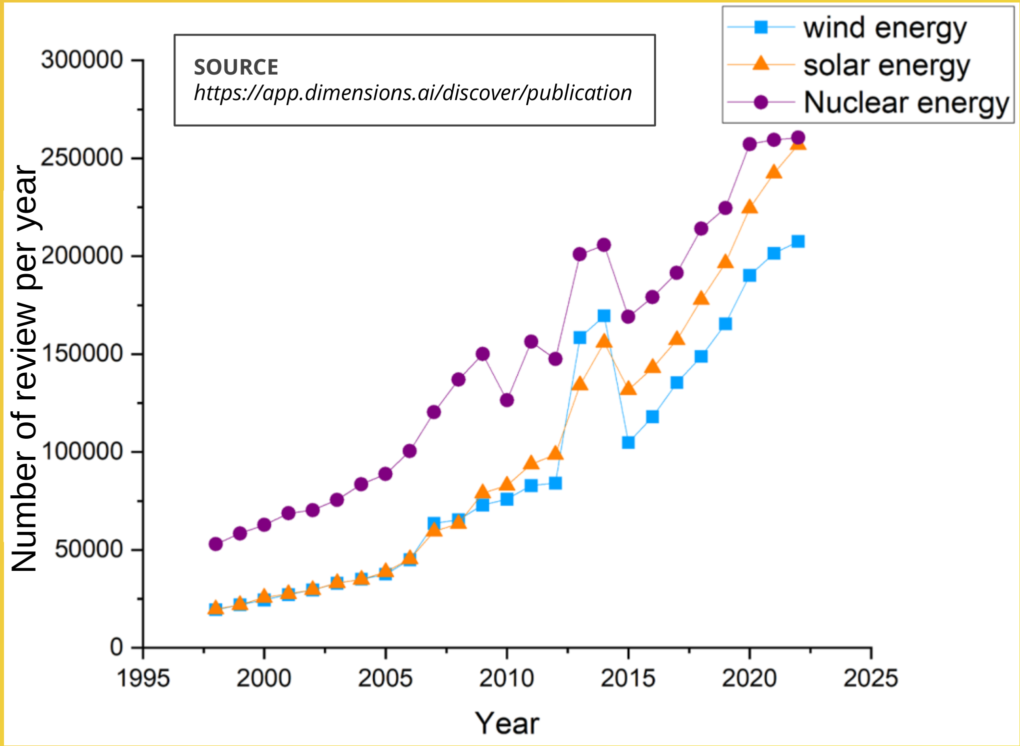
04
Case Study
A hypothetical evaluation with Italy dataset

01) The growing interest in PV



WARNING: This is just to provide an idea of the interest generated by the topic. However, the number of reviews and publications isn't a comprehensive measure to evaluate the overall interest. Other elements should be considered too.

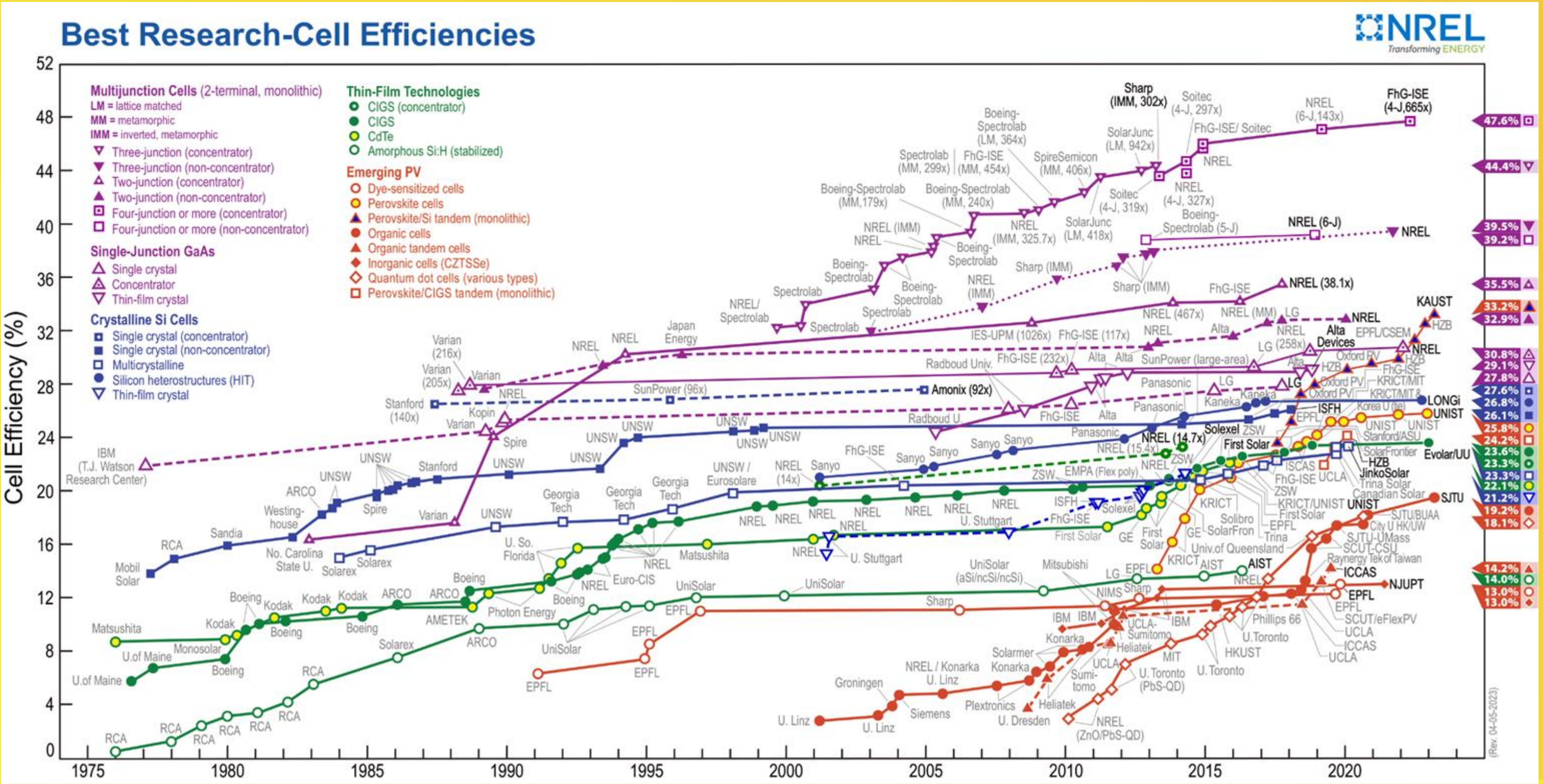
01) The growing interest in PV



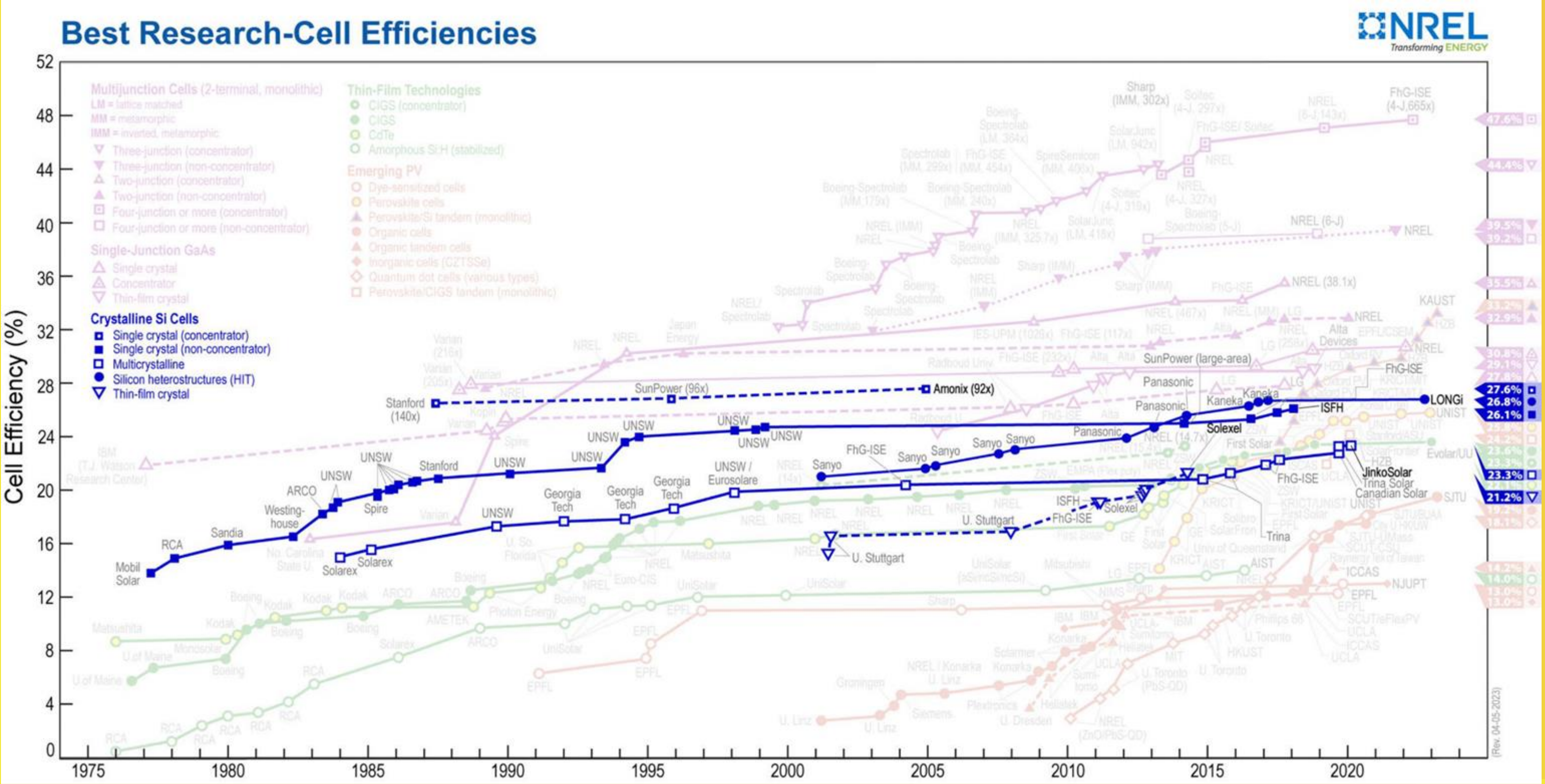
Is still possible see that the number of publications for some other renewable resources is reaching a plateau.

