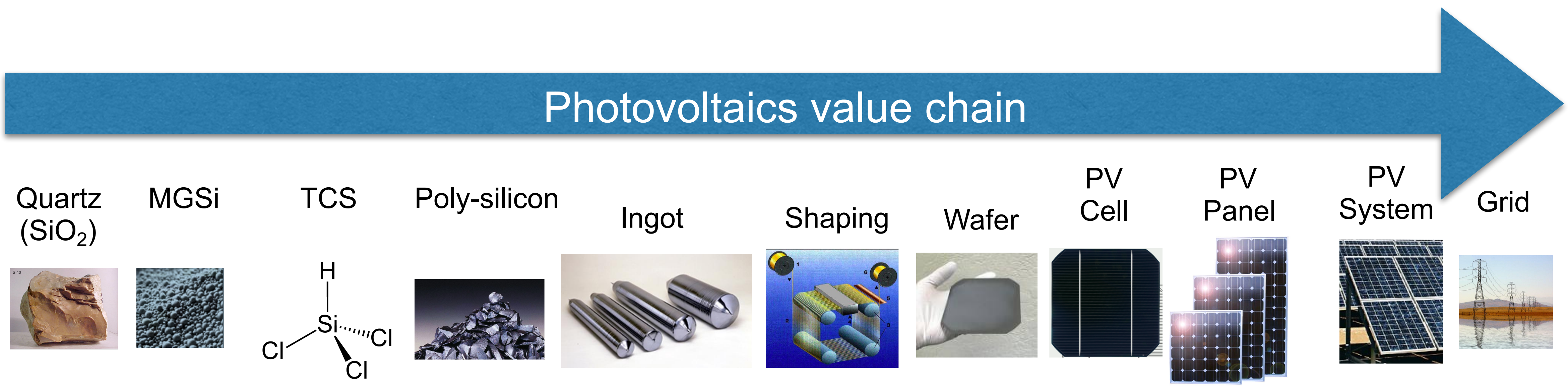
Latest Technology Developments in Photovoltaics

Green Council

Hong Kong, 7th November 2019

Long value chain …



Try to look at 360° - from materials to delivering electrons to customers

Focus today

Some facts

In order to understand **New PV Technologies**, it is useful to consider first where PV ranks in the energy space today, and how it got there.

Some facts

Solar electricity from photovoltaics is now the **cheapest form of NEW electricity generation** available on earth.

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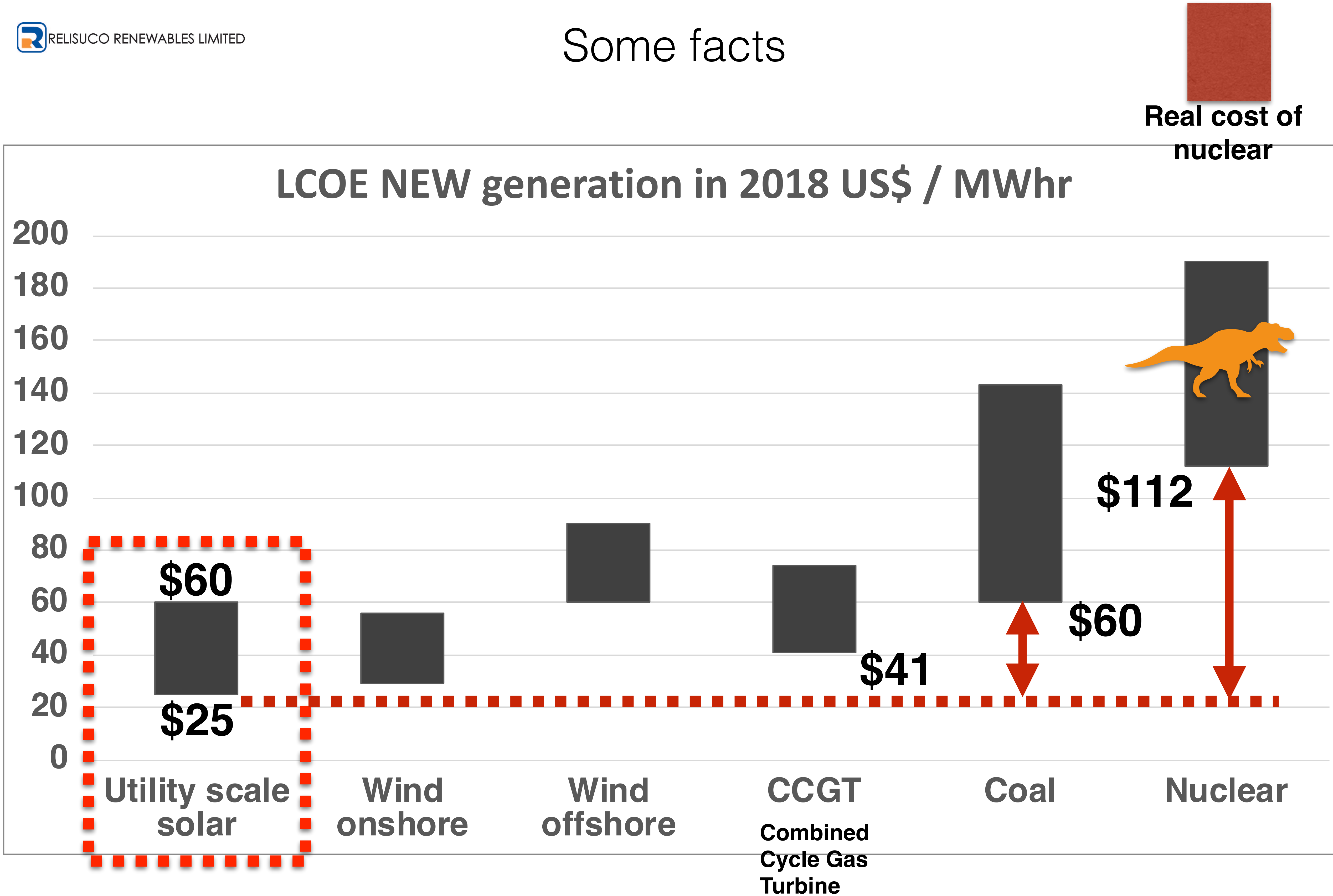
Some facts



Source: LAZARD'S LEVELIZED COST OF ENERGY ANALYSIS—VERSION 12.0, RR

Some facts

… and constantly getting cheaper … examples of PV electricity **auctions in 2019*:**

- "Portugal **€14.8 / MWhr**"
- "Brazil **$17.5 / MWhr**"
- "L.A. **$19.97 / MWhr**"

* Effectively forward pricing in 2021-2022

How did it happen ? A technology breakthrough ?

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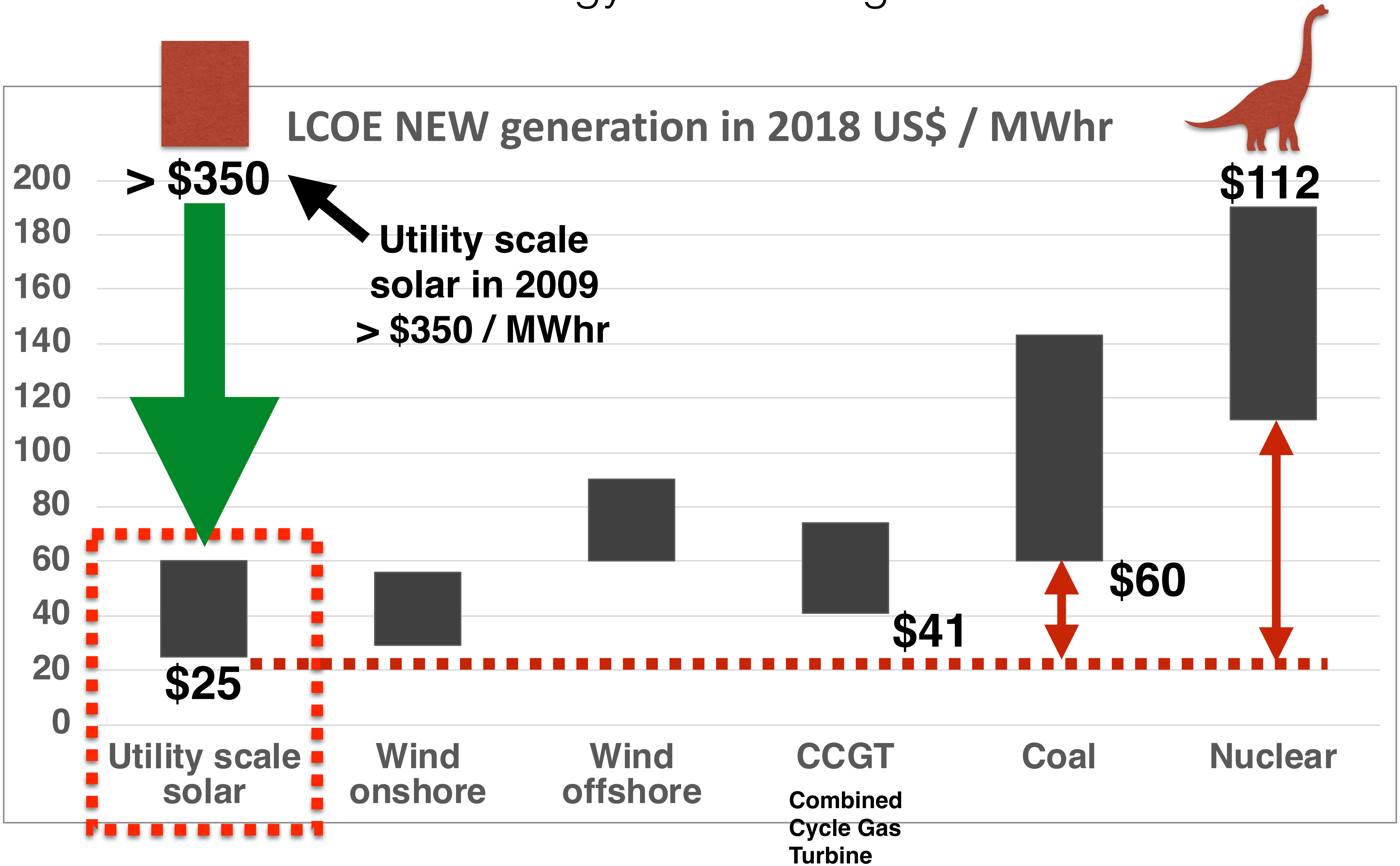
Technology breakthrough … ?



Source: LAZARD'S LEVELIZED COST OF ENERGY ANALYSIS—VERSION 12.0, RR

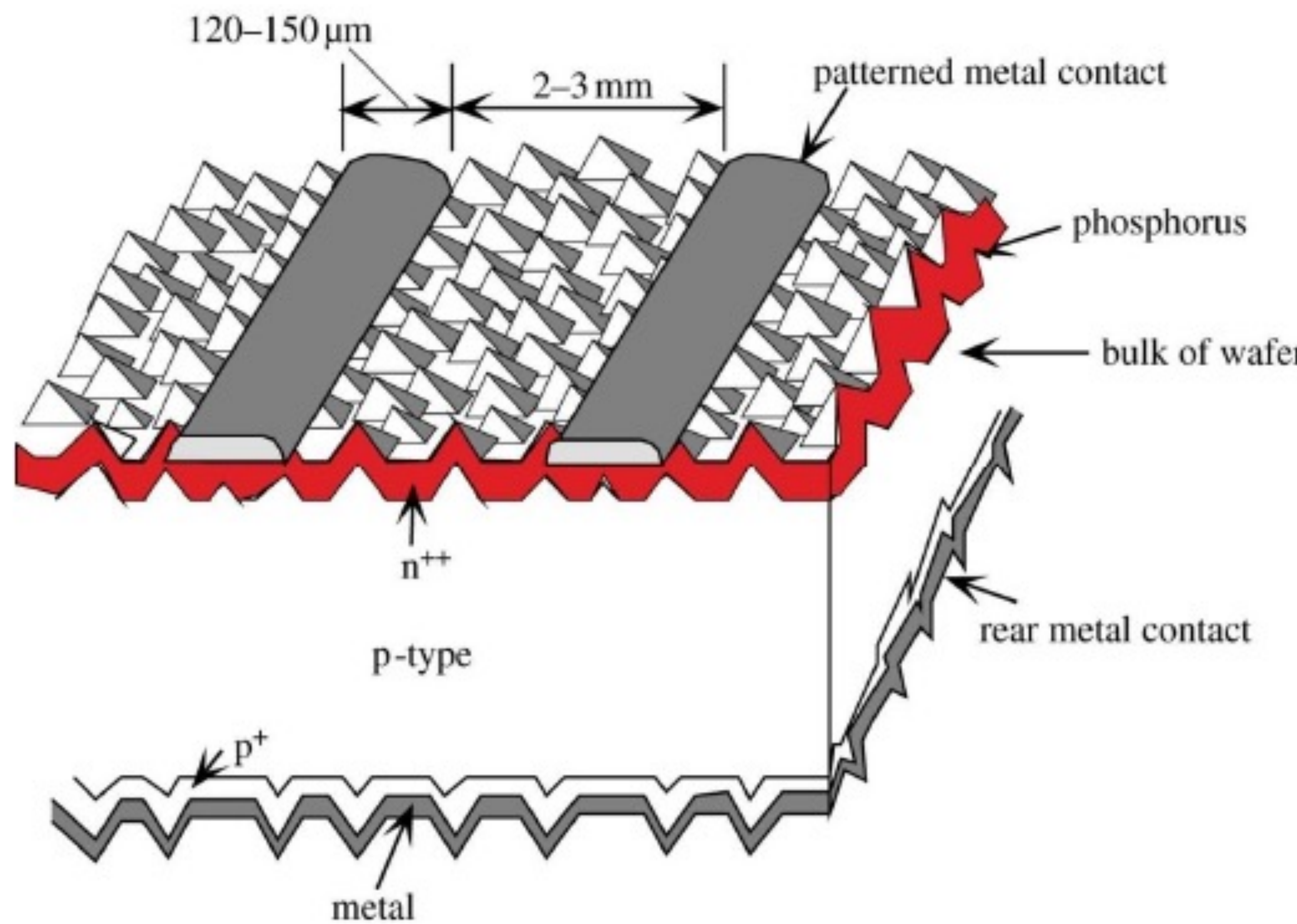
Technology breakthrough … ?