Skip

01) Efficiency (overall perspective)



01) Efficiency (c-Si cells)



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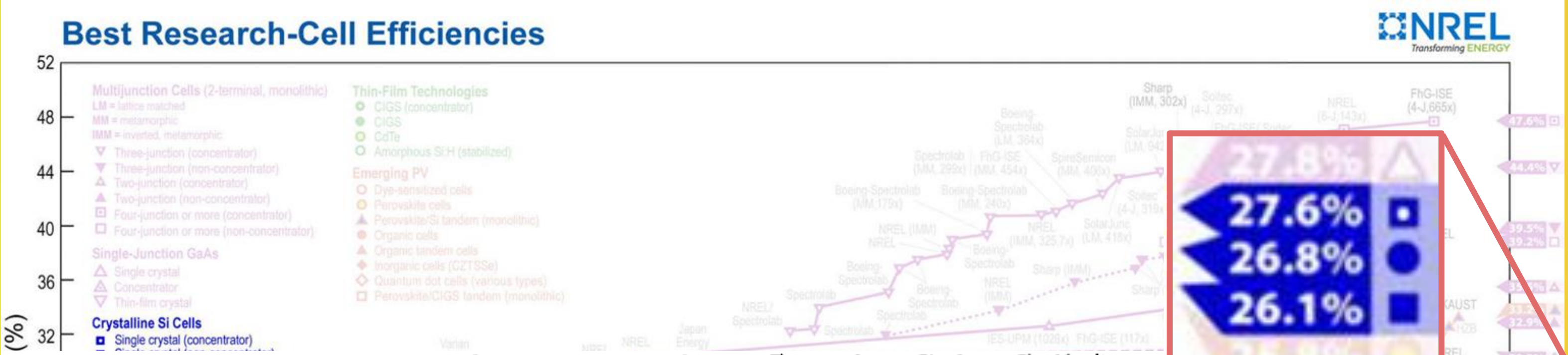
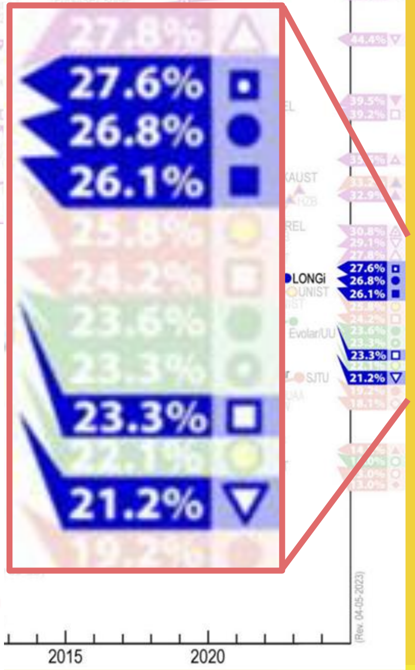


Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells*

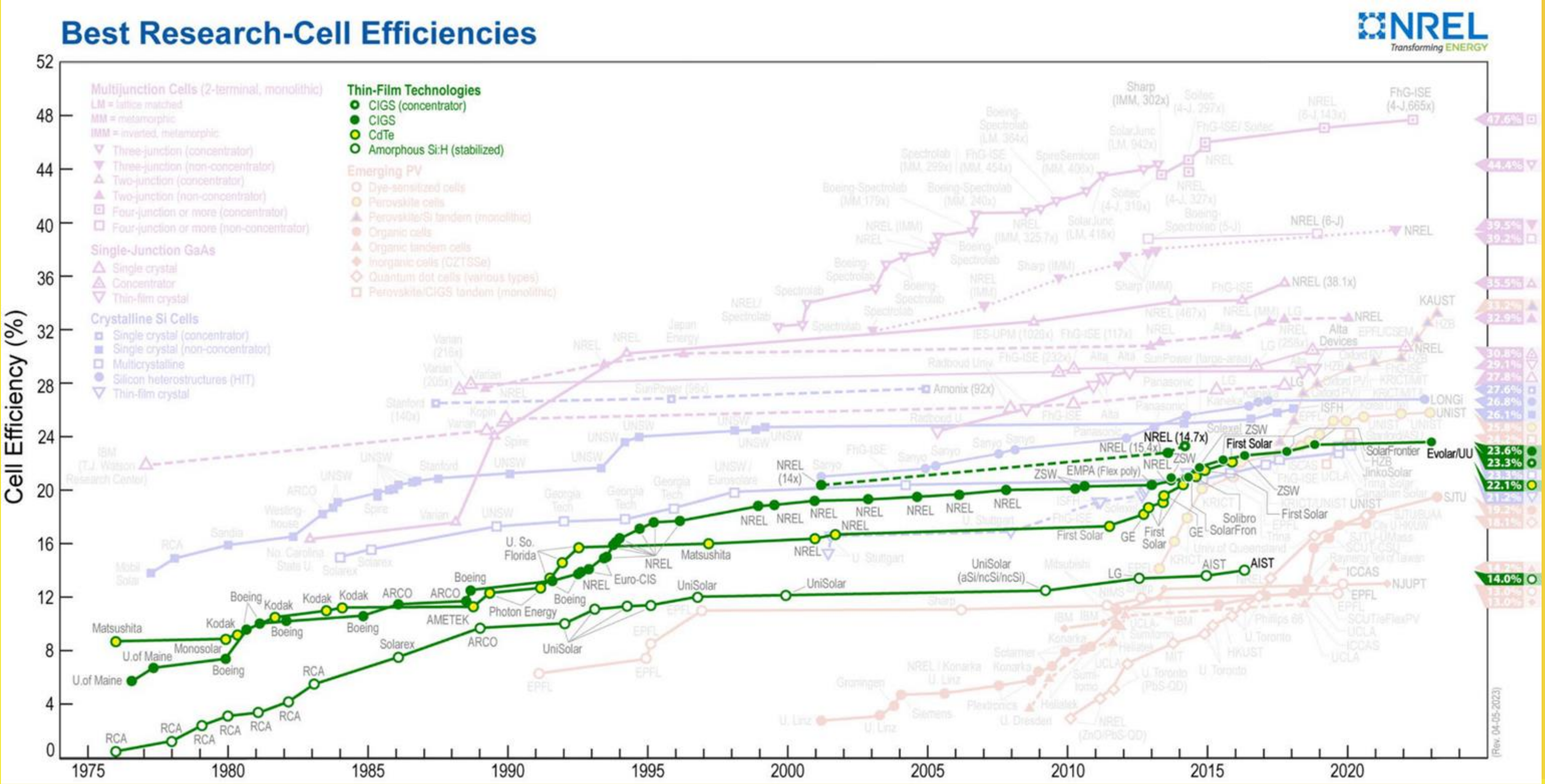
William Shockley and Hans J. Queisser
Shockley Transistor, Unit of Clevite Transistor, Palo Alto, California

(Received May 3, 1960; in final form October 31, 1960)

In order to find an upper theoretical limit for the efficiency of *p-n* junction solar energy converters, a limiting efficiency, called the *detailed balance limit* of efficiency, has been calculated for an ideal case in which the only recombination mechanism of hole-electron pairs is radiative as required by the principle of detailed balance. The efficiency is also calculated for the case in which radiative recombination is only a fixed fraction f_c of the total recombination, the rest being nonradiative. Efficiencies at the matched loads have been calculated with band gap and f_c as parameters, the sun and cell being assumed to be blackbodies with temperatures of 6000°K and 300°K, respectively. The maximum efficiency is found to be 30% for an energy gap of 1.1 ev and $f_c=1$. Actual junctions do not obey the predicted current-voltage relationship, and reasons for the difference and its relevance to efficiency are discussed.



01) Efficiency (Thin-Film)



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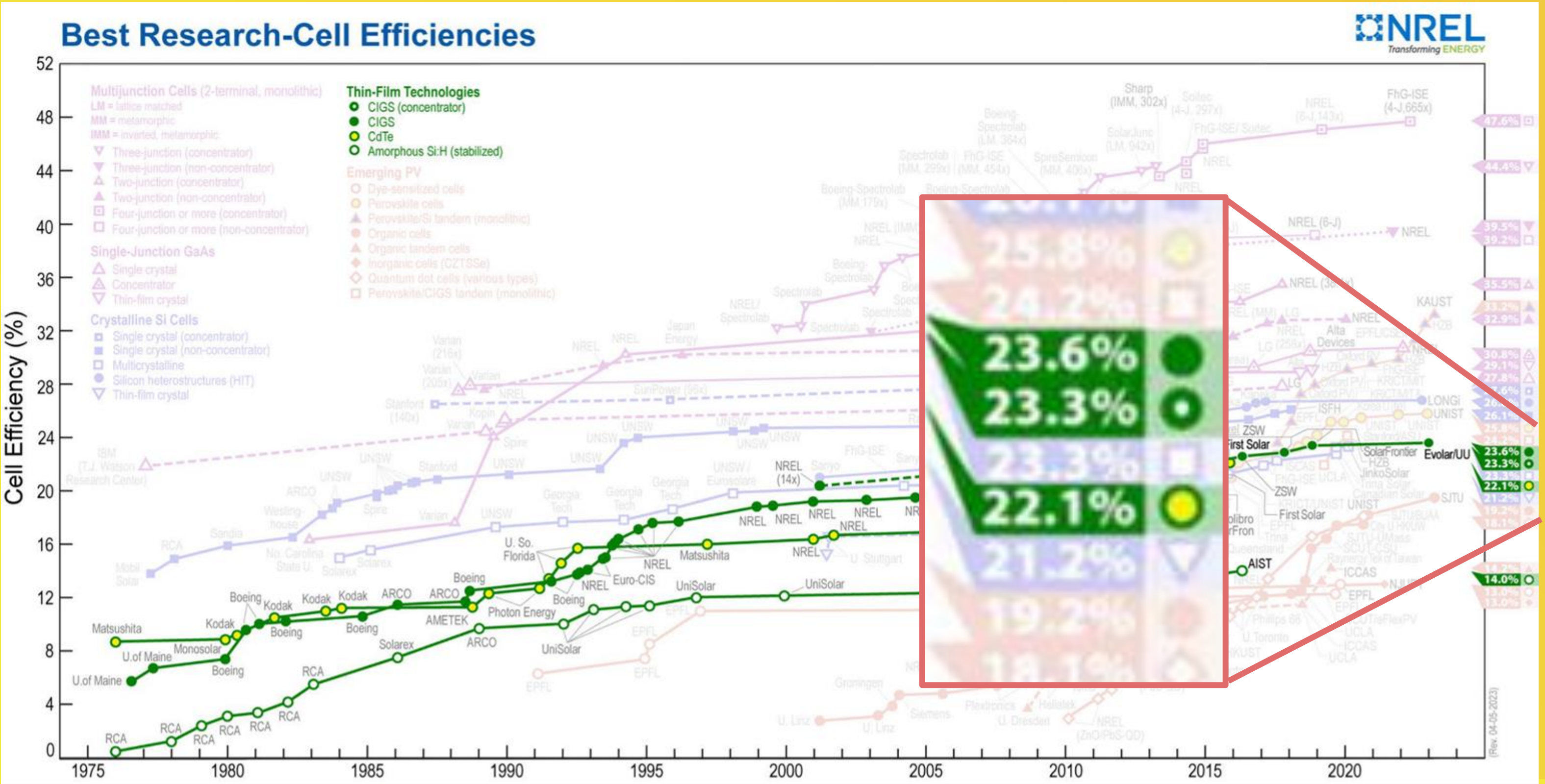
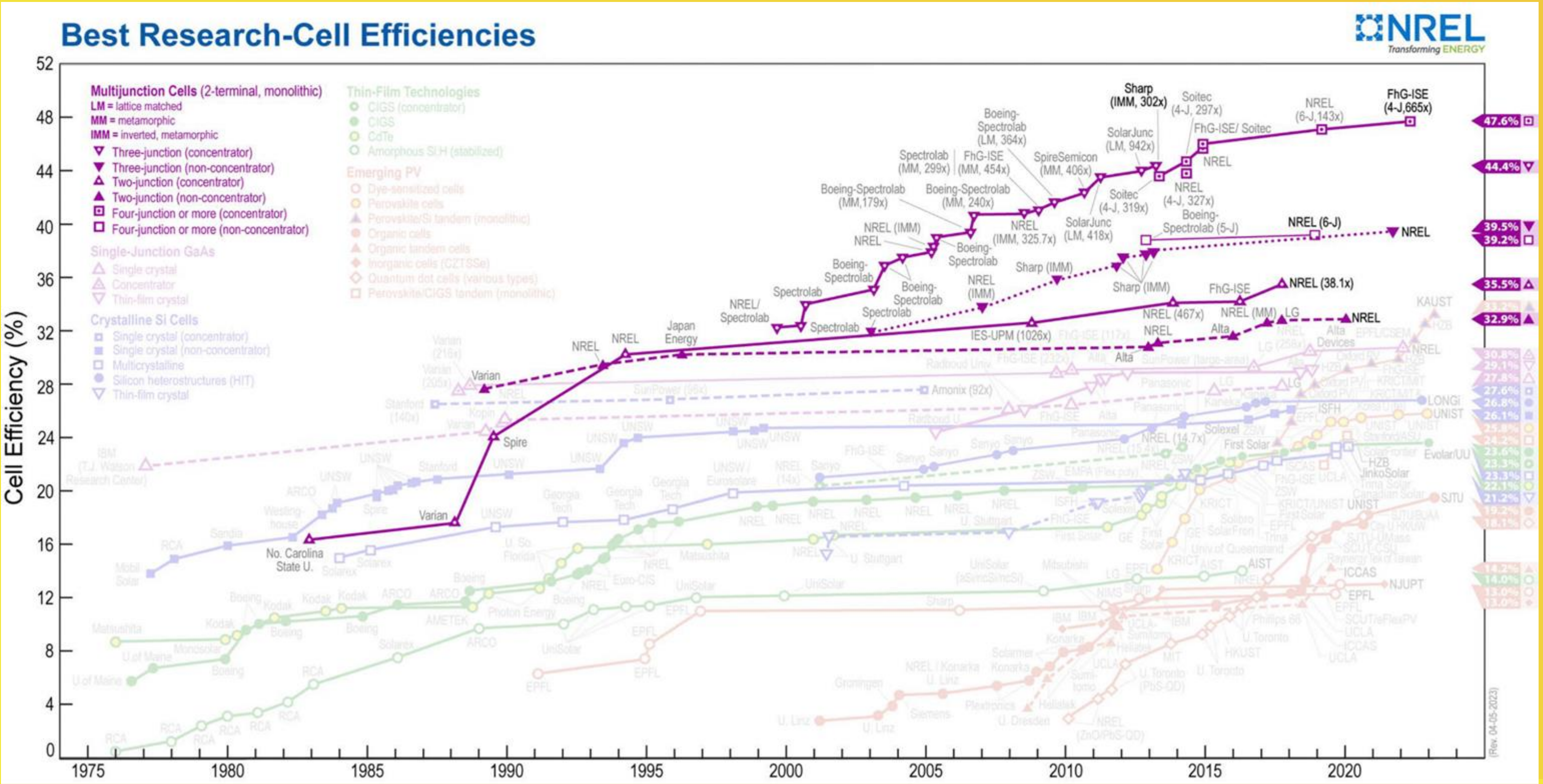


01) Efficiency (Multijunction cells)



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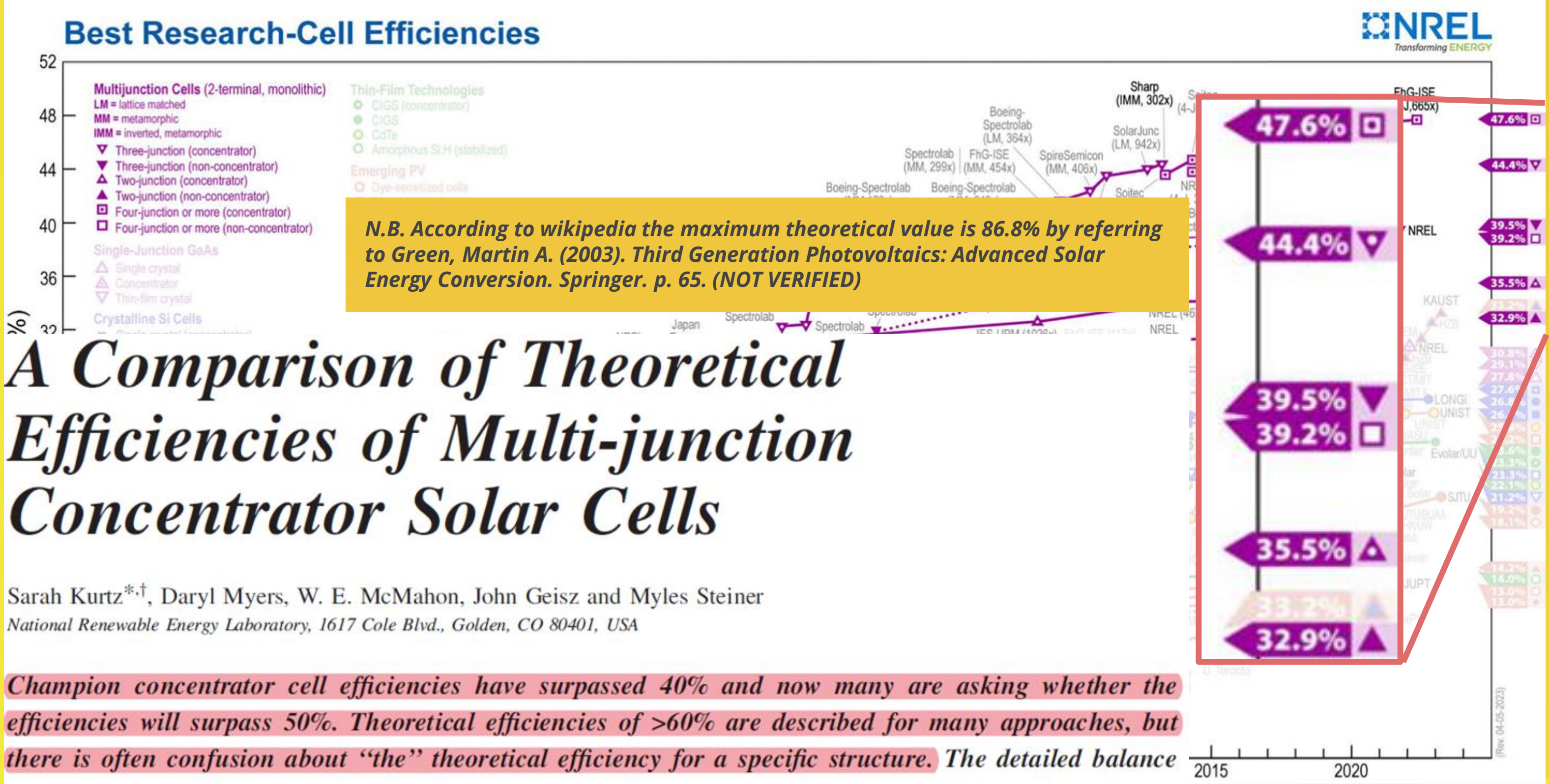


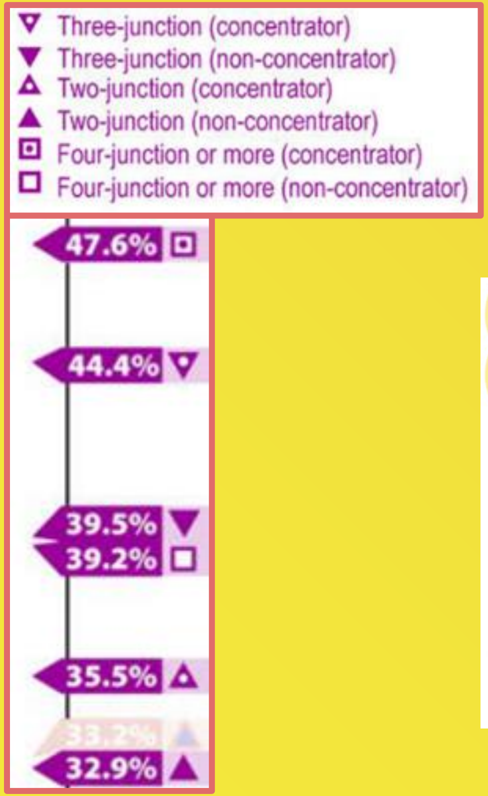
N.B. According to wikipedia the maximum theoretical value is 86.8% by referring to Green, Martin A. (2003). Third Generation Photovoltaics: Advanced Solar Energy Conversion. Springer. p. 65. (NOT VERIFIED)

A Comparison of Theoretical Efficiencies of Multi-junction Concentrator Solar Cells

Sarah Kurtz*,†, Daryl Myers, W. E. McMahon, John Geisz and Myles Steiner
National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401, USA

Champion concentrator cell efficiencies have surpassed 40% and now many are asking whether the efficiencies will surpass 50%. Theoretical efficiencies of >60% are described for many approaches, but there is often confusion about "the" theoretical efficiency for a specific structure. The detailed balance

01) Efficiency (CPV and # of junc)



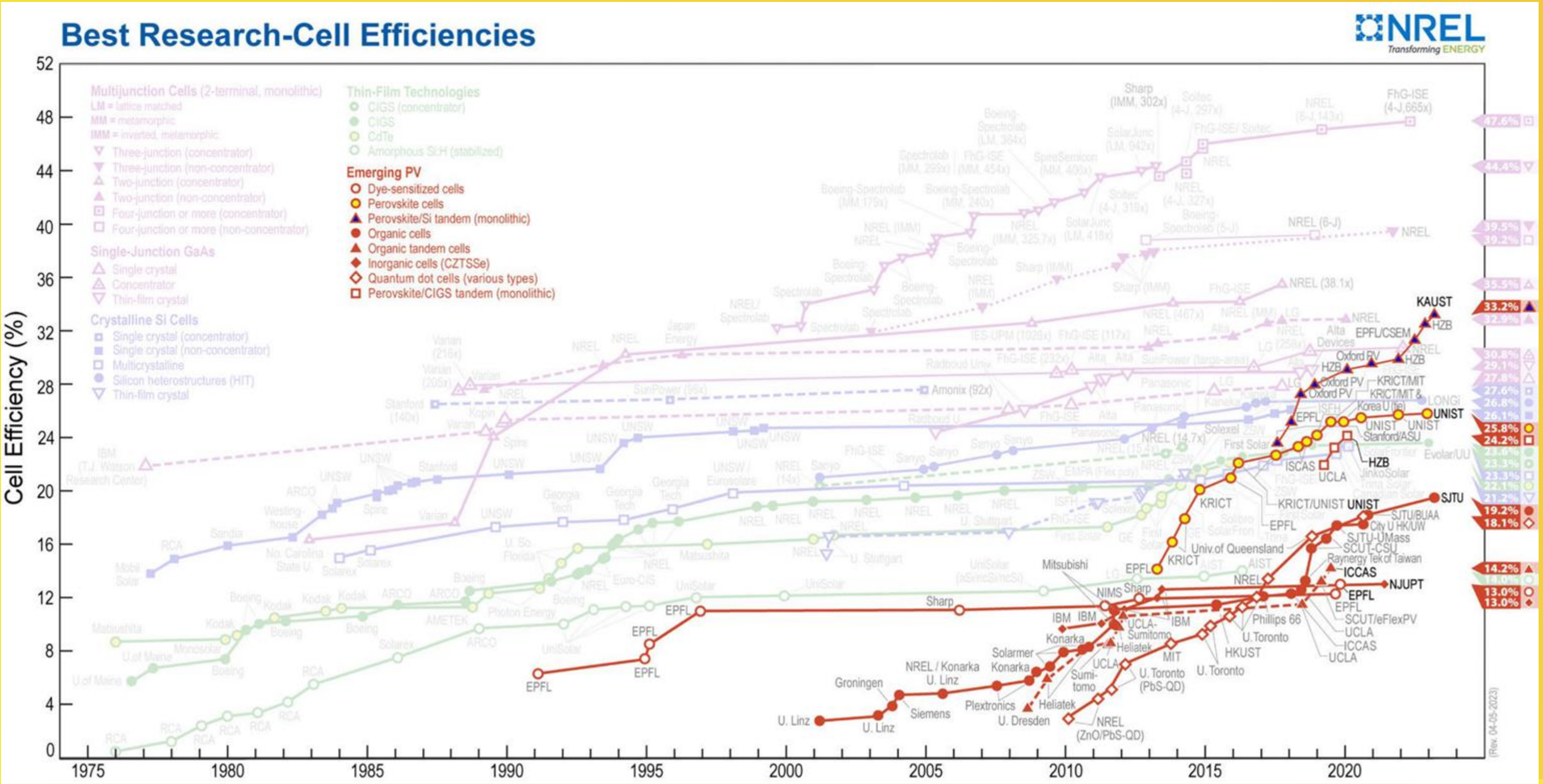
We can see that higher number of junctions provides a higher efficiency. Additionally, we can observe increased performances while concentrated light is used.

Six-junction III–V solar cells with 47.1% conversion efficiency under 143 Suns concentration

John F. Geisz ✉, Ryan M. France, Kevin L. Schulte, Myles A. Steiner, Andrew G. Norman, Harvey L. Guthrey, Matthew R. Young, Tao Song and Thomas Moriarty

Single-junction flat-plate terrestrial solar cells are fundamentally limited to about 30% solar-to-electricity conversion efficiency, but multiple junctions and concentrated light make much higher efficiencies practically achievable. Until now, four-junction III–V concentrator solar cells have demonstrated the highest solar conversion efficiencies. Here, we demonstrate 47.1% solar conversion efficiency using a monolithic, series-connected, six-junction inverted metamorphic structure operated under the direct spectrum at 143 Suns concentration. When tuned to the global spectrum, a variation of this structure achieves a 1-Sun global efficiency of 39.2%. Nearly optimal bandgaps for six junctions were fabricated using alloys of III–V semiconductors. To develop these junctions, it was necessary to minimize threading dislocations in lattice-mismatched III–V alloys, prevent phase segregation in metastable quaternary III–V alloys and understand dopant diffusion in complex structures. Further reduction of the series resistance within this structure could realistically enable efficiencies over 50%.