Bill Gates: We need global 'energy miracles' (2010)

http://edition.cnn.com/2010/TECH/02/12/bill.gates.clean.energy/index.html

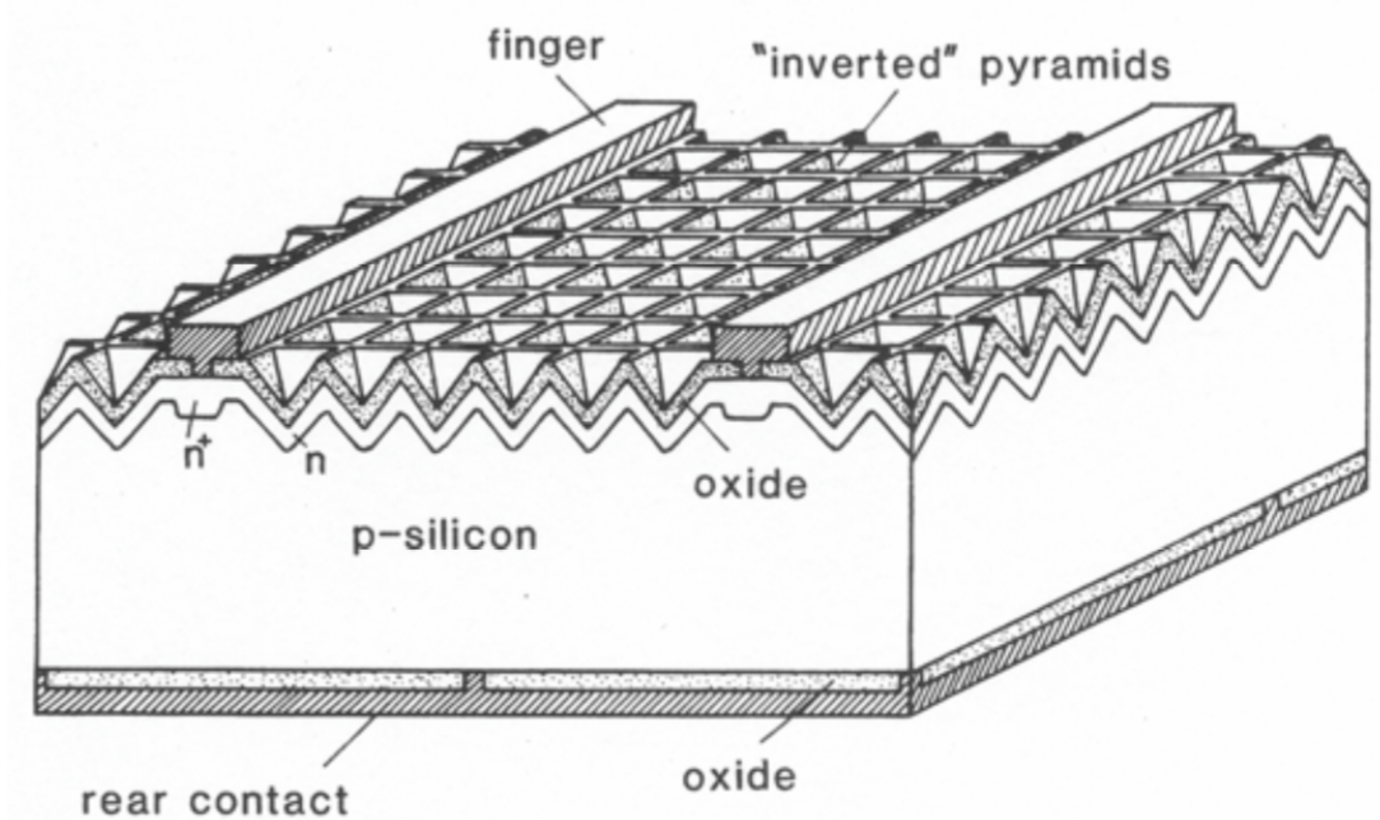
Technology breakthrough … ?

In 2016 the dominant solar cell architecture was the Aluminium Back Surface Field solar cell (Al-BSF), **in production since the 1970s.**



Technology breakthrough … ?

… **the commercially dominant solar cell architecture in production today** is the Passivated Emitter Rear Contacted (PERC) cell, **developed in the early 1980s (UNSW).**



Source: UNSW

Technology breakthrough … ?

$billions have been lost by ill-advised investors in “new-tech” **because they did not know / understand what works and what doesn’t.** Photovoltaics has been a graveyard of ambitions …

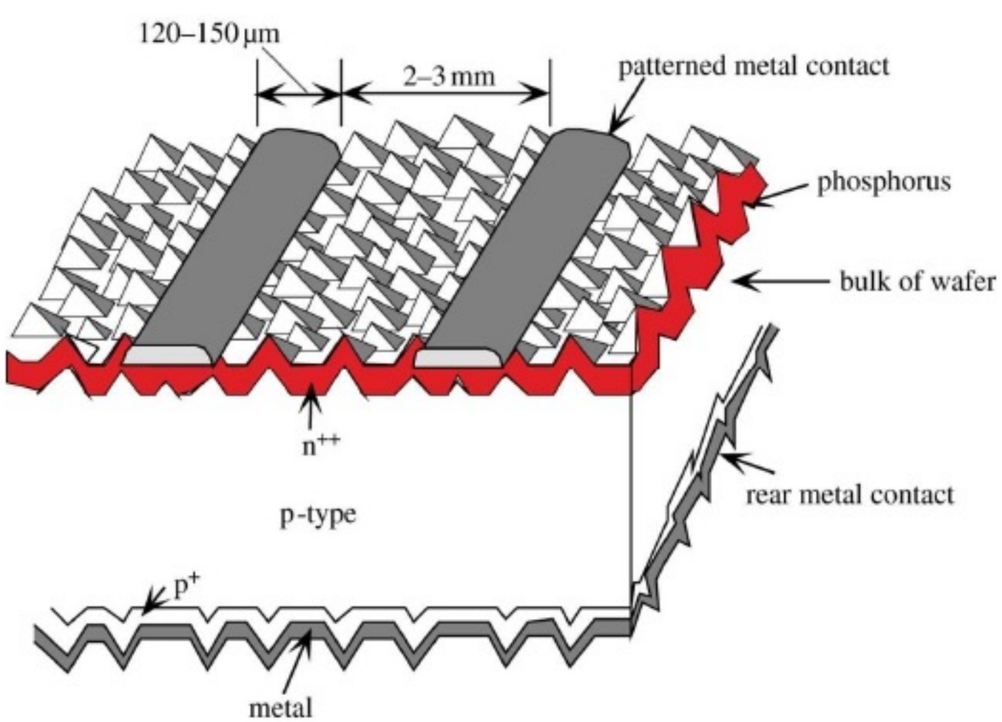
APPLIED MATERIALS®
bp solar
Q CELLS
TESLA
SolarCity
abound solar

SUNTECH
Suniva®
BOSCH Invented for life
phoenix SOLAR
woongjin
SIEMENS
SunEdison®
SHARP
evergreensolar Think Beyond.
Shell Solar
REC
SOLON
YINGLI SOLAR
SAMSUNG
SAMSUNG FINE CHEMICALS
SOLYNDRA®

No technology breakthrough … So how did it happen ?

… no breakthrough

Proven, OPEN, 40 year old **technology**



+

a **large subsidised market**

… just scale and competition

and …
someone that knows how to build something at huge scale, fast, and drive down costs relentlessly

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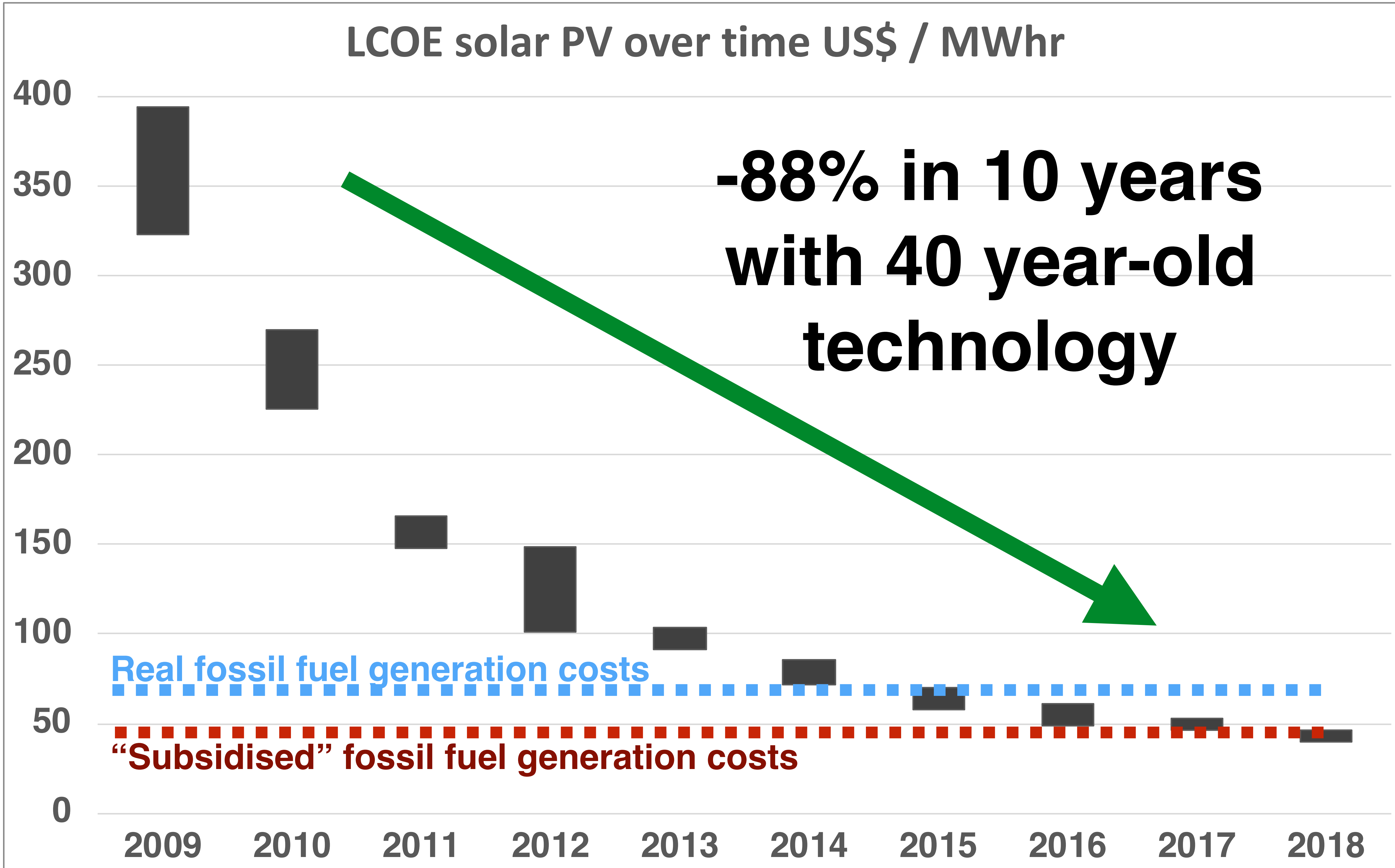
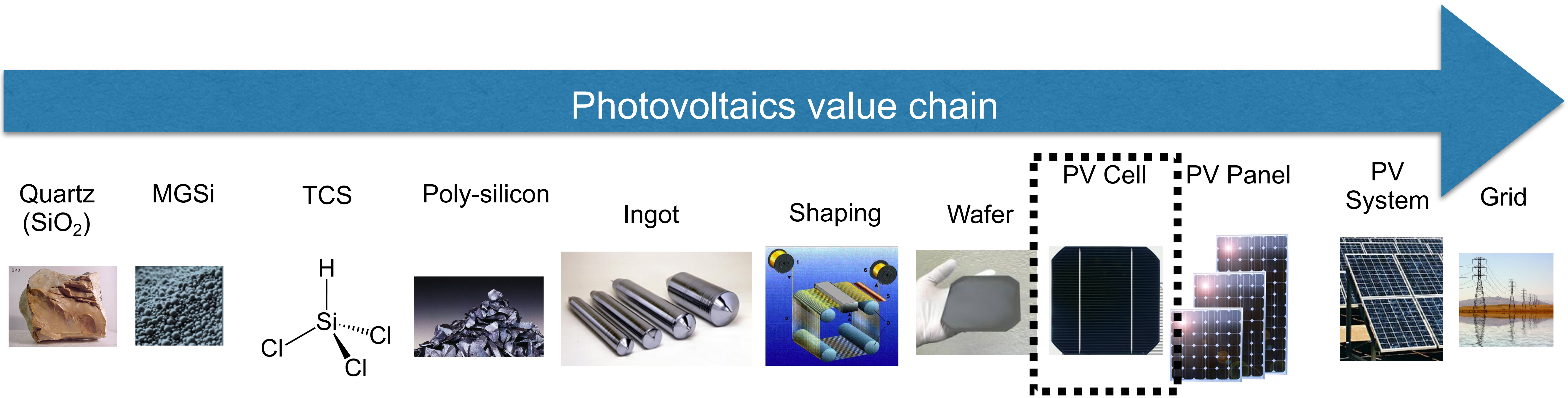
… just scale and competition



Source: LAZARD’S LEVELIZED COST OF ENERGY ANALYSIS—VERSION 12.0, RR

What next ?