01) Efficiency (Perovskite cells)



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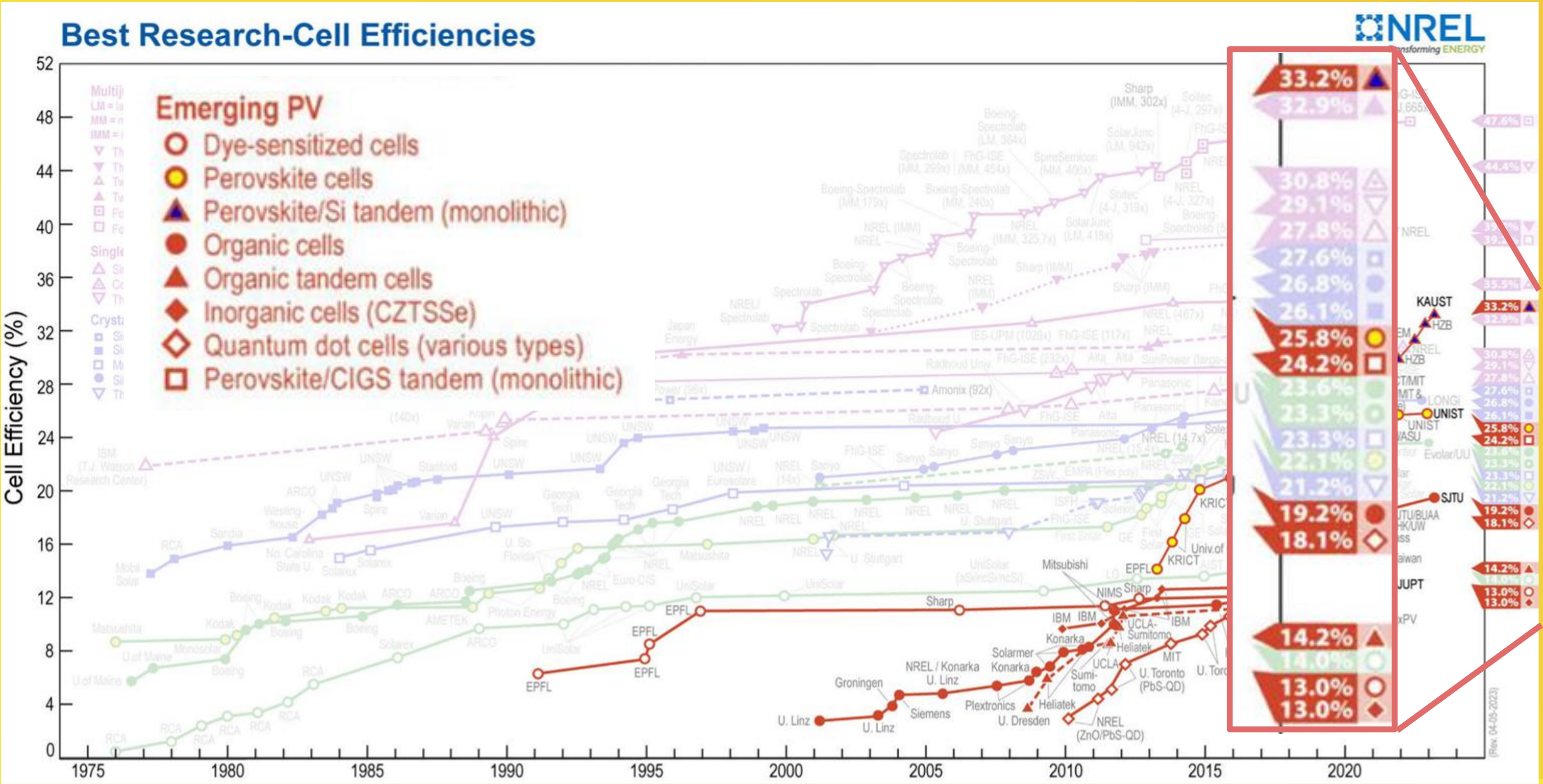
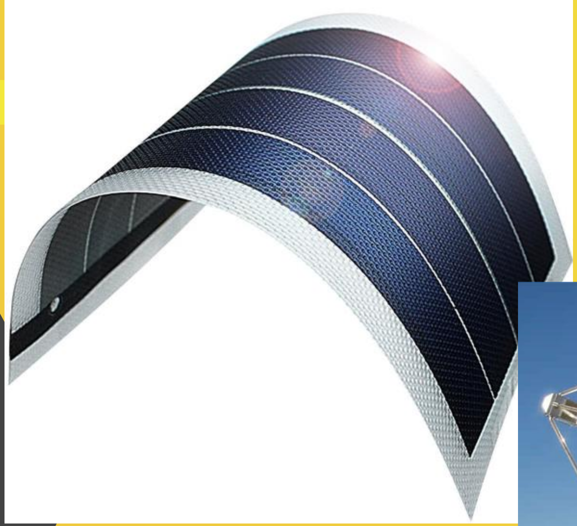
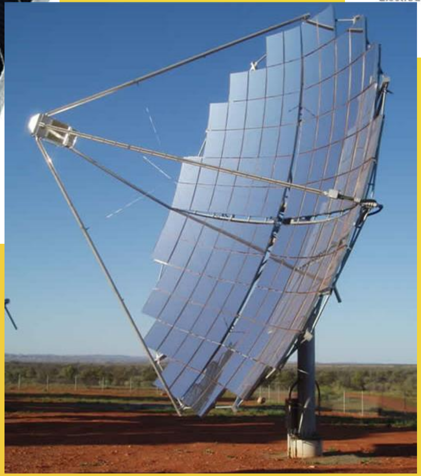
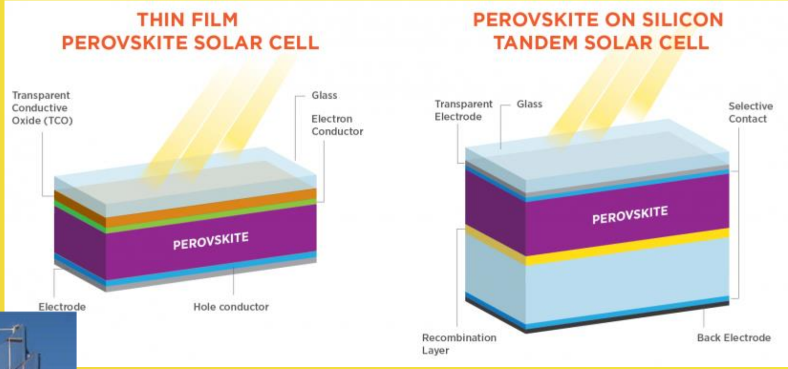
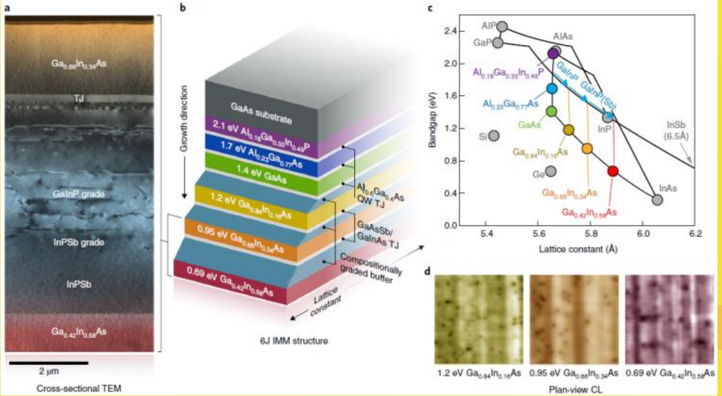


02) c-Si’s contenders









https://www.energy.gov/eere

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02) Thin-films

These are small films, that ranges from few *nm* to *ten μm*[1].
The main possible materials are CdTe and CIGS (Copper Indium Gallium Selenide)

PROS:

- Potential of growing efficiency;
- Low temperature film deposition;
- Flexibility with plastic substrate;

CONS:

- Toxicity of Cadmium and resources availability issues;
- Materials do not have cross-industry applicability;

[1] Conventional c-Si wafers are up to 200 μm

02) Perovskite cells

They are named after the eponymous ABX3 crystal structure, with the most studied PV material being methylammonium (MA^{+}) lead (Pb^{+2}) iodide (I^{-}), or MAPbI3. Perovskite cells are built with layers of materials that are printed, coated, or vacuum-deposited onto a substrate.

PROS:

- Emerging and quickly growing technology;

CONS:

- High cost manufacturing techniques;
- Not durable and stable enough for industrial applications (the duration is around 2000h);

02) Multijunction cells

These involve the use of several different materials stacked in multiple layers. Common material used are combinations of GaInP, GaAs and Ge.

PROS:

- The efficiency is the highest compared with all the previous technologies;
- This architecture can also be transferred to other solar cell technologies;

CONS:

- The cost of the cells is high (around 10^3 higher than c-Si[(2)]) due to the different materials used and the complex fabrication techniques;

[2] According to Aneesh Nainani at Standford (2019)

02) CPV technology (in MJ)

The concentration of solar power is also used in thermal power plants for increasing optical efficiency of materials. By using lenses and curved mirrors, it is possible to focus sunlight onto small but highly efficient cells.

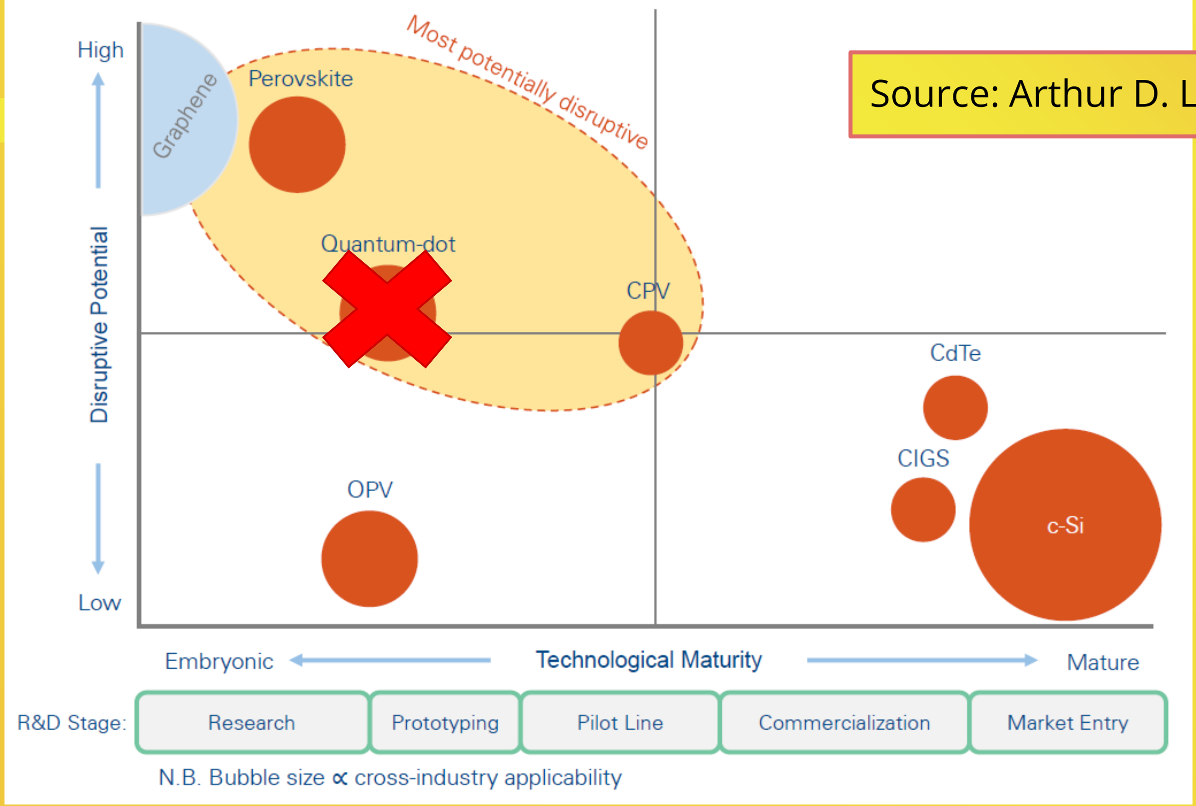
PROS:

- It is possible to enhance the efficiency of multijunction;
- It is needed a smaller quantity of solar cells, reducing the cost of BoS and of initial installation of PV systems;

CONS:

- The cost for the needed tracking technology is high reducing the effectiveness of the initial cost reduction due to the small quantity of cells and BoS needed;
- CPV have not cross-industry applicability;

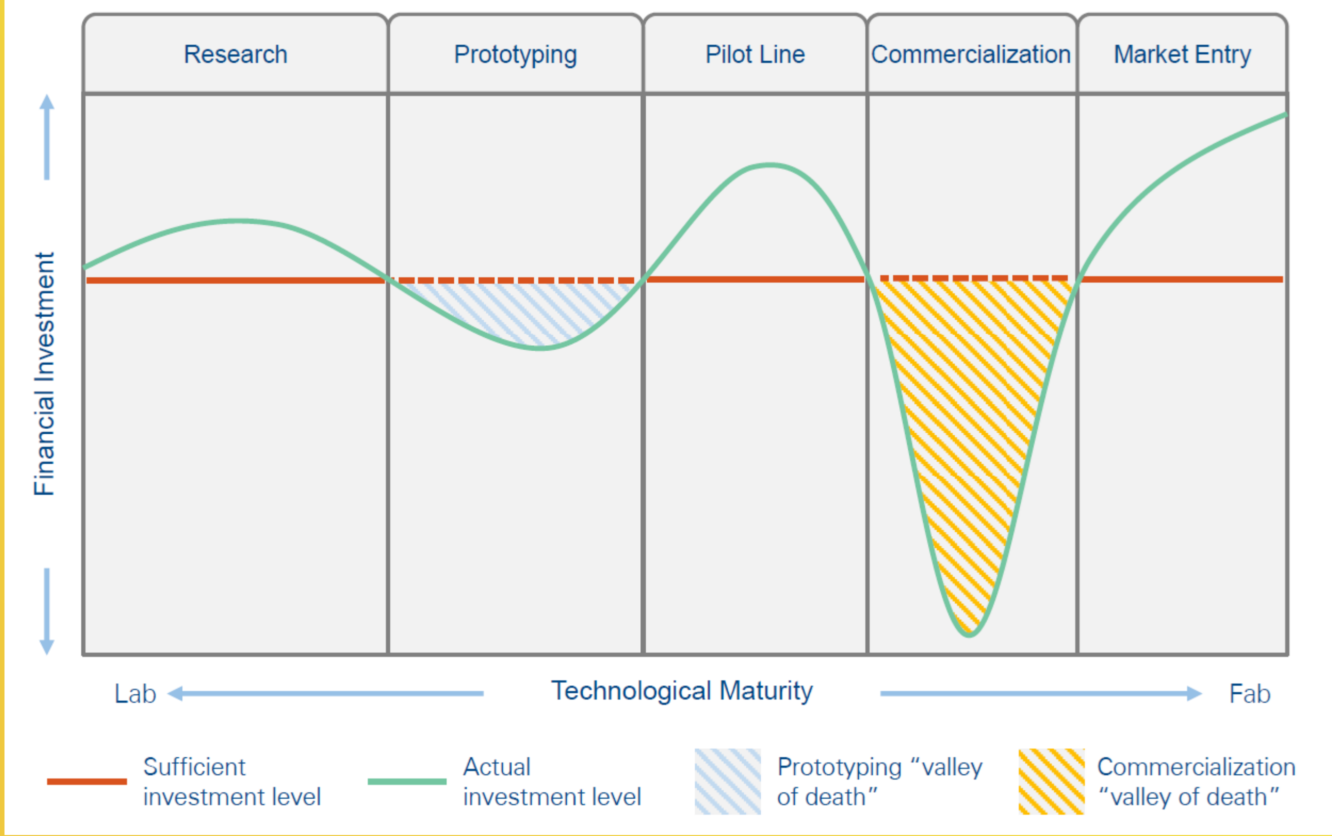
02) The actual situation



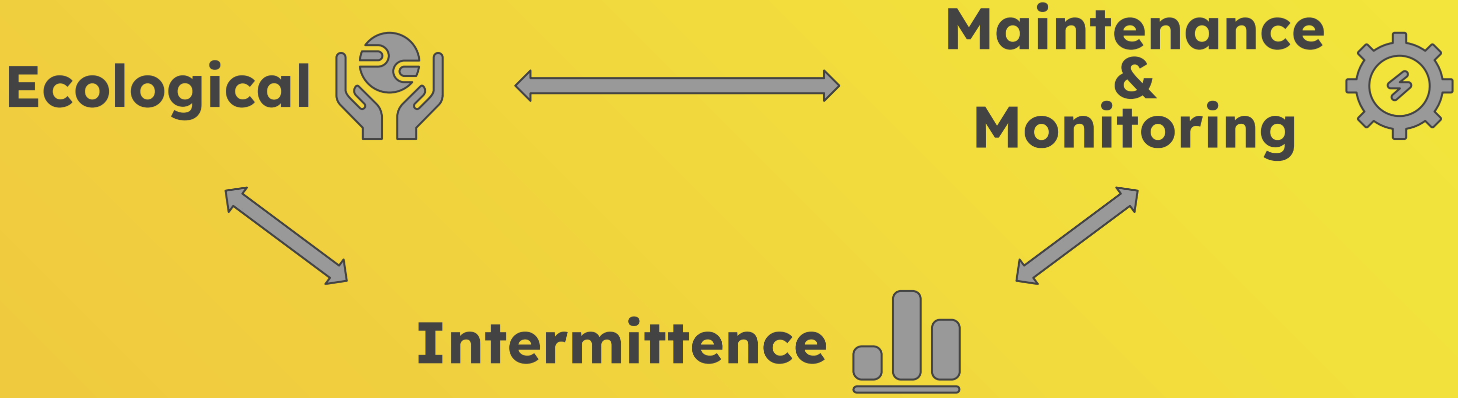
Source: Arthur D. Little analysis

02) The actual situation

Source: US Departement of Energy - SunShot Initiative (simplified)



03) Common problems/issues



03) Ecological issues

It is important to evaluate the environmental impact of PV with it being an important method for energy production.

Land and water usage

Waste treatment

Air pollution

Hazardous materials

03) Ecological issues*

Land and water usage

3.2 acres/MW to 13.9 acres/MW
(1 acres ~ 0,005 km^2)

Compared with other technologies:

- Wind uses ~ 3-10 times more land than PV
- Coal+CCS uses ~ 5-13 times more land than PV

Possibility of hampering the vegetation restoration process after the farm's dismissing

Sometimes animals are removed from their habitat and bird fatality is found during their migration.

Decreasing vegetation is needed to remove coverage (in CPV more important), but this increases dust accumulation so efficiency decreases.

*doi.org/: 10.3390/en16010319; 10.1177/0734242X211003977V; 10.1016/j.scitotenv.2020.143528; 10.1016/j.rser.2022.112279;

03) Ecological issues*

Land and water usage

The main use of water is for cleaning rather than cooling. There are cooling systems that save water such as dry system and water recycling.

600-650 gallons/MWh
2200-2500 liters/MWh

Water is also used for industrial production and manufacturing. The usage of water is around:

- 180 kg of water per kg of Si (production);
- 470 kg of water per kg of Si (multi-crystalline conversion).

*doi.org/: 10.3390/en16010319; 10.1177/0734242X211003977V; 10.1016/j.scitotenv.2020.143528; 10.1016/j.rser.2022.112279;

03) Ecological issues*

Land and water usage

Solutions: *FPV systems, BIPV, Agrivoltaics,*

Floating PV

Building Integrated PV

Agrovoltaic

doi.org/: 10.3390/en16010319; 10.1177/0734242X211003977V; 10.1016/j.scitotenv.2020.143528; 10.1016/j.rser.2022.112279;

03) Ecological issues

Air pollution

14 to 73 g of CO_2 equivalent for each kWh of electricity produced

In comparison to burning oil, the production of CO_2 equivalent for kWh is around 750 g

Reduction of 10 to 53 times!

Breakdown of lifecycle GHG emissions for wind energy and solar PV (% of total) (Nugent and Sovacool, 2014).

Energy source	Fabrication	Construction	Operation	Decommissioning
Solar PV	71.3%	19%	13%	−3.3%
Wind	71.5%	24%	23.9%	−19.4%

Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook

Muhammad Tawalbeh[a,*], Amani Al-Othman[b], Feras Kafiah[c], Emad Abdelsalam[c], Fares Almomani[d], Malek Alkasrawi[e]

[a] Sustainable and Renewable Energy Engineering Department (SREE), University of Sharjah, P. O. Box: 27272, Sharjah, United Arab Emirates
[b] Department of Chemical Engineering, American University of Sharjah, P.O. Box 26666, United Arab Emirates
[c] Electrical and Energy Engineering Department, Al Hussein Technical University, Amman 11831, Jordan
[d] Chemical Engineering Department, Qatar University, Qatar
[e] Paper Science & Chemical Engineering Department, University of Wisconsin Stevens Point, WI 54481, USA

03) Ecological issues

Hazardous materials

Problems for health can arise

Health and environmental impacts of the chemical compounds involved in PV cells' manufacturing (Aman et al., 2015).

Compounds	Purpose	Health and environmental impacts
Acetone (C_3H_6O)	Cleaning out microscopic dirt and dust-off chips.	Eyes and nose irritation, throat infection, kidney and liver problems, nerve damage, birth defects and sexual problems including lower ability to reproduce males.
Ammonia (NH_3)	Production of antireflective coatings	Skin and eyes irritation, throat and lungs infections, mouth and stomach burns.
Arsenic (As)	Production of Gallium arsenide (GaAs) solar PV cells	Toxic and carcinogens, heart and liver problems, lung cancer, throat infection, nausea, vomiting, reduced blood cells, dark and red spot on skin, hands and feet etching.
Cadmium (Cd)	Manufacturing cadmium telluride (CdTe) solar cells	Toxic and carcinogenic, kidney, prostate and respiratory system infections, diarrhea, and lung cancer.
Hexavalent Chromium (Cr-VI)	Coating material in solar panel, screws and solar chassis board.	Carcinogenic
Hydrochloric acid (HCl)	Production of electrical grade silicon, clean and etch semiconductors	Skin irritation, eyes, nose, mouth and throat infections, food digestion, and respiratory depression.
Hydrogen (H_2)	Manufacturing amorphous-Si solar cells.	Flammable and highly explosive.
Iso-propanol (C_3H_8O)	Cleaning out microscopic dirt and dust-off chips.	Vomiting, Eyes irritation, depression, dermatitis, nausea, unconsciousness, respiratory failure, death or coma.
Lead (Pb)	Wiring and welding photovoltaic electrical components	Carcinogenic, brain, kidneys and nervous system damage, weakness in bones, anemia, and miscarriage.
Nitric acid (HNO_3)	Cleaning and removing dopants from wafers and reactors	Chemical burns.
Polybrominated biphenyls (PBBs)	Circuit boards and solar panel inverters	Toxic, carcinogenic and cause endocrine disrupters.
Polybrominated diphenylethers (PBDEs)	Circuit boards and solar panel inverters	Toxic, carcinogenic and cause endocrine disrupters.
Silicon (Si)	PV semiconductor material	Causes respiratory problems, irritating skin and eyes.
Sulfur hexafluoride (SF_6)	Semiconductors etching and cleaning reactors	Strong greenhouse gas.
Toluene (C_7H_8)	Clean out microscopic dirt and dust-off chips	Headaches, hearing and memory loss, confusion, pregnancy problems, and retarded growth.
1,1,1-Trichloroethane ($C_2H_3Cl_3$)	Clean out microscopic dirt and dust-off chips	Dizziness, reduced blood pressure, unconsciousness, and heart problems.
Xylene (C_8H_{10})	Clean out microscopic dirt and dust-off chips	Skin and eye irritation, liver kidneys, nose and throat infections, and pregnancy problems.