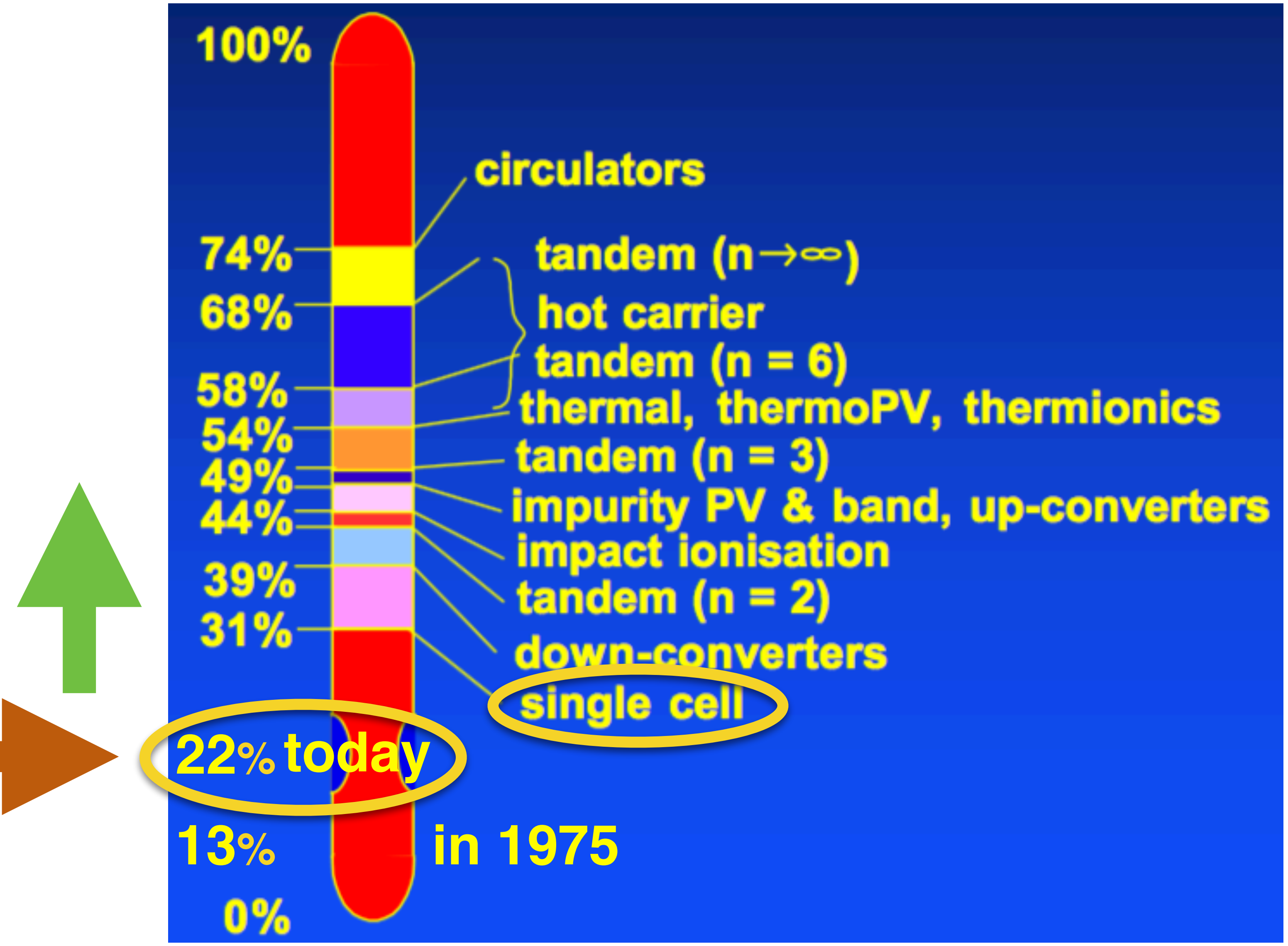
What next ?



focus often is on PV cell but actually WHOLE value chain is very important

What next ?

- In **2016-19 competitive LCOE reached in most regions.**
- But in the efficiency race we are just at the beginning**.**
- **Opportunities to do better with PV efficiency in future.**



Theoretical conversion efficiency of different PV cell architectures.

(100% = energy of solar spectrum that reaches earth's surface)

Source: UNSW

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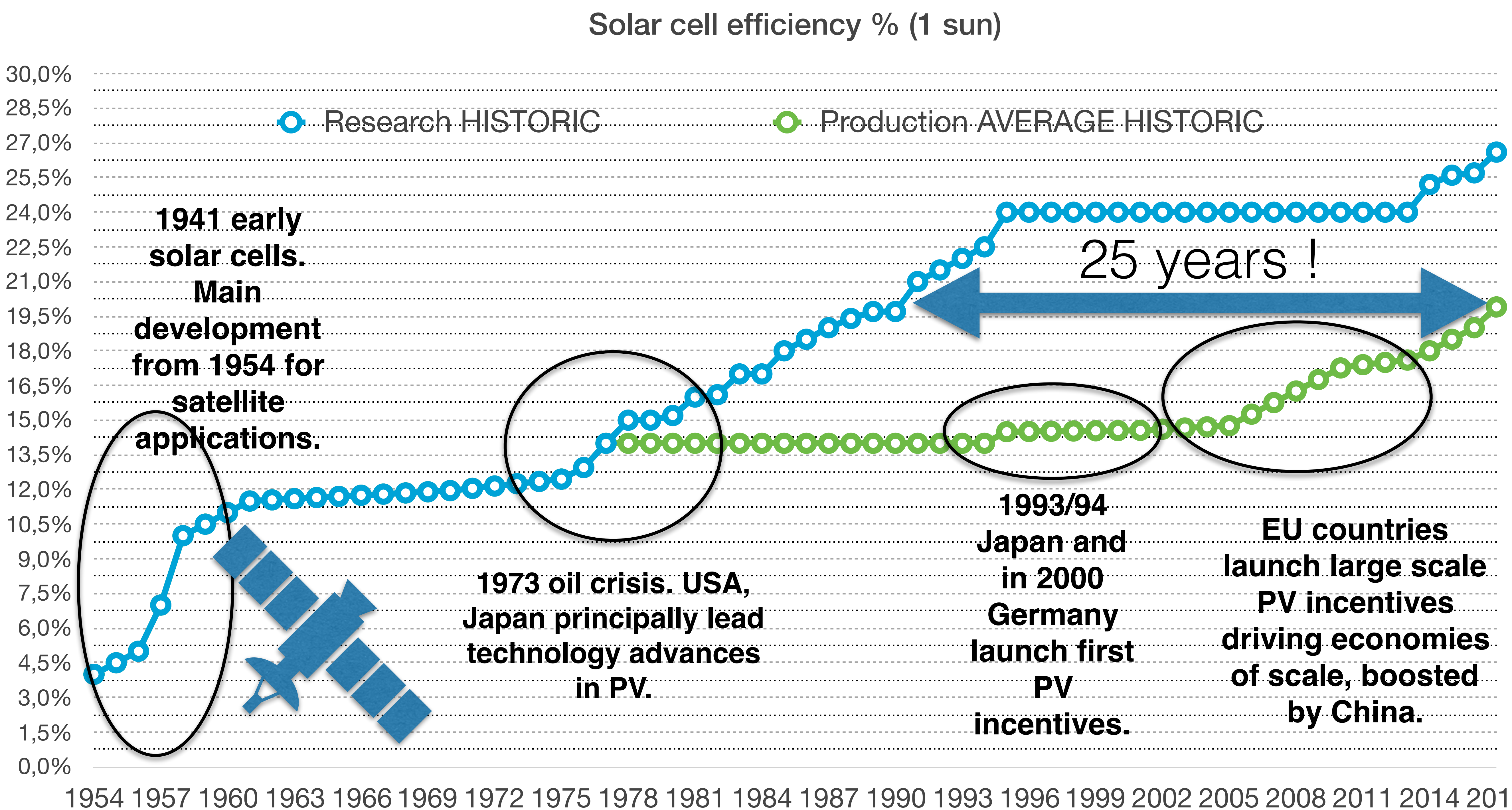
From the beginning to today

- From 1954 to 2019 (65 years) …. solar PV cell efficiency **from 3.5% to 22%** **(average top 10)** (1 sun).



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What next ?

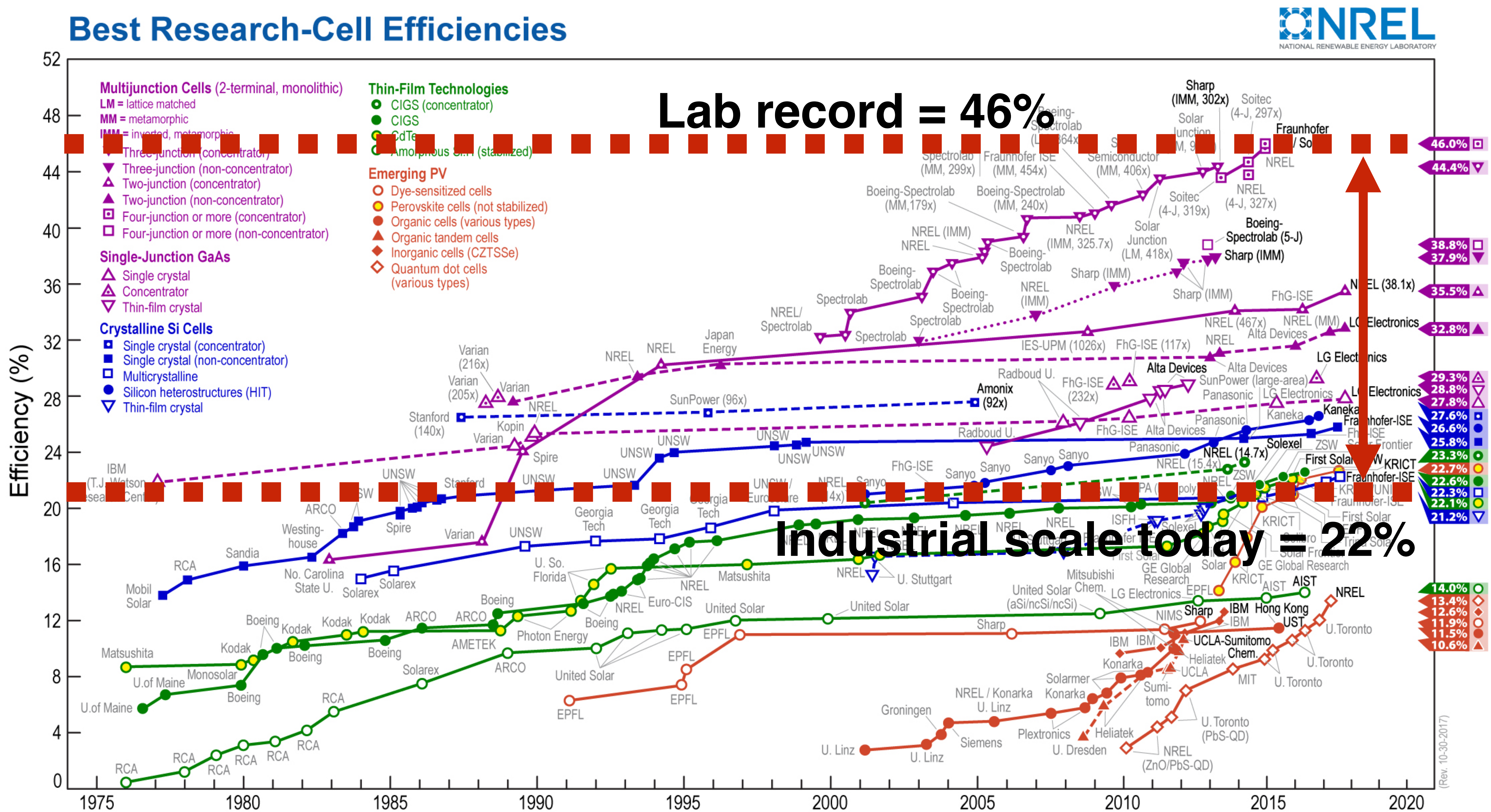
- Many more players in PV in competition (≈ x 15) compared to 20 years ago, create a virtuous flywheel of activity from which all stakeholders benefit.
- **Key driver: largely open technologies in c-Si PV.**
- 1994 global production : 60 MW LCOE > US$ 5.00 / kWh
- 2018 global production : 110 GW (≈ **x 1800**) LCOE < US$ 0.04 / kWh

PV value chain	yesterday (< 2000)	today
research institutes	20	> 150
material suppliers	5	> 50
equipment manufacturers	5	> 100
component manufacturers	20	> 500
wafer manufacturers	5	> 30
cell manufacturers	15	> 200
PV module manufacturers	20	> 1000

New solar cell architectures

New solar cell architectures

- Lab cell efficiency records … so **we know how to to it.**



[NREL cell efficiencies summary]

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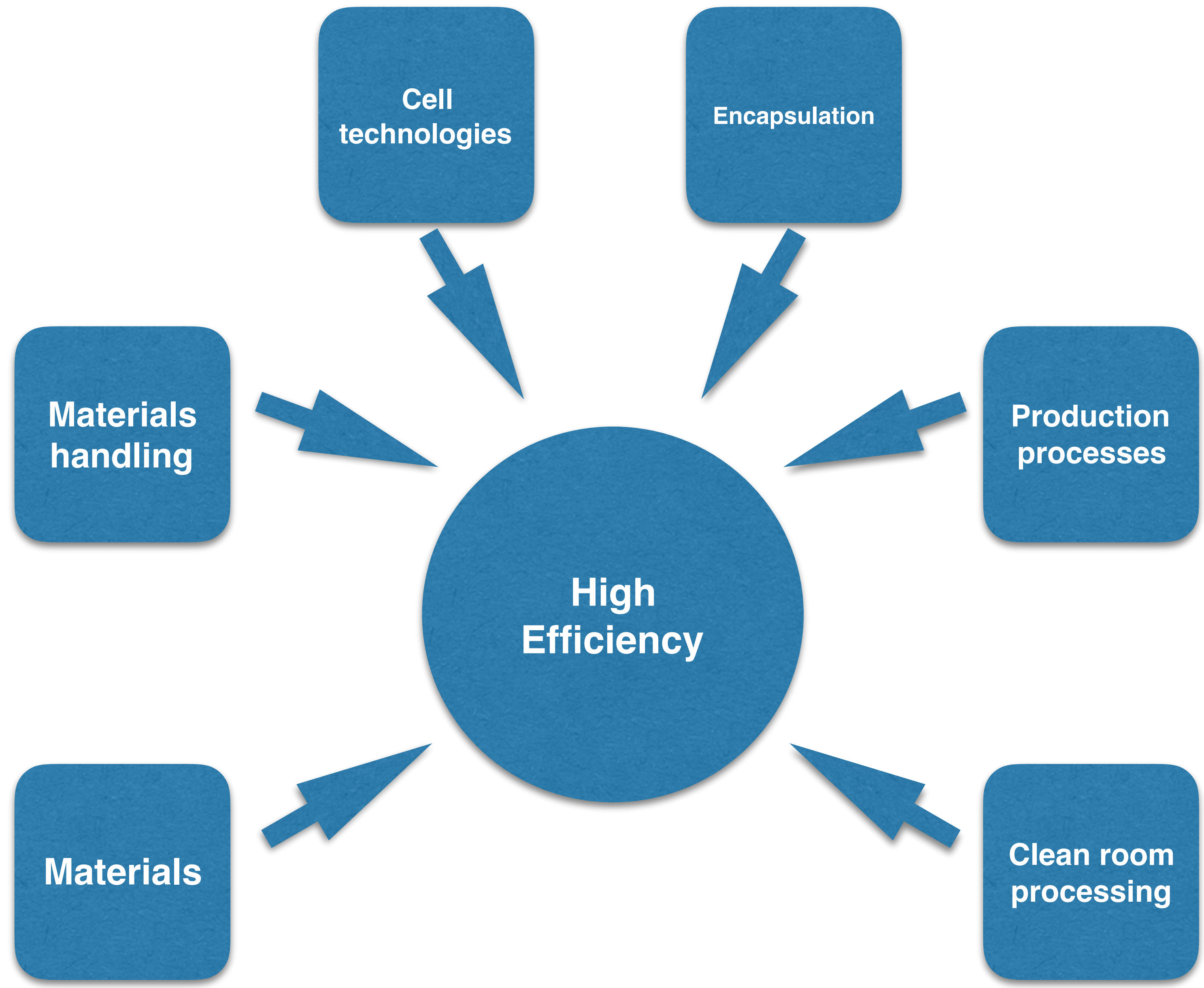
New solar cell architectures

- **No secrets but moving out of the lab is hard:**
  - complex value chain
  - **need to validate processes on a large scale, must be robust & proven** over time
  - PRC delivered LCOE but killed profits so **no sizeable investments in the USA, EU, Japan out of the lab**



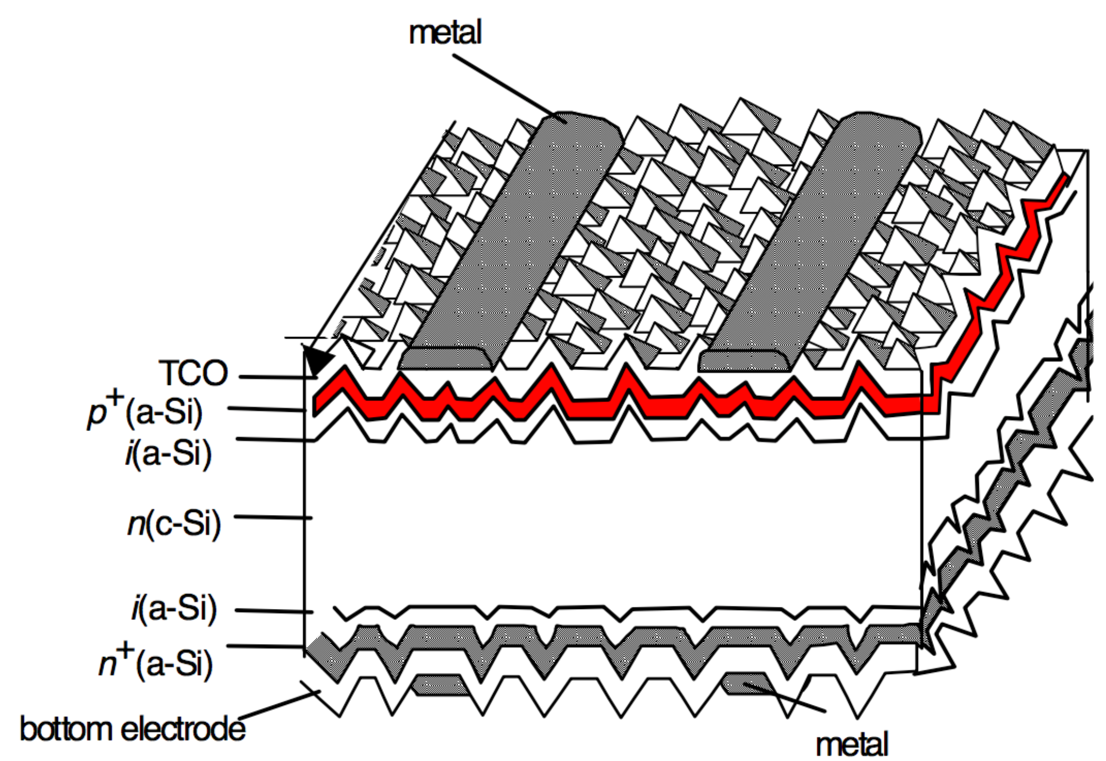
New solar cell architectures

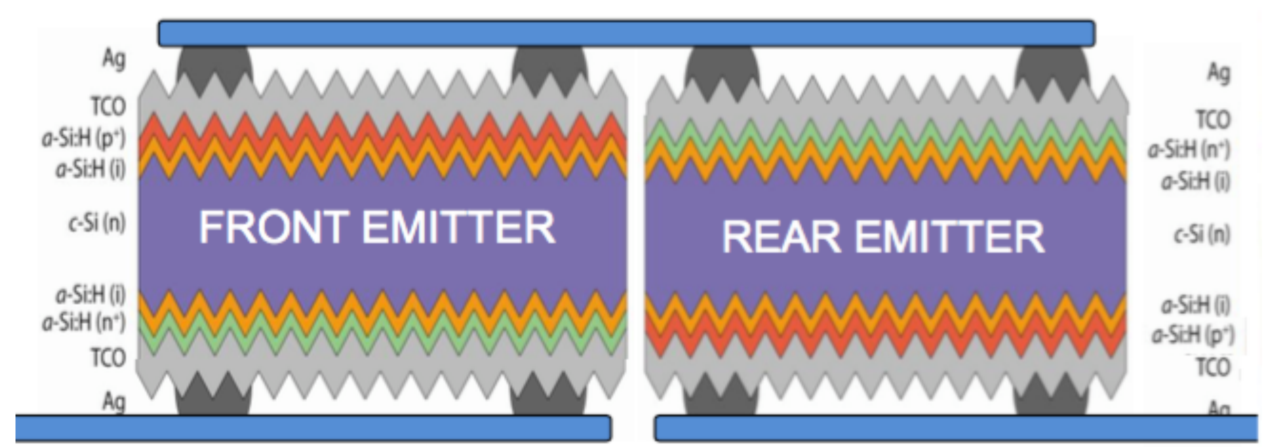
- What is **next after PERC cells ?**
- Most likely **heterojunction cells (HJT)** that originate from research done in the 1970s at the University of Marburg and at Yorktown Heights laboratory in 1974.
- In 1983 at Osaka University the first amorphous silicon / polycrystalline stacked solar cell was demonstrated.
- Panasonic was first to invest in R&D on the concept and entered the first HIT cell in mass production in 1997 (with proprietary technology).
- Why so long ? Patent expiry and manufacturing tools.
- **HJT solar cell production lines ramping up now** and in some cases will reach production in the GW scale in 2020.

New solar cell architectures

- **Advantages:**
  - Crystalline Si
  - Wafer Thickness Does Not Limit Performance Down to ~ 80 µm
  - Streamlines Unit Operations Through In-Line Processing
  - Excellent Temperature Coefficient and Low Light Performance
  - High Voc (due to excellent surface passivation)
  - No LID, no PID (on mono n-type substrates)
  - Bifacial cell architecture by design
- **Disadvantages:**
  - J_{SC} loss due to absorption in amorphous silicon
  - Fill factor (FF) loss due to series resistance in front TCO
  - Risks to Early Adopter & Trail Breaker in both Toolsets and Supply Chain
  - Limited number of technology providers, early days, steep learning curve in technology / manufacturing (few common steps with Al-BSF / PERC processes)

HJT will boost cell efficiencies from 22% to 25% over the next few years





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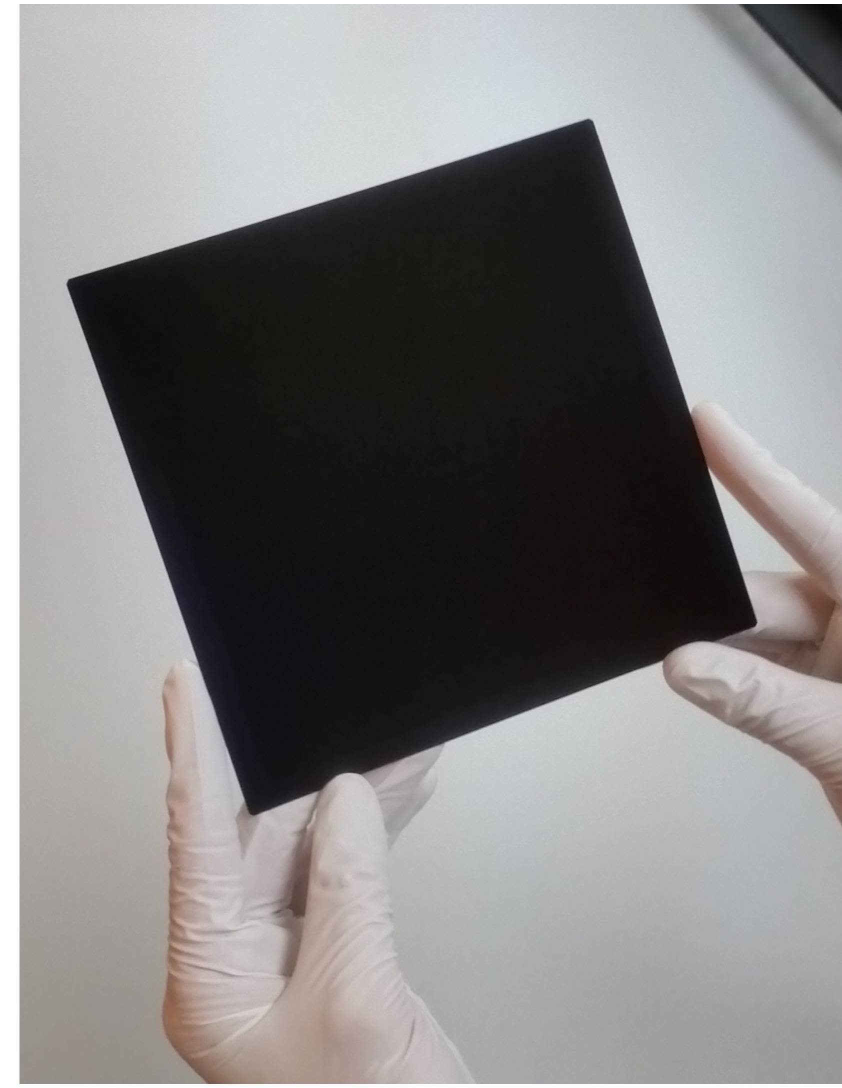
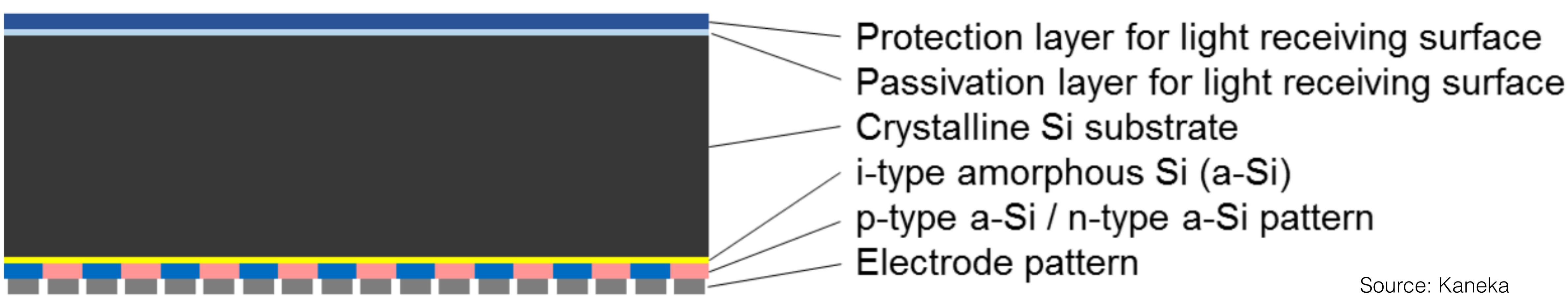
New solar cell architectures

- Beyond HJT ?
- HBC (Heterojunction Back Contact).
- **HBC lab efficiency reached 26.7%** - single junction on a mono-crystal n-type wafer.
- Bettered previous Panasonic record by 0.9%.



Schema della cella HBC sviluppata dalla Giapponese Kaneka.



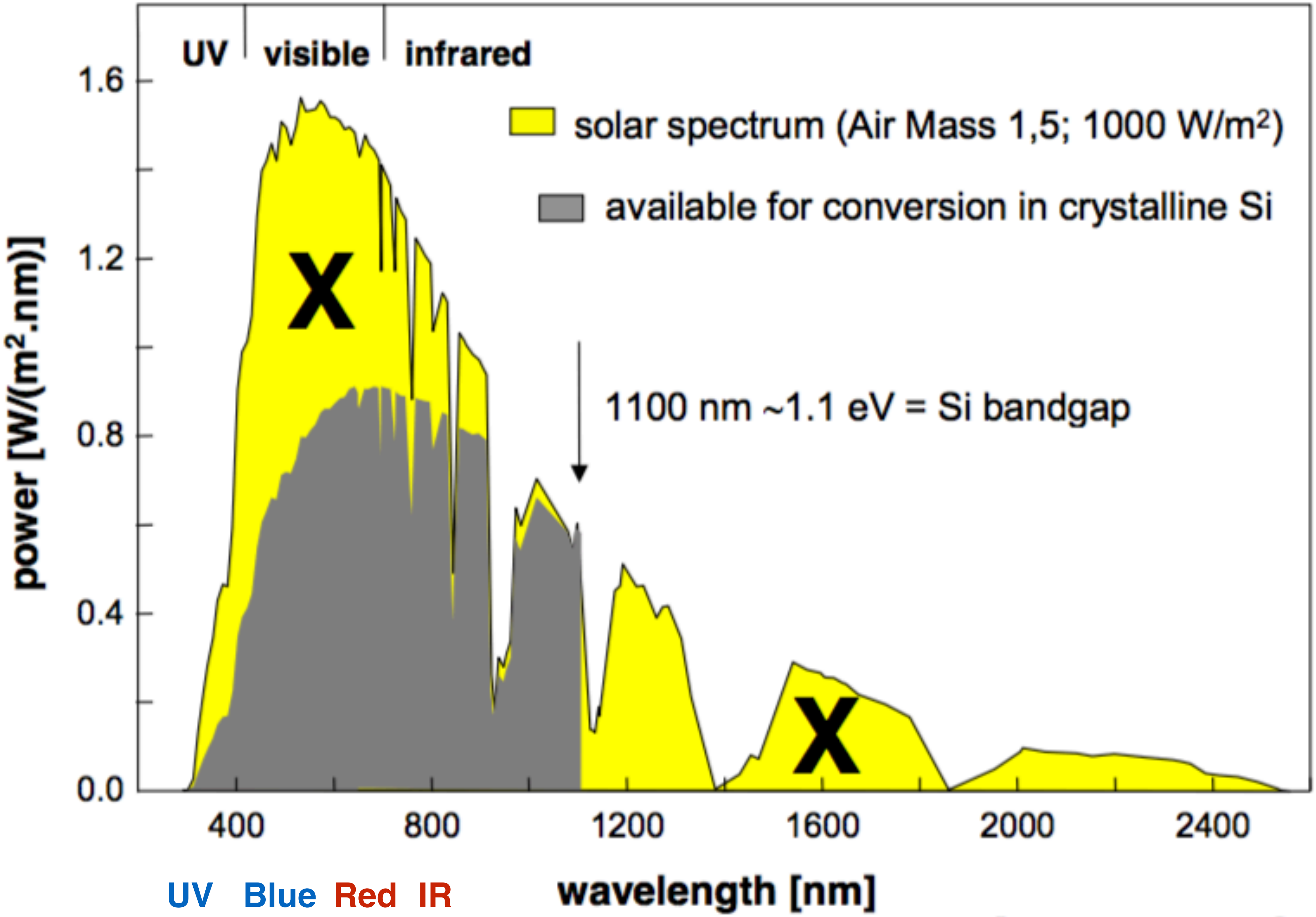
Source: Kaneka

In summary:

- Shockley, Queisser (1961): theoretical cell efficiency limit with a single junction = **33%**
- Silicon's specific limit is = **29.4%**
- Current record, silicon (2018) = **26.7%**
- Reached **90% of theoretical efficiency !**
- Is this it ? NO !