03) Ecological issues

Hazardous materials

Problems for

Health and environmental impacts of the chemical compounds involved in PV cells' man

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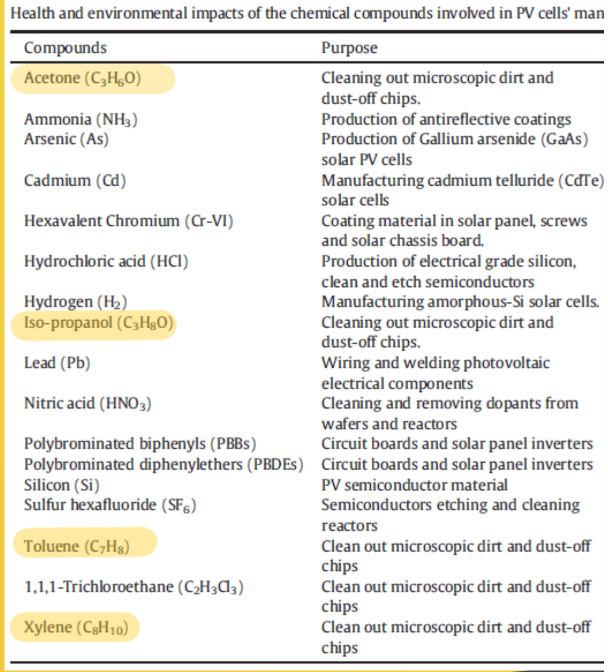
03) Ecological issues

Hazardous materials

Problems for



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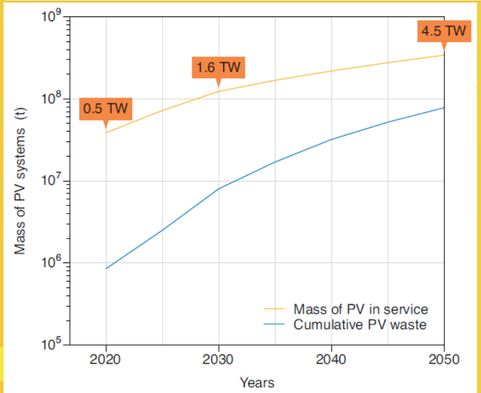
03) Ecological issues

Waste treatment

The Waste Electrical and Electronic Equipment (WEEE) standards include solar waste in the category of electronic waste, in an attempt to mitigate the negative influence of continual development.

PV installation is increasing → Future waste increasing at EOL of PV panels

Nature Energy | VOL 5 | July 502 2020 | 502–510 | www.nature.com/natureenergy



Mton of waste:

Today	2030	2050
~1	~8	~80

03) Maintenance & Monitoring*

It is important to have real time monitoring systems and techniques for maintaining the potential of the PV panels and farms. The efficiency of a solar panel can decrease for various reasons:

Temperature

Dust and dirty

Malfunction and damages

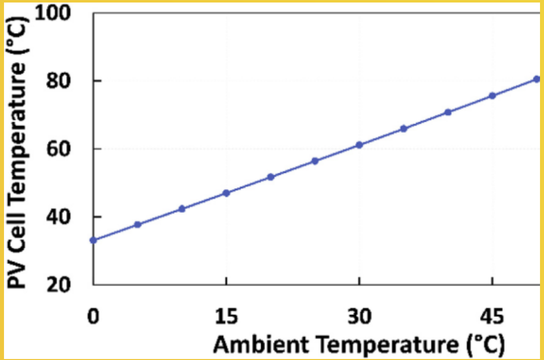
doi.org/: 10.1016/j.solmat.2019.109948; 10.1016/j.csite.2020.100674; 10.1016/j.rser.2017.09.042; 10.1088/2516-1083/ac890b; 10.1016/j.renene.2022.06.105

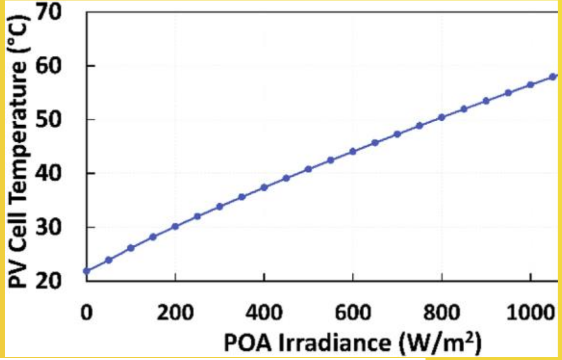
03) Maintenance & Monitoring

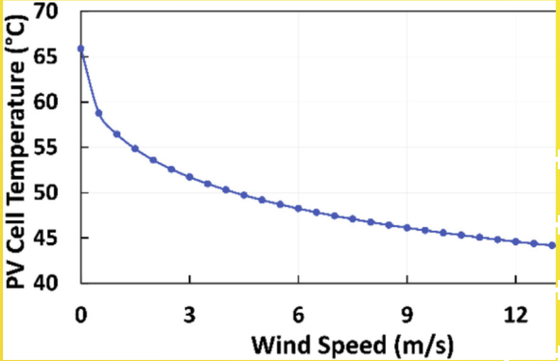
Temperature

$$\eta_{PV} = \eta_{PV,Tref}\,[1 - \beta_{ref}\,(T_{PV,cells} - T_{ref})]$$

The cells temperature have dependence from environmentals conditions:







Simulation from Solar Energy Materials and Solar Cells 200 (2019) 109948

Fixed conditions: POA = 1000 W/m^2 Wind Speed = 1 m/s
Ambient Temperature = 25°C

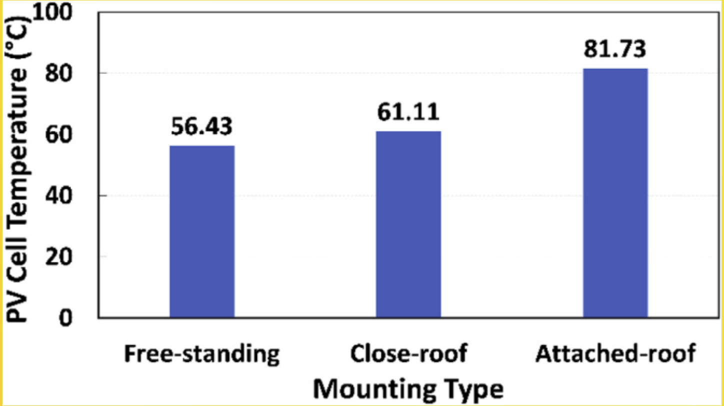
03) Maintenance & Monitoring

Temperature

$\eta_{PV} = \eta_{PV,Tref} [1 - \beta_{ref} (T_{PV,cells} - T_{ref})]$

Also the position of standing PV modules has an influence on the PV cells temperature

Simulation from Solar Energy Materials and Solar Cells 200 (2019) 109948



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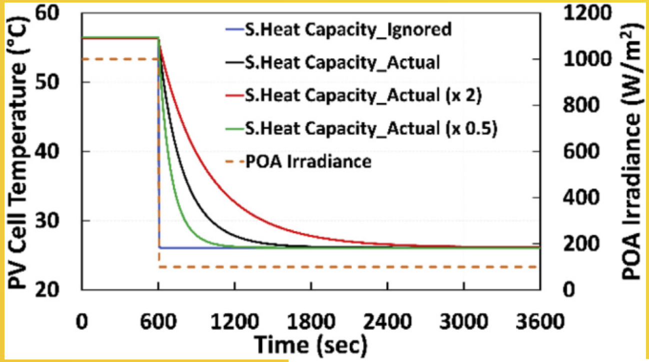
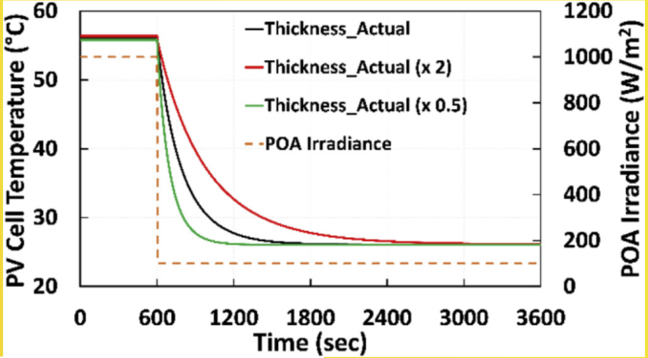
03) Maintenance & Monitoring

Temperature

$\eta_{PV} = \eta_{PV,Tref}\,[1 - \beta_{ref}\,(T_{PV,cells} - T_{ref})]$

The material properties such as specific heat capacity, density and layer thickness has a very pronounced effect on the temperature through the time constant.



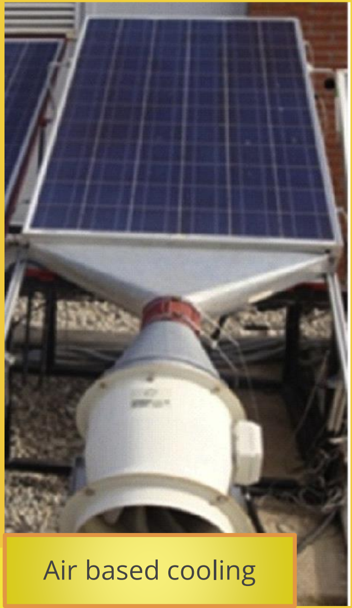


Simulation from Solar Energy Materials and Solar Cells 200 (2019) 109948

03) Maintenance & Monitoring

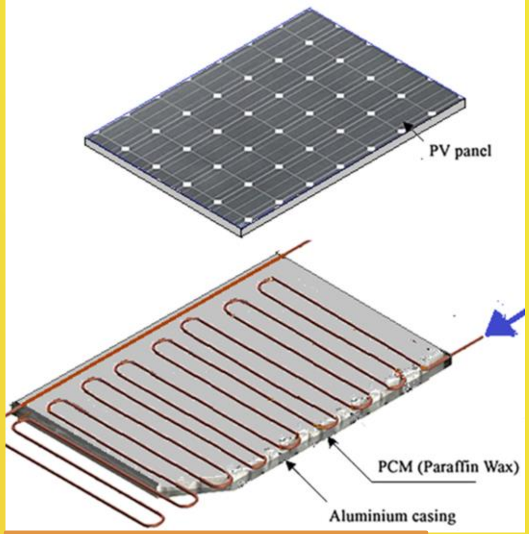
Temperature

Solutions: *Cooling systems*



Air based cooling

Water based cooling



Phase changing based cooling

03) Maintenance & Monitoring

Dust and dirty

This can strongly reduce the efficiency depending on the geographical position of the PV cell

$CaCO_3$

SiO_2

NaCl

Dust density doesn't increase linearly with exposure time, but strongly depends on climatic conditions during the exposure period. In addition of this dust can interact with water and air producing mud and crystalline solution hard to remove.

Observed dust effects on PV performance in different countries.

Study & location	Duration	Dust effect
KSA [95]	One Month	The average degradation rate of the efficiency was 7% per month
KSA [66]	Five weeks	The average power reduction without any cleaning action was around 6%
KSA [26]	Six weeks	The average power reduction was 13% for a plain glass module
KSA [40]	Six months	The output power decrease by as much as 50% without cleaning
Qatar [42]	100 days	The efficiency decreased by around 10% because of dust accumulation
Palestine [98]	One week	5 to 6% decrease in the solar panel efficiency
Egypt [99]	21 days	5% reduction of the output for 15° tilt angle
Egypt [97]	One month	The output power decreased about 17.4% per month
UAE [100]	Five weeks	The output power reduction after 5 weeks was about 10%
Spain [101]	Two months	After 15 days without rain the losses were greater than the 4%. The losses reach up to 15% after 2 months without raining
USA [102]	Two months	With soiling rates of less than 1.0% per month in the low desert and peak rates of 11.5% per month in heavy agricultural regions of the Central Valley, California.
Athens [103]	Eight weeks	6.5% power output reduction

03) Maintenance & Monitoring

Dust and dirty

Solutions: *Cleaning systems*

Spontaneous processes

Deciding a correct inclination for the PV rainfall, wind and gravity removes dust.

Mechanical methods

Using air or water fluxes or vibrations with programmable or IRT monitored systems.

Electrostatic methods

Using EM fields and PET surfaces to remove ionic particles of dust

Self-cleaning surfaces

Micro and nanoscale fabricated surfaces can be made hydrophobic so the dust doesn't deposit.

03) Maintenance & Monitoring

Malfunctions and damages

One of the main challenges that the PV industry faces is its vulnerability to faults due to its exposure to harsh environmental conditions.