New solar cell architectures

- The **answer is to go beyond the limits of single junction** architectures:



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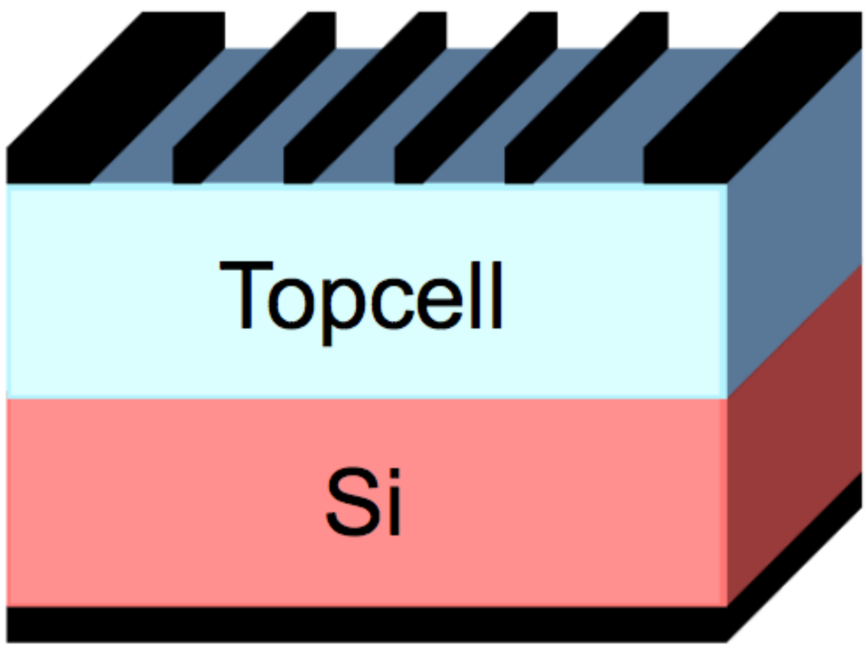
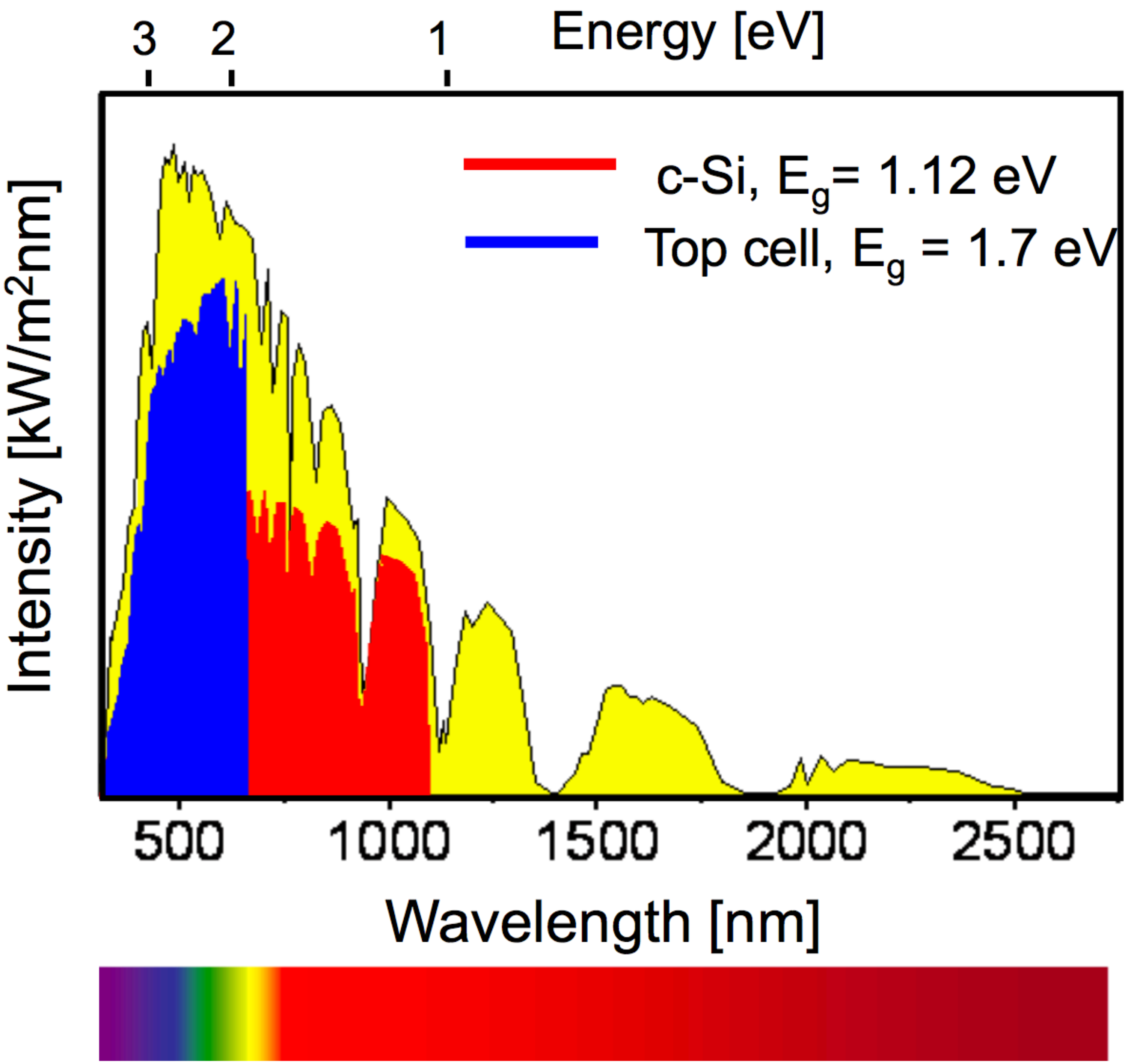
New solar cell architectures

- Simplest multijunction is a **two stacked cell** or **tandem cell**
- **add another cell on top of a silicon cell**





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New solar cell architectures

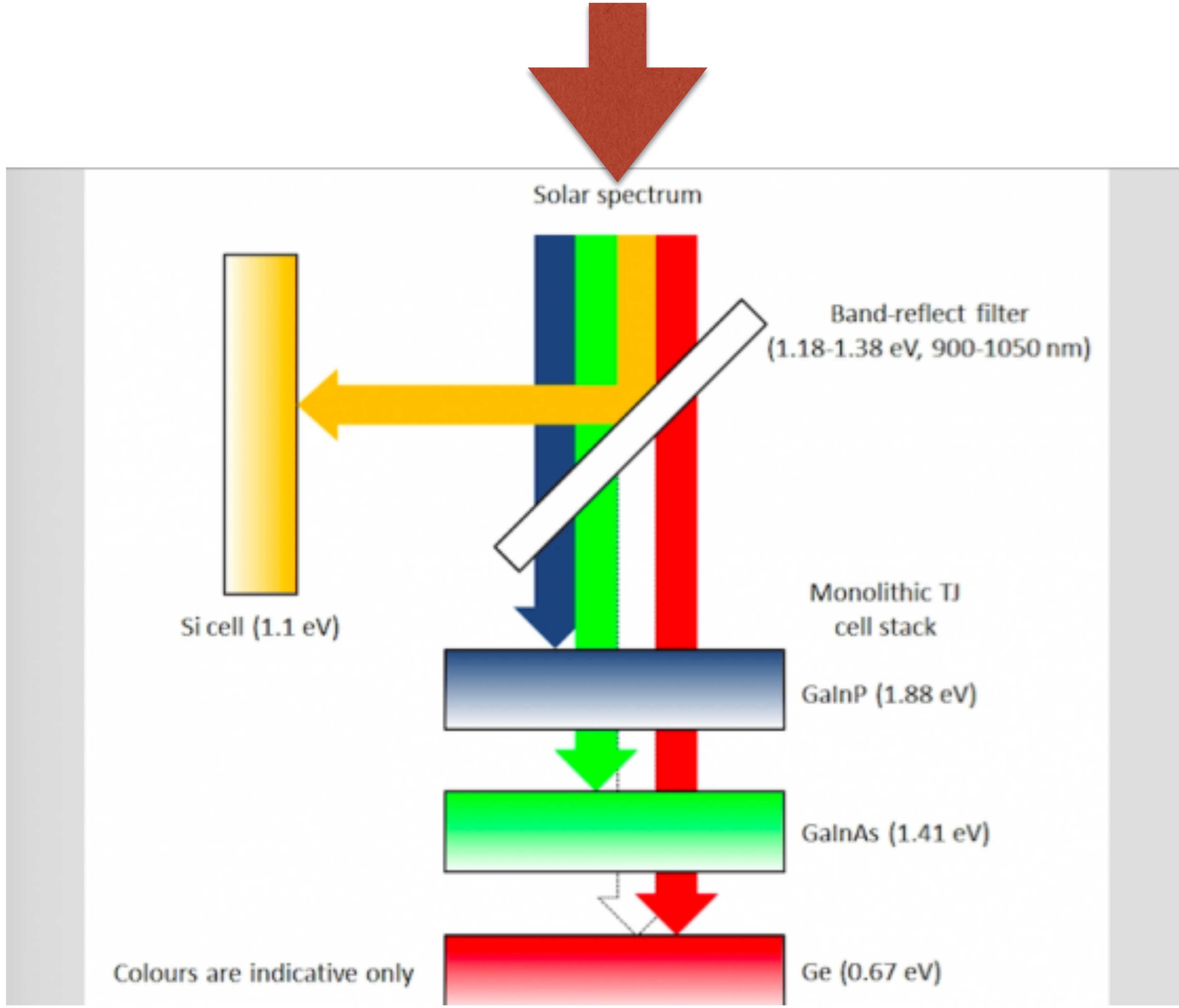
- The **efficiency limits** under these conditions (using the Shockley-Queisser calculation method) are:

Number of junctions	Theoretical efficiency limit	
single band gap material	**33%**	(29.4% for silicon)
two band gaps (tandem cell)	**42%**	
three band gaps (multijunction cells)	**49%**	
Quantum dots	**65%**	
infinite number of stacked cells	**68%**	(not practical)

- So the answer is obvious in theory! **We need to move to stacked cell concepts and in future Quantum Dots.**

New solar cell architectures

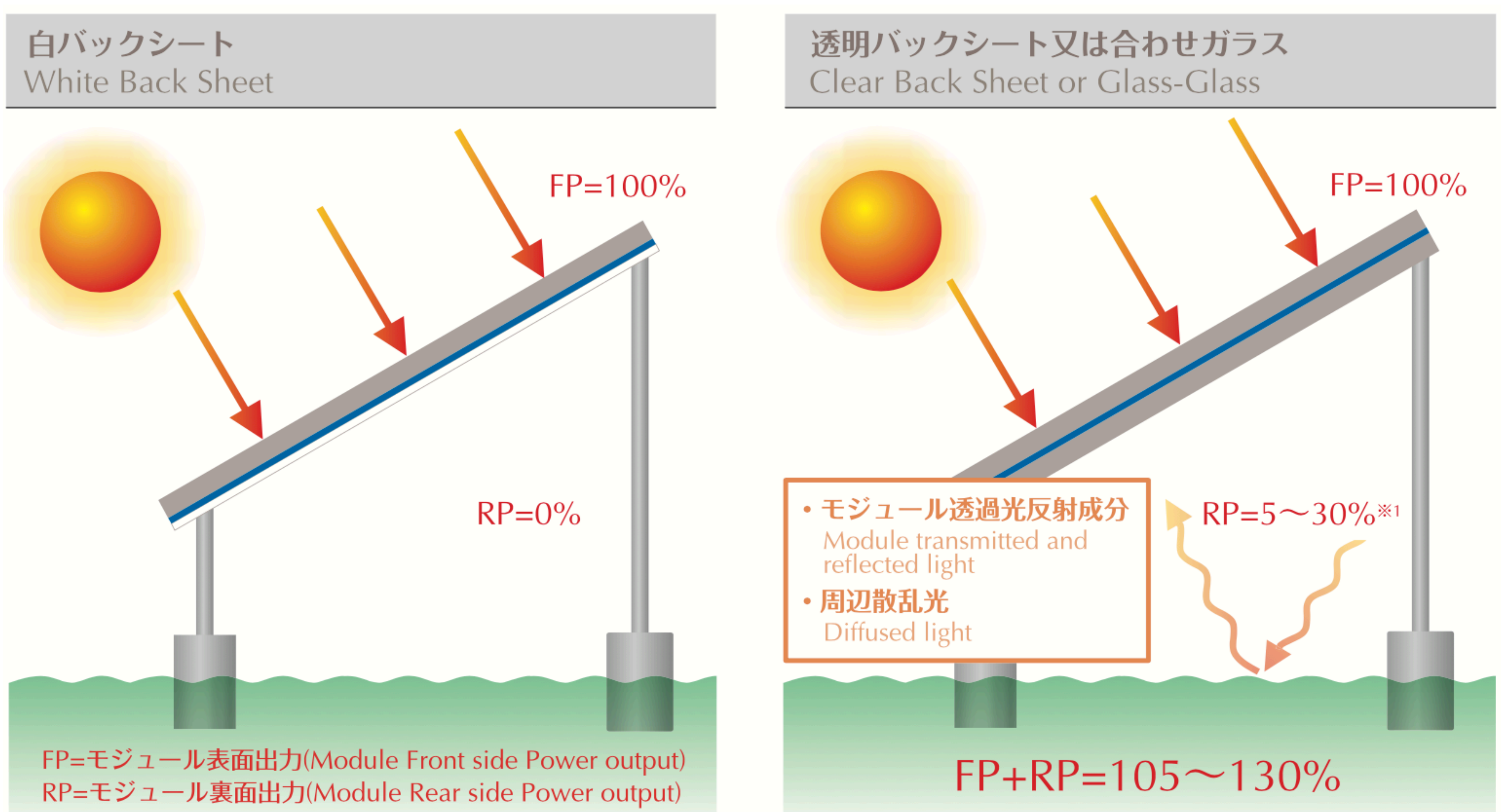
- Example: UNSW (Australia) new **4 junction cell**.
- **Efficiency 34.5%** (1 sun).



Source: UNSW

New solar cell architectures

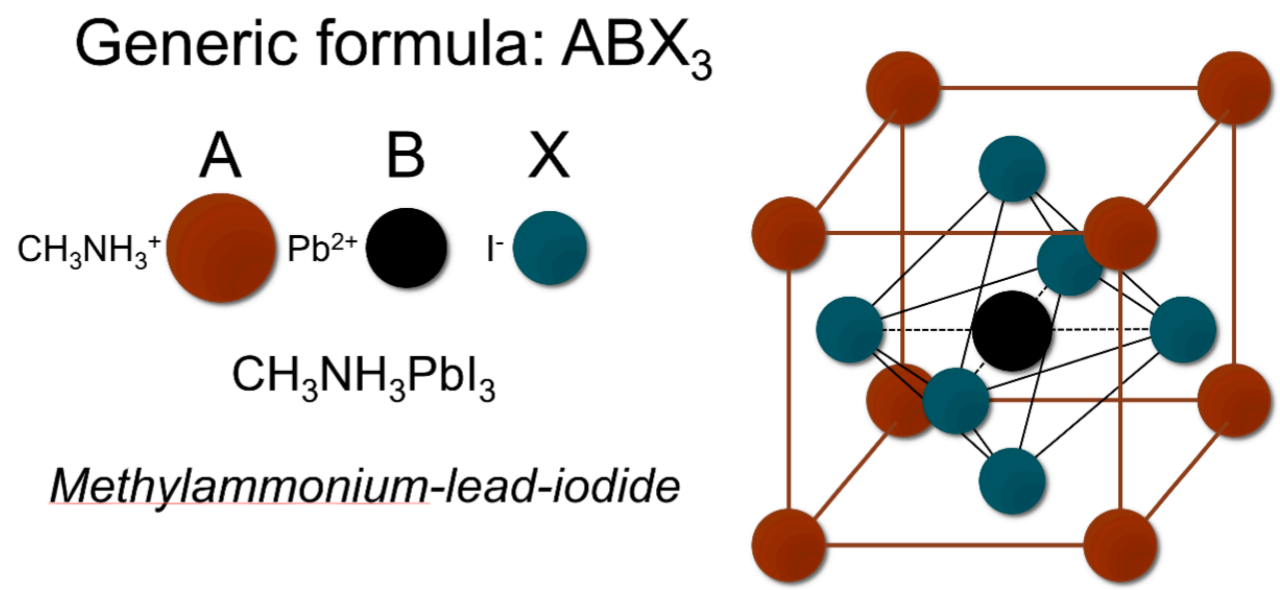
- **also simple solutions** from the past (1970s) … **bifacial cells / panels** allow to increase the amount of energy produced by up to 50% by capturing energy from light reflected to the rear of the panel.

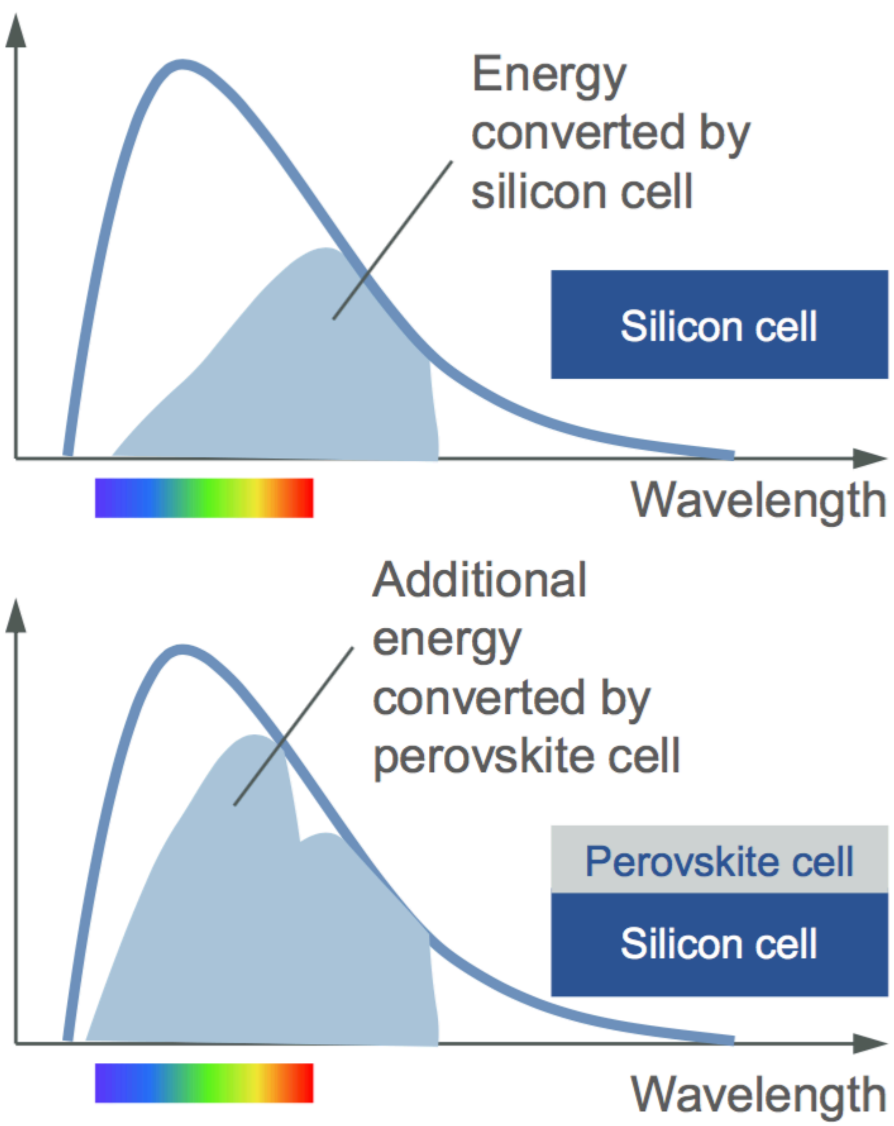


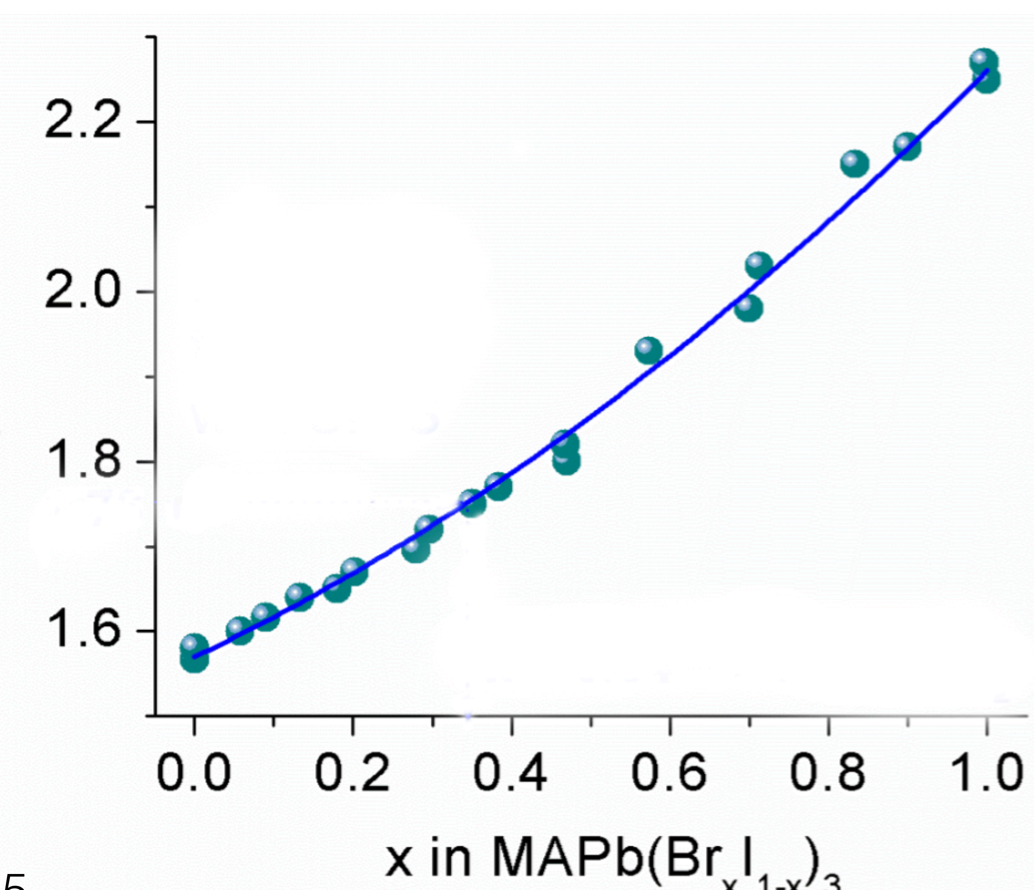
New solar cell materials

New solar cell materials

- **Perovskites**: modular band-gap energy between 1.57 eV and 2.23 eV depending on bromine or iodine presence: $CH_3NH_3Pb(Br_xI_{1-x})_3$.
- Excellent **coupling with silicon** that has a band gap energy of 1.1 eV.







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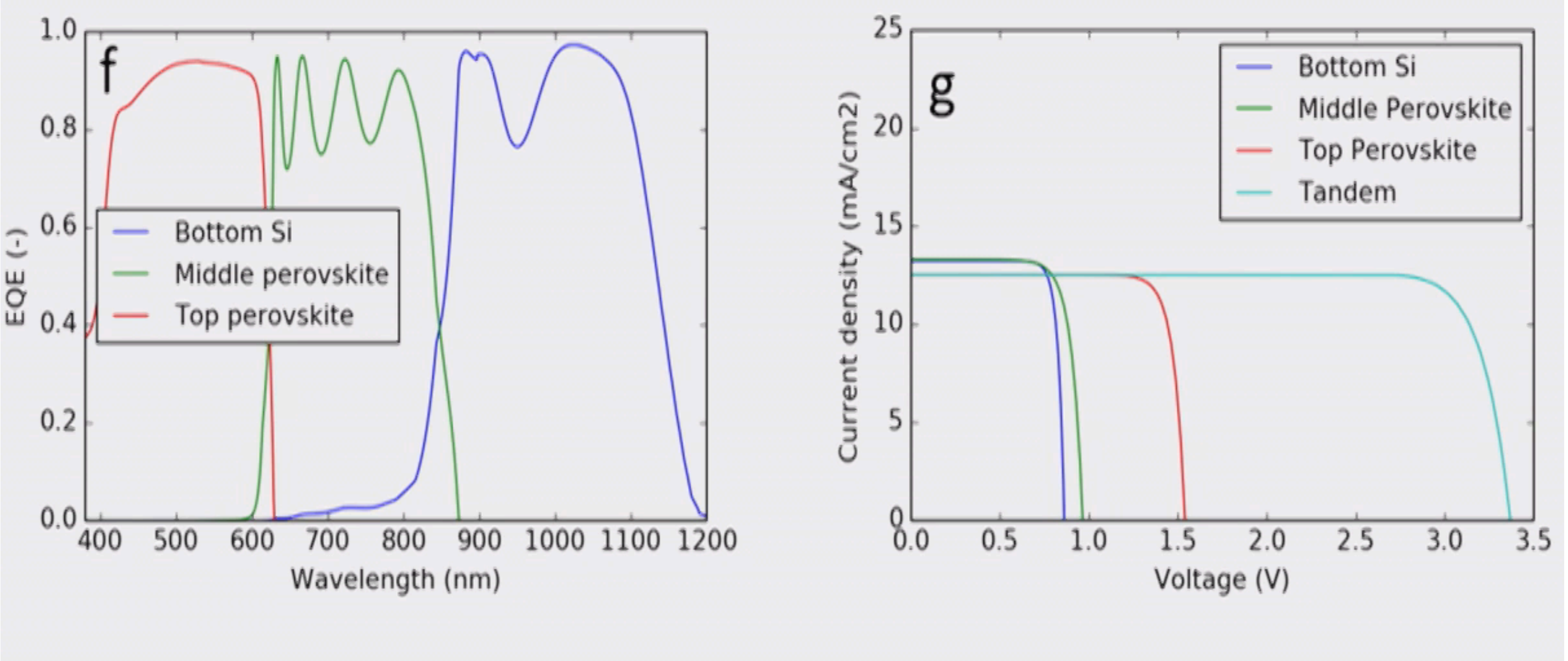
New solar cell materials

- Already a reality in the lab: tandem **silicon-perovskite** cell has reached **28%** efficiency (Oxford PV, 2018).
- Tandem **silicon heterojunction-perovskite** cell could reach **30% efficiency.**
- Triple junction **perovskite-perovskite-silicon** we could reach **35.5%** efficiencies.