Temperature

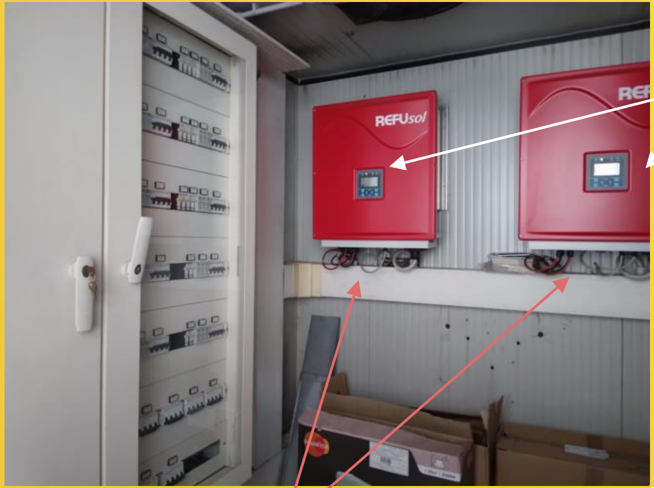
Incipient

Shading

Islanding

03) Maintenance & Monitoring

Typically in small industries the monitoring is made manually or by using simple software



IRT power output monitor

Transformers

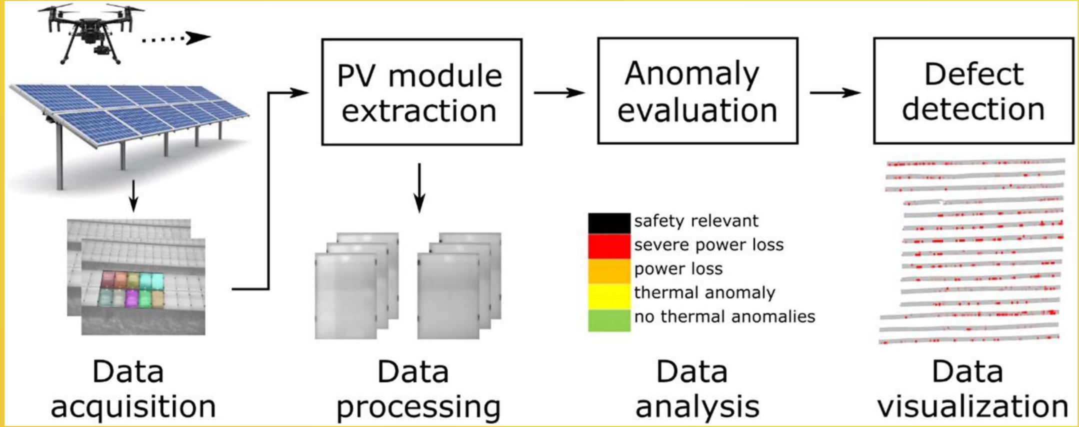
Photo taken by PRESSVIT s.r.l. Zibido San Giacomo (MI)

BUT IN BIG PLANTS ITS HARDER TO PERFORM

03) Maintenance & Monitoring

Malfunctions and damages

Solution: ML techniques and IRT monitoring



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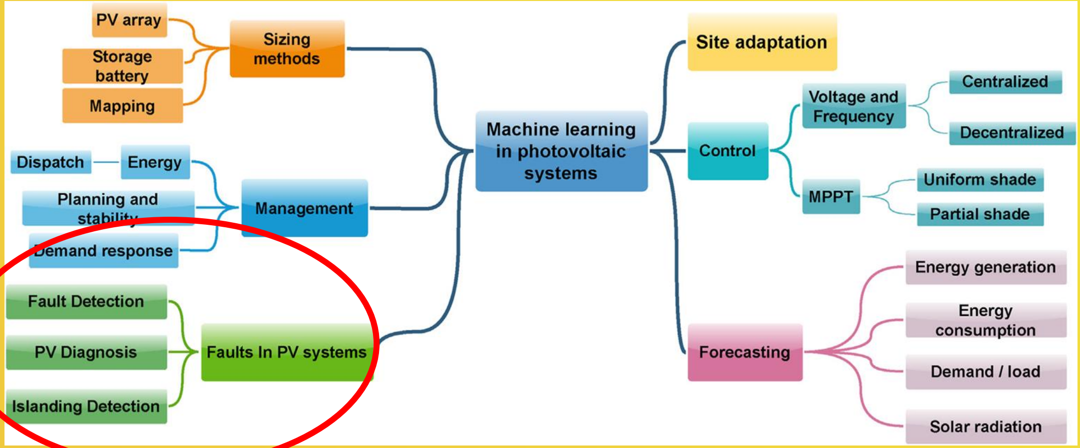
03) Maintenance & Monitoring

Malfunctions and damages

Solution: ML techniques and IRT monitoring

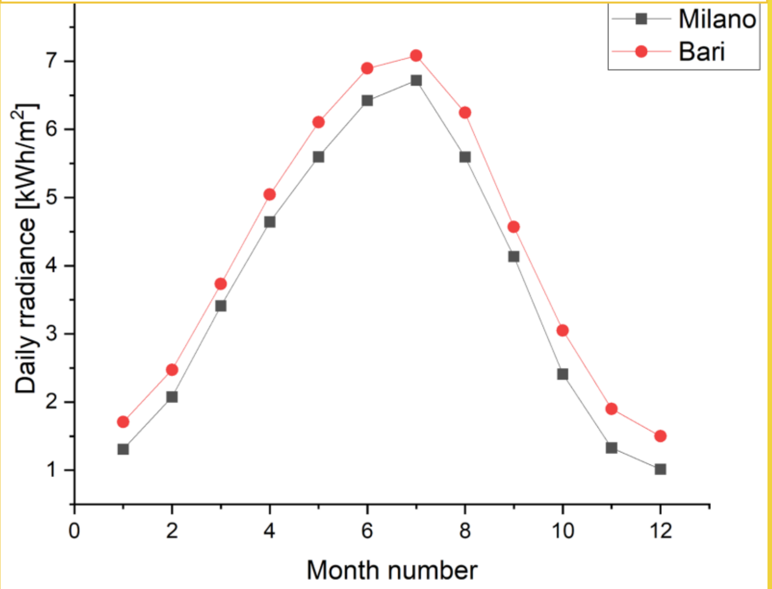


Renewable Energy 196 (2022) 298-318 : problem categories where ML has been applied to

03) Intermittence

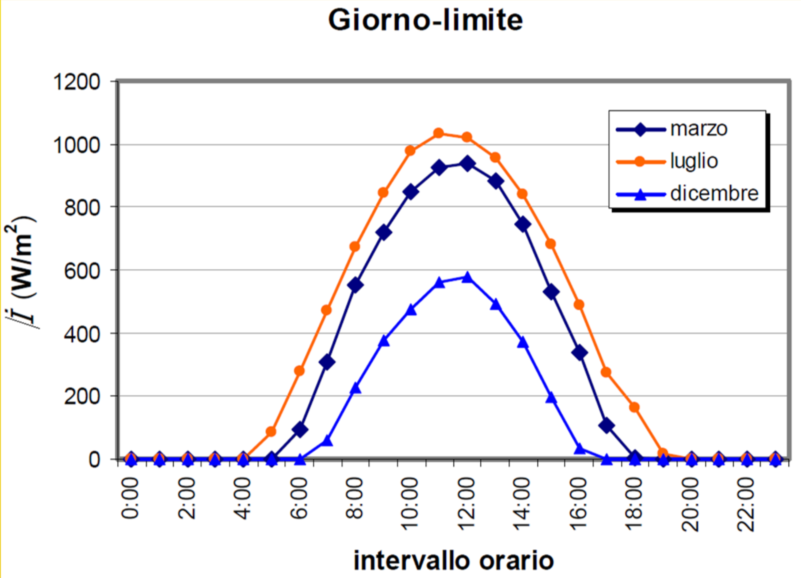
ENEA and TERNA data are used for the current part

Monthly variation



http://www.solaritaly.enea.it/CalcRggmmOrizz/Calcola1.php

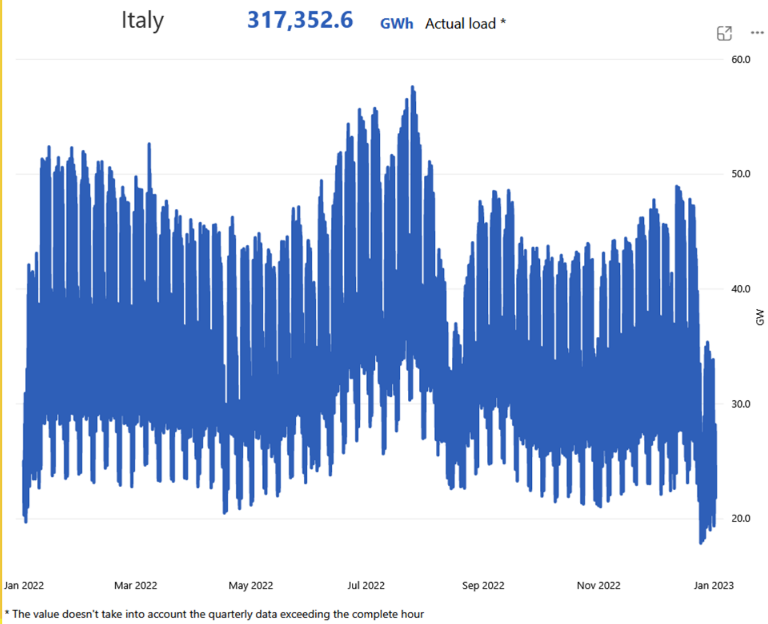
Daily variation



ENEA-SOLTERM, Priolo Gargallo (Siracusa) station. Means given by 2004-2006 years.

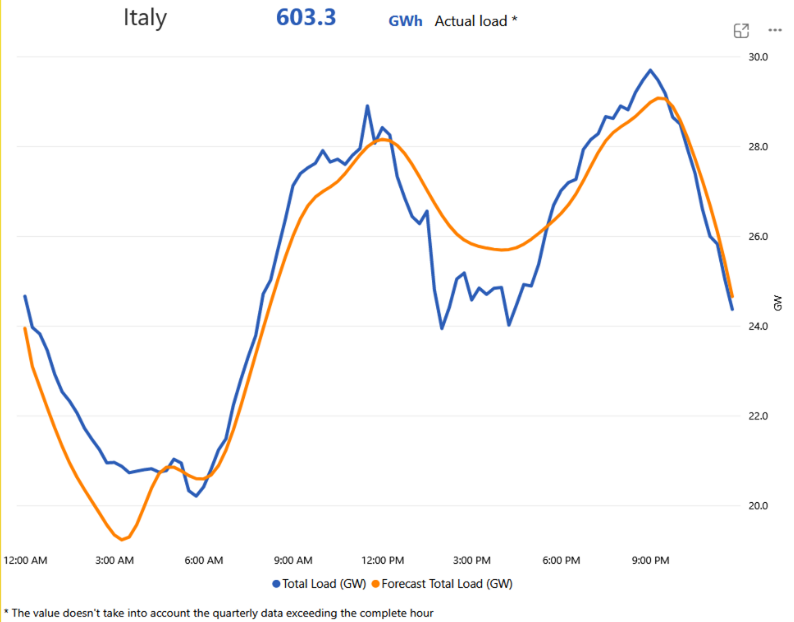
03) Intermittence

Energy usage (year)



01/01/2022 to 01/01/2023

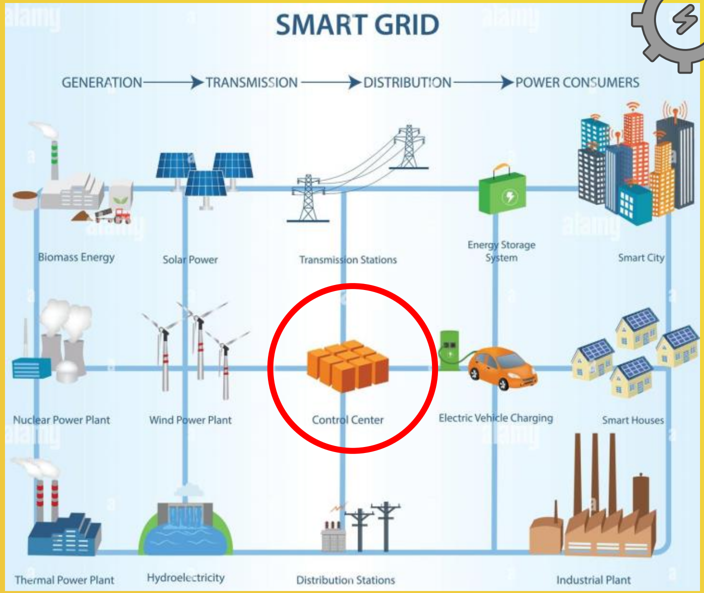
Energy usage (day)



05/06/2023

03) Intermittence

Solutions



04) Case study for Italy an estimation

What would happen if all roof in Italy were covered by c-Si commercial solar panels

Working hypothesis and simplifications:

- The irradiance of the sun is given as seen in ENEA's calculation by considering ***horizontal solar panels*** (so horizontal roofs): http://www.solaritaly.enea.it/CalcComune/Calcola.php
- Each region has different ***irradiance given by its capital*** ;
- The ***total roof surface*** in Italy is given as seen in: https://www.energoclub.org/page/potenziale-del-fotovoltaico ;
- The roof distribution for the country follows the ***density of the population*** of the regions (also tried with area distribution for the regions)[3];
- The ***efficiency*** of the panels is ***constant*** and around ***20%***;

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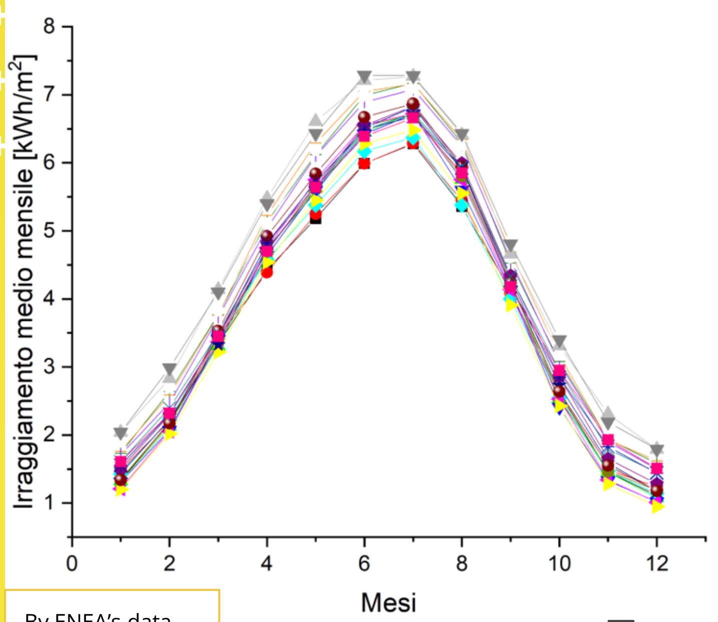
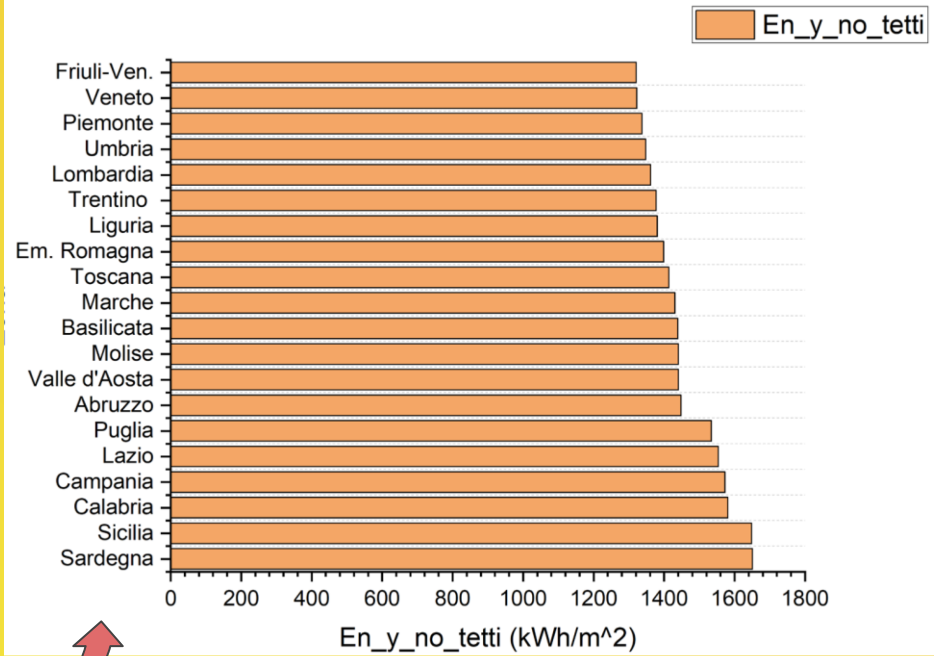
[3]Data taken by ISTAT

04) Case study for Italy an estimation

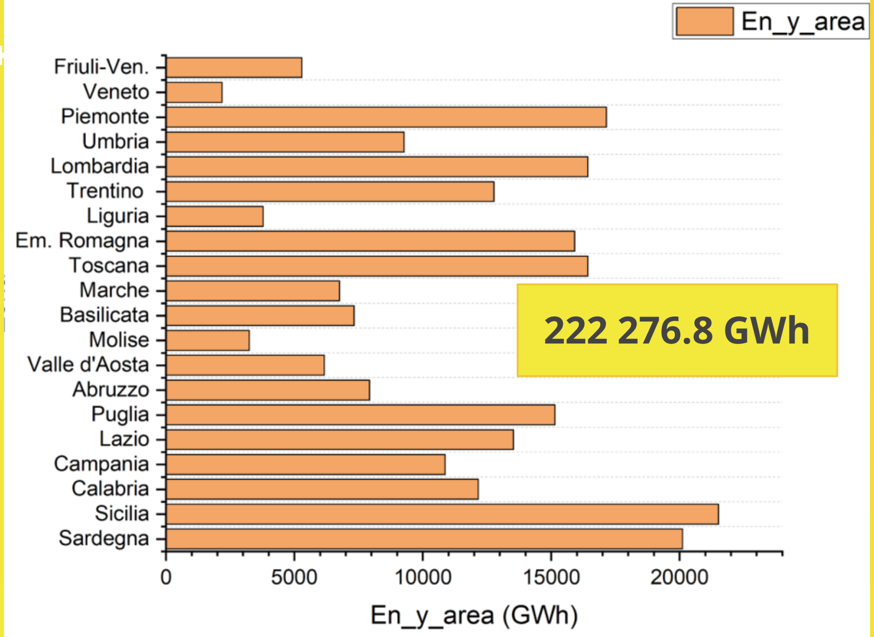


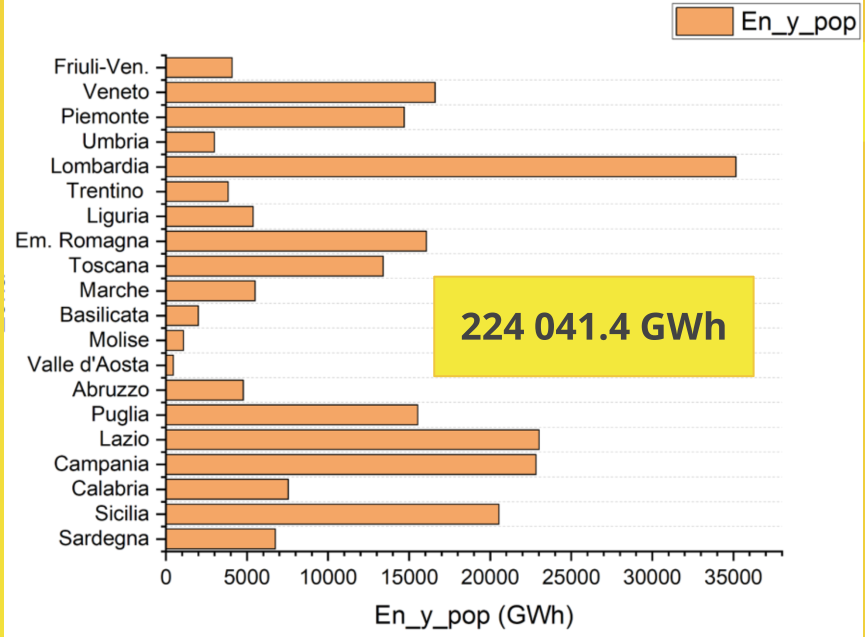
By ENEA's data



04) Case study for Italy an estimation

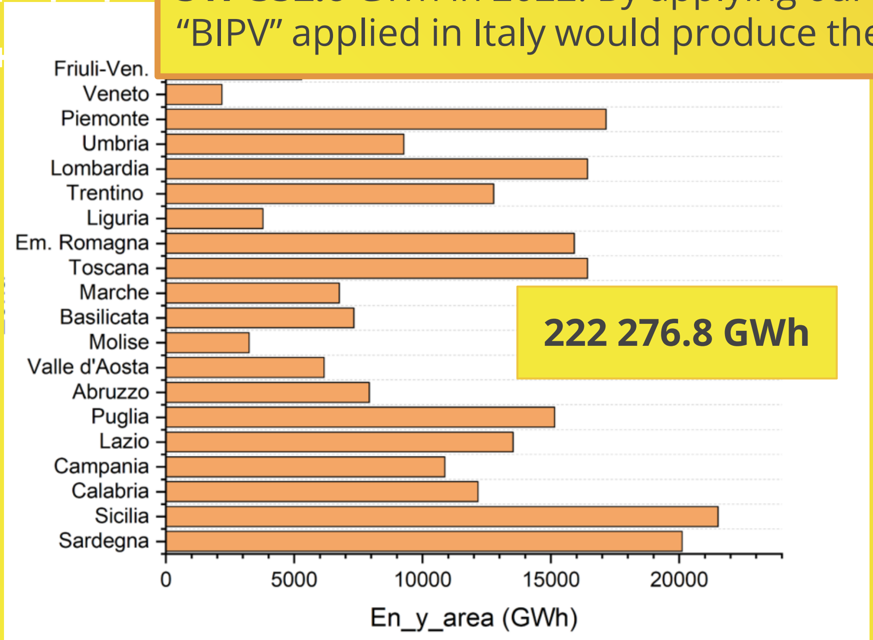
If we consider a roof surface of 763.53 km² we obtain:

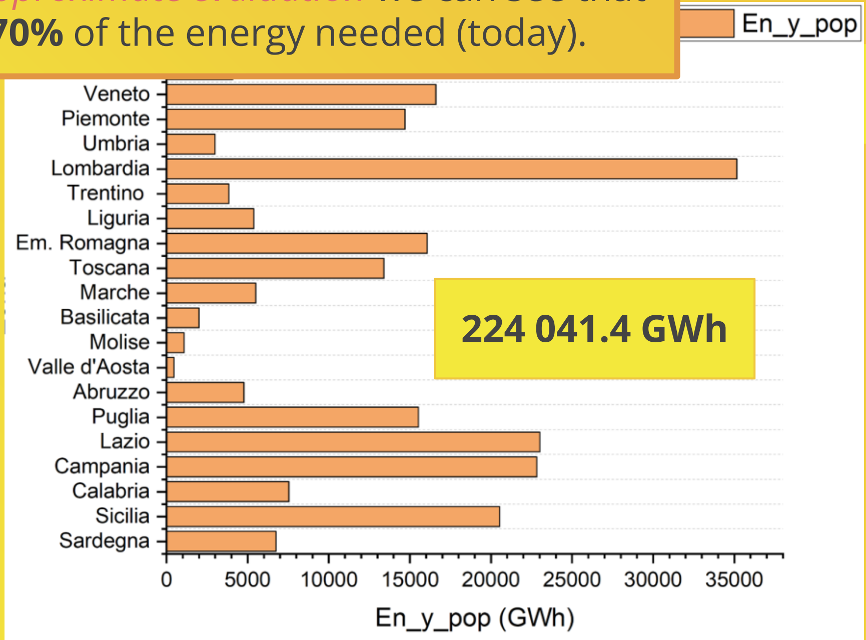




04) Case study for Italy an estimation

As seen on previous slides about intermittence, the total energy usage in Italy is **317 352.6** GWh in 2022. By applying our *approximate evaluation* we can see that "BIPV" applied in Italy would produce the **70%** of the energy needed (today).





Conclusions

As we can see, the complete and smart PV integration in the electrical system is a challenge we must take on. Useful new technologies such as ML approaches can help us to have more ***control*** and ***forecast*** possibilities. It is however ***impossible to ignore*** the effect on the environment of PV and vice-versa.

Future aims

- Properly analyze smart grids and machine learning potentials;
- Study the storage technologies;
- Develop a more realistic estimation of the Italy Case study taking into account more complex factors such as cleaning and temperature for evaluating efficiency in addition the economical factors;