"Theoretically" should give **35.5% efficiency**, with current single-junction cell performances

New solar cell materials

- Main **weakness of perovskites** is chemical and physical **stability** of the compound over time, and **defects** in the crystal lattice during manufacturing.
- But … promising research …

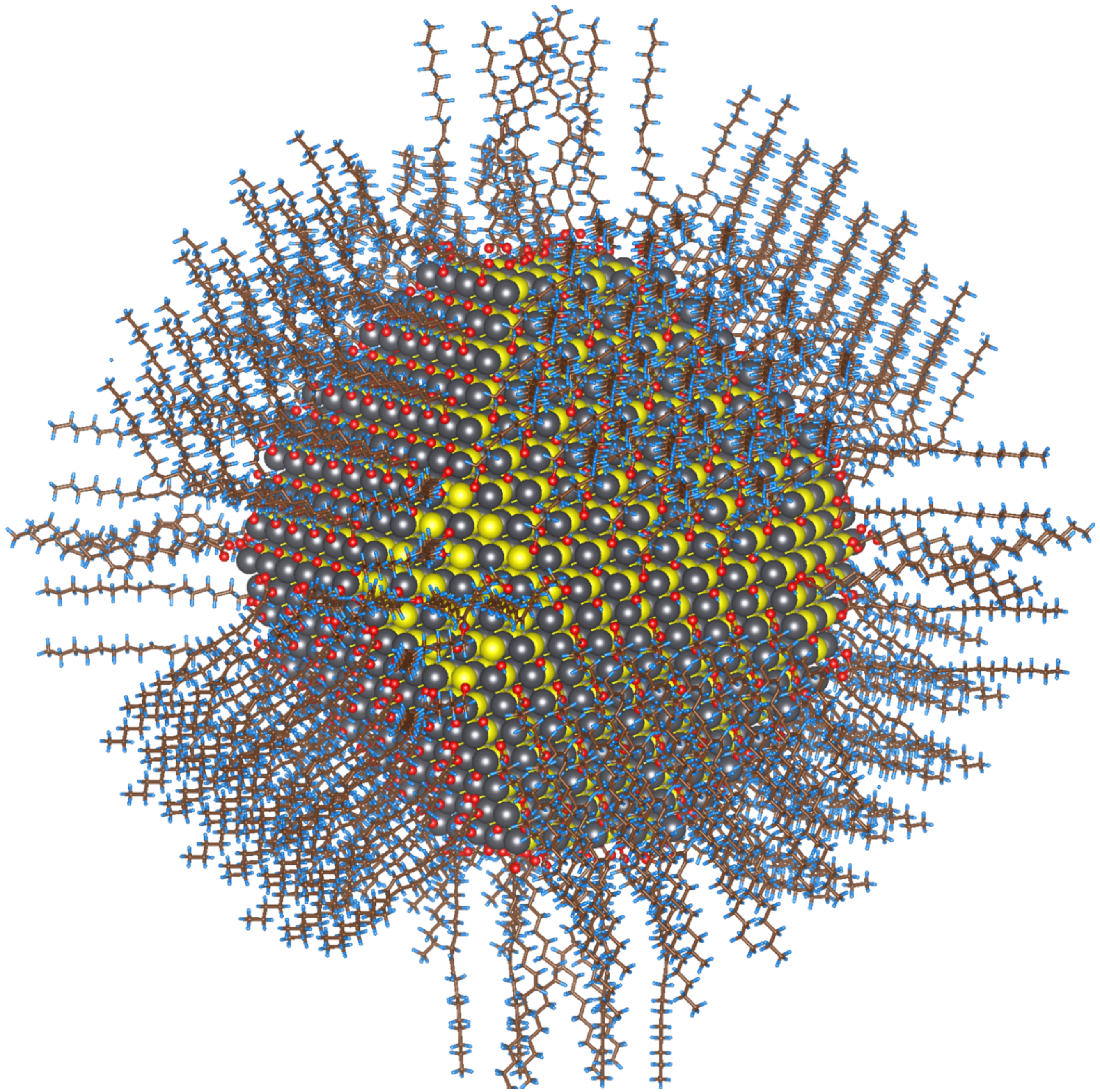
$MAPbI_3$ Self-Recrystallization Induced Performance Improvement for Oxygen-Containing Functional Groups Decorated Carbon Nanotube-Based Perovskite Solar Cells

*Jie Chen, Ti Chen, Tangliang Xu, Jia-Yaw Chang, and Keiko Waki**

- Tokyo Institute of Technology (10/2019) demonstrated **greater stability** of perovskites combined with Carbon Nanotubes.
- CNTs served to protect against moisture damage and **drove production of perovskites with fewer defects.**

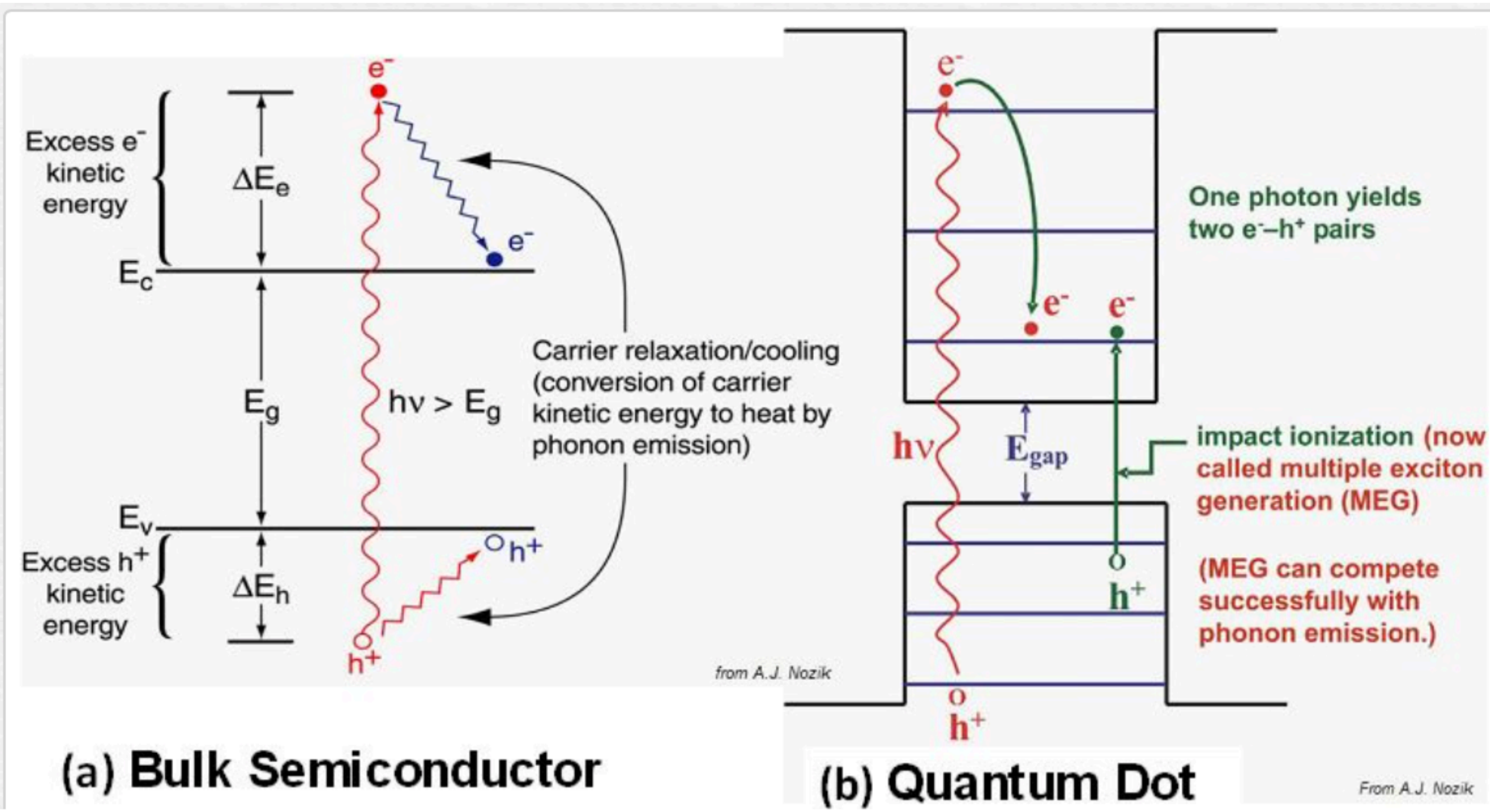
New solar cell materials

- In future: **Quantum Dots** (QD) are **nanocrystals of II-VI, III-V, or IV-VI group semiconductors**.
- Varying the QD dimension we can tune the band-gap energy thanks to the Quantum Confinement effect.
- So silicon for e.g. has a band-gap energy of 1.1eV while its nanocrystal equivalent can reach 1.5eV.
- So we can produce optimised QD materials **that could allow us to absorb the entire solar spectrum.**



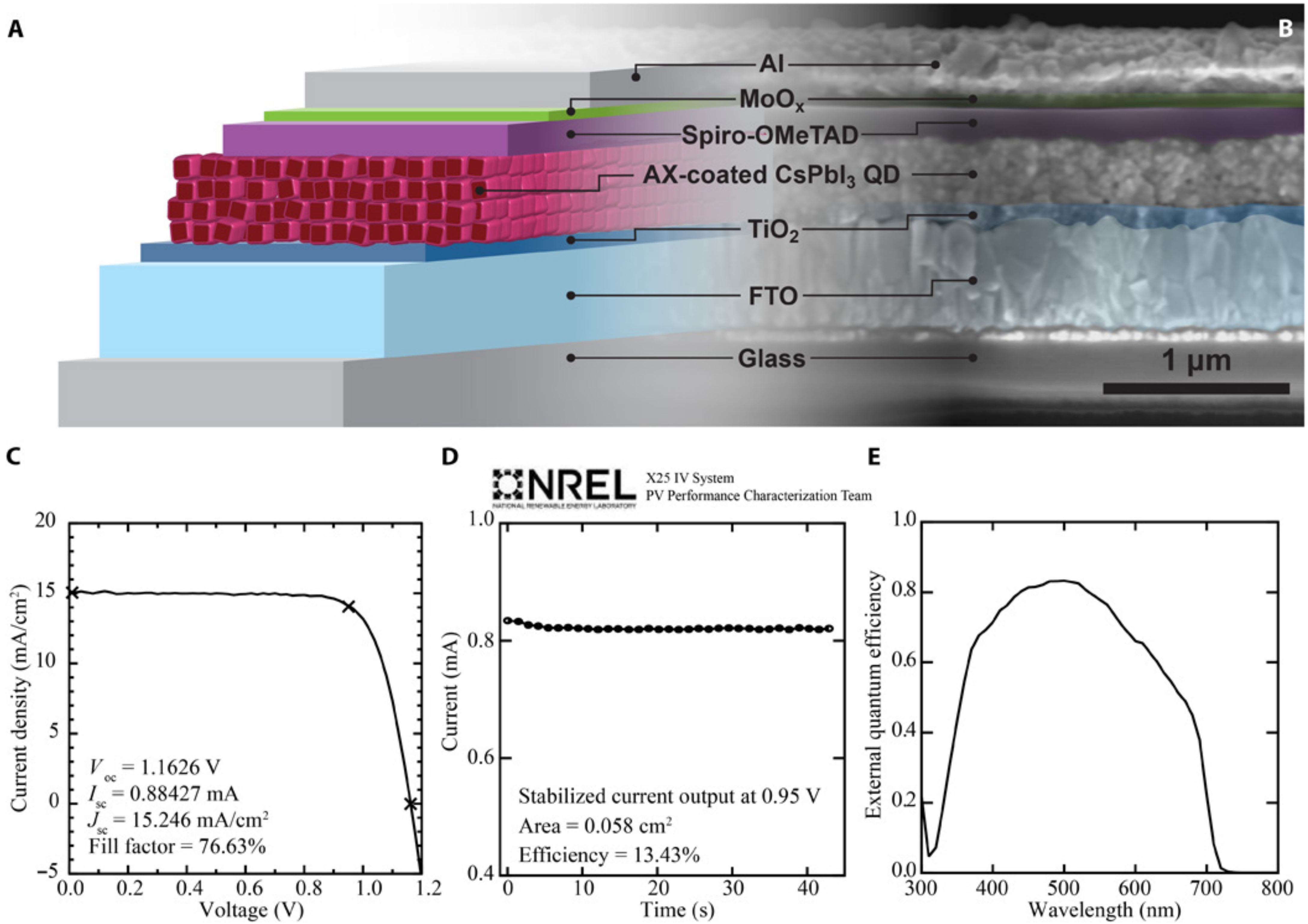
New solar cell materials

- Unlike bulk semiconductors such as crystalline silicon, **quantum dots can generate multiple exciton (electron-hole pairs) after collision with one photon of energy exceeding the bandgap.**
- In bulk semiconductor absorption of photon with energy exceeding the bandgap promotes an electron from the valance band to higher level in the conduction band these electrons are called hot carrier. The excited electron (hot carrier) undergoes non-radiative relaxation (thermalization: multi-phonon emission) before reaching the bottom of the conduction band. **However, in a quantum dot the hot carrier undergoes impact ionization process (carrier multiplication).** Therefore, absorption of a single photon generates multiple electron-hole pairs. This phenomena is called **multiple exciton generation MEG**. **Therefore, absorption of UV photons in quantum dots produces more electrons than near infrared photons.**



New solar cell materials

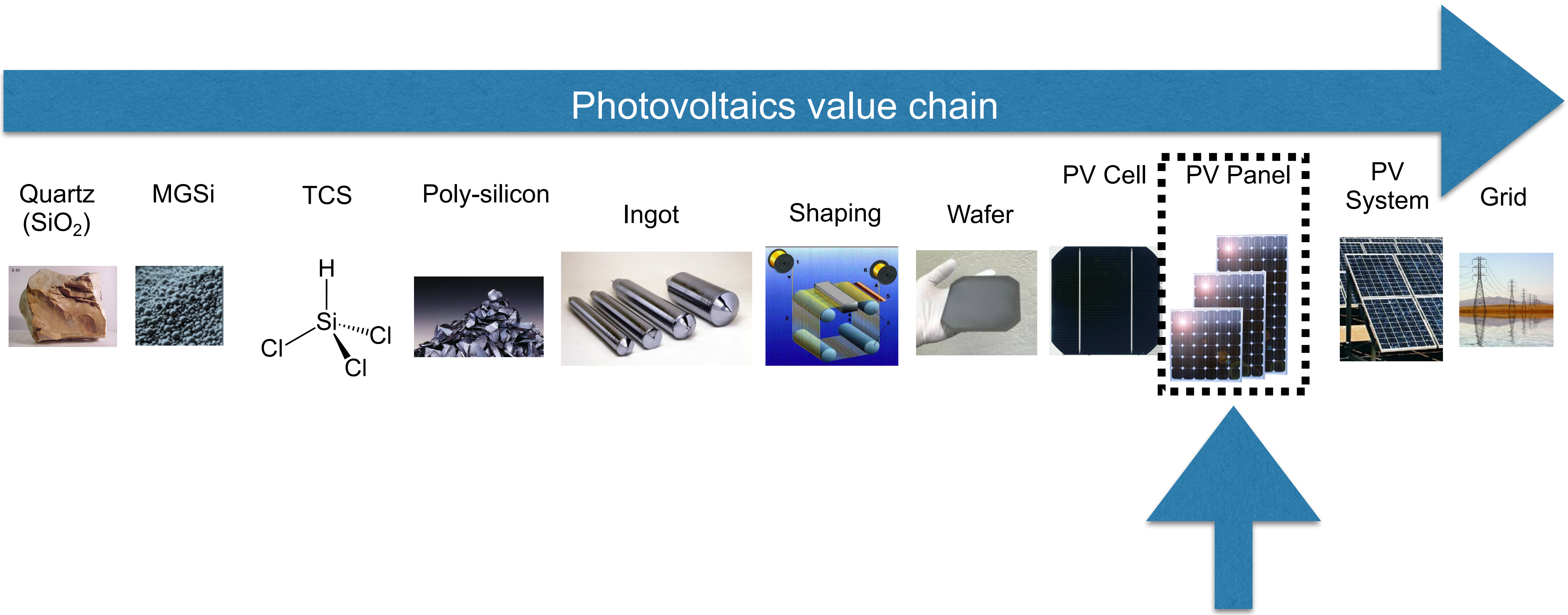
- **Cell record QD efficiency 13.4%** (in 2010 2.9%). NREL (USA).



Source: NREL

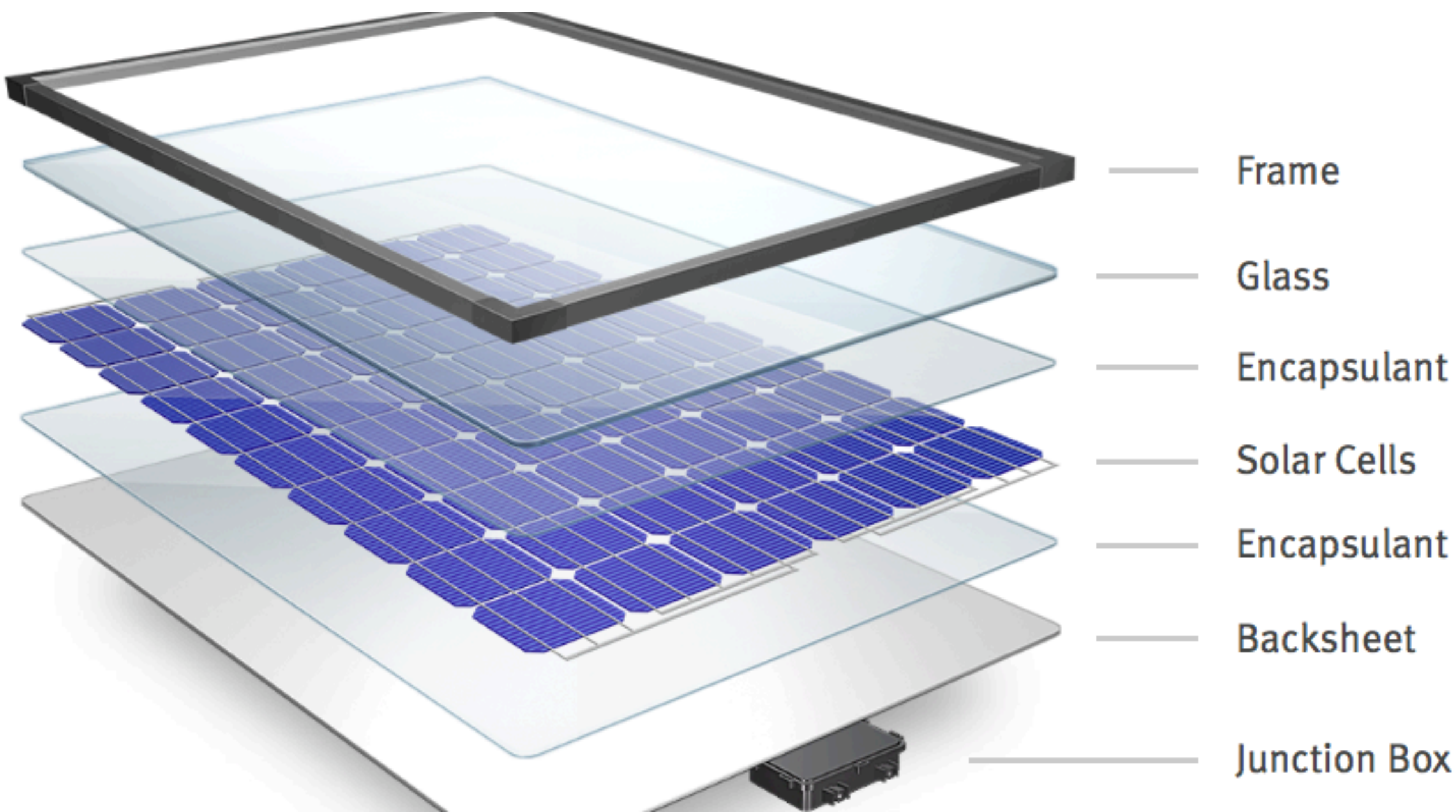
New packaging techniques, components, accessories

PV panel package



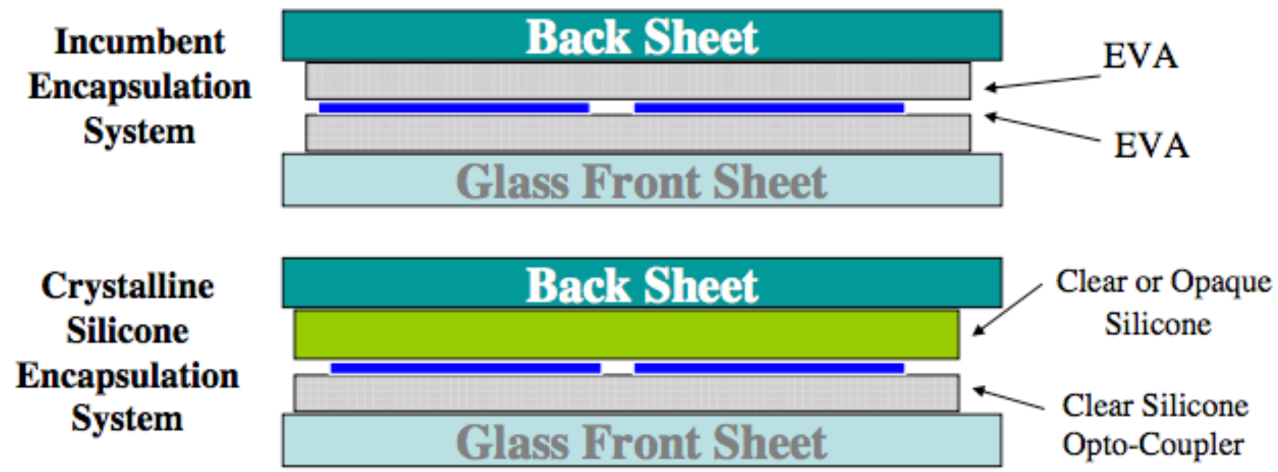
PV panel package

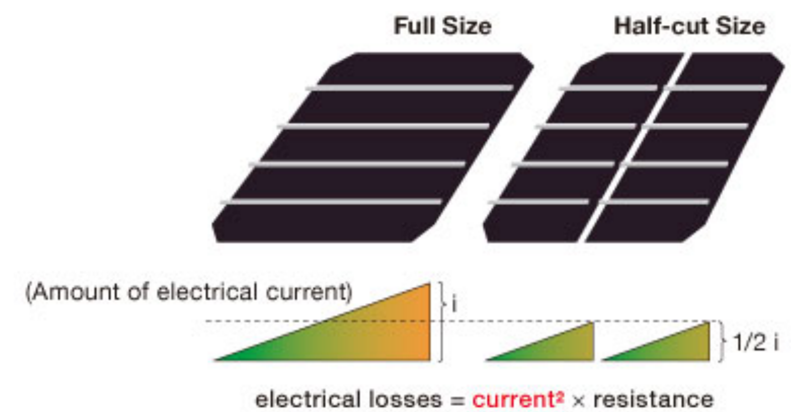
Panel encapsulation has been very stable for over 40 years … this is about to change … **fundamental for performance and durability.**

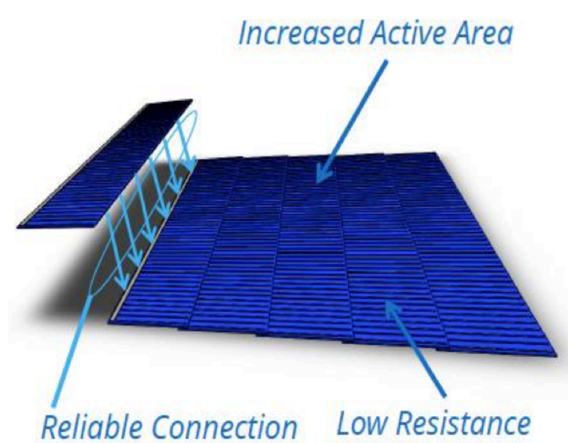


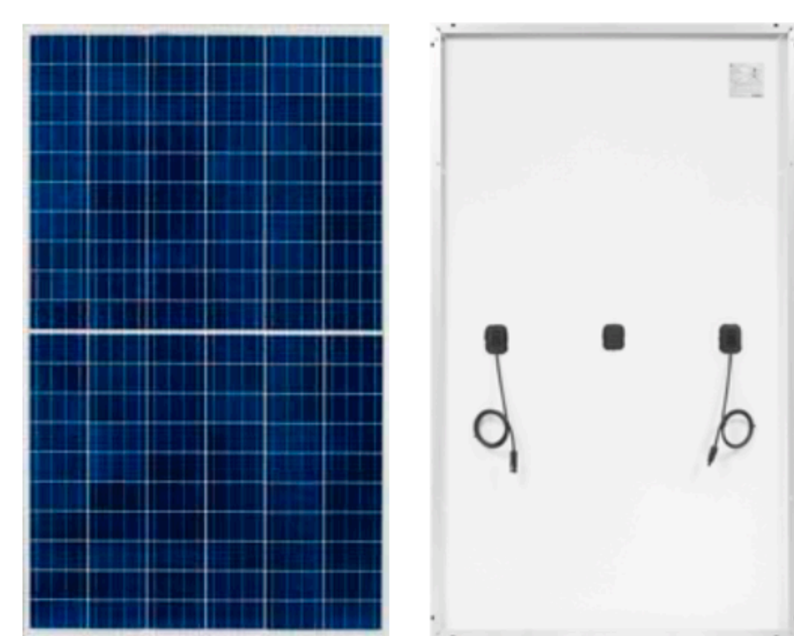
PV panel package

- **Glass covers:** thinner, advanced anti-reflective coatings.
- **Encapsulants:** Si–O bond much stronger than C–C bond, UV resistant, better moisture resistance, lower temp process.
- **Half - cut cells:** lower resistance losses, increases efficiency during maximum irradiation (1.5-3% gain).
- **Cell interconnection:** using conducting adhesives, lower resistance losses.
- **Separate junction boxes:** shorter cables lowers resistance, lower operating temp.









New manufacturing technologies

New manufacturing technologies

- **Unchanged PV value** chain since 1970s …

- relatively complex and capex intensive.
- No major innovation for 50 years.

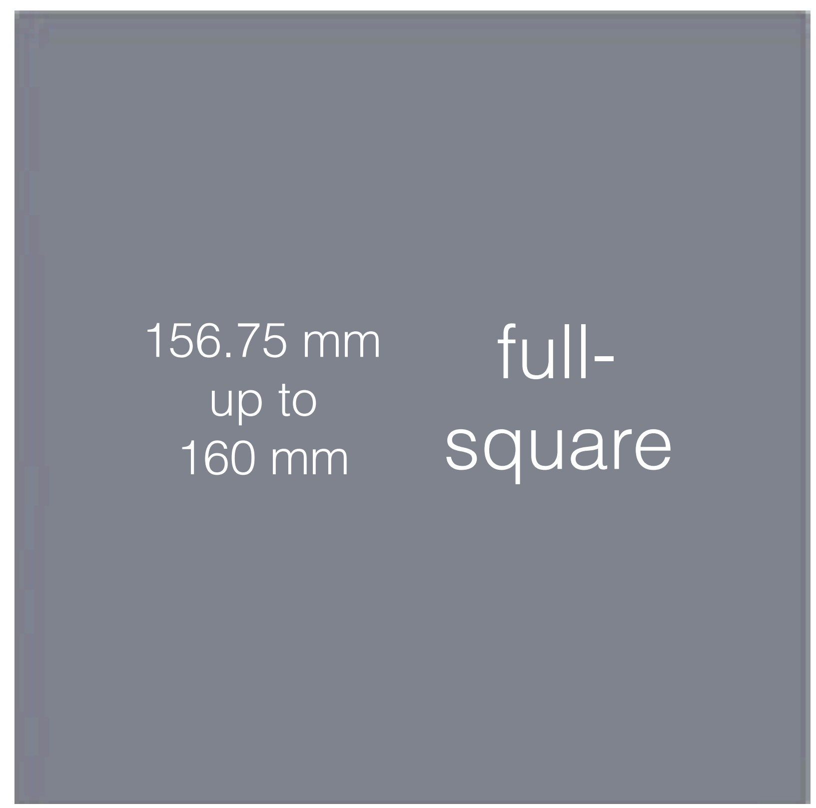
New manufacturing technologies

- Production technologies from the semi-conductor industry may **revolutionise PV manufacturing in future** …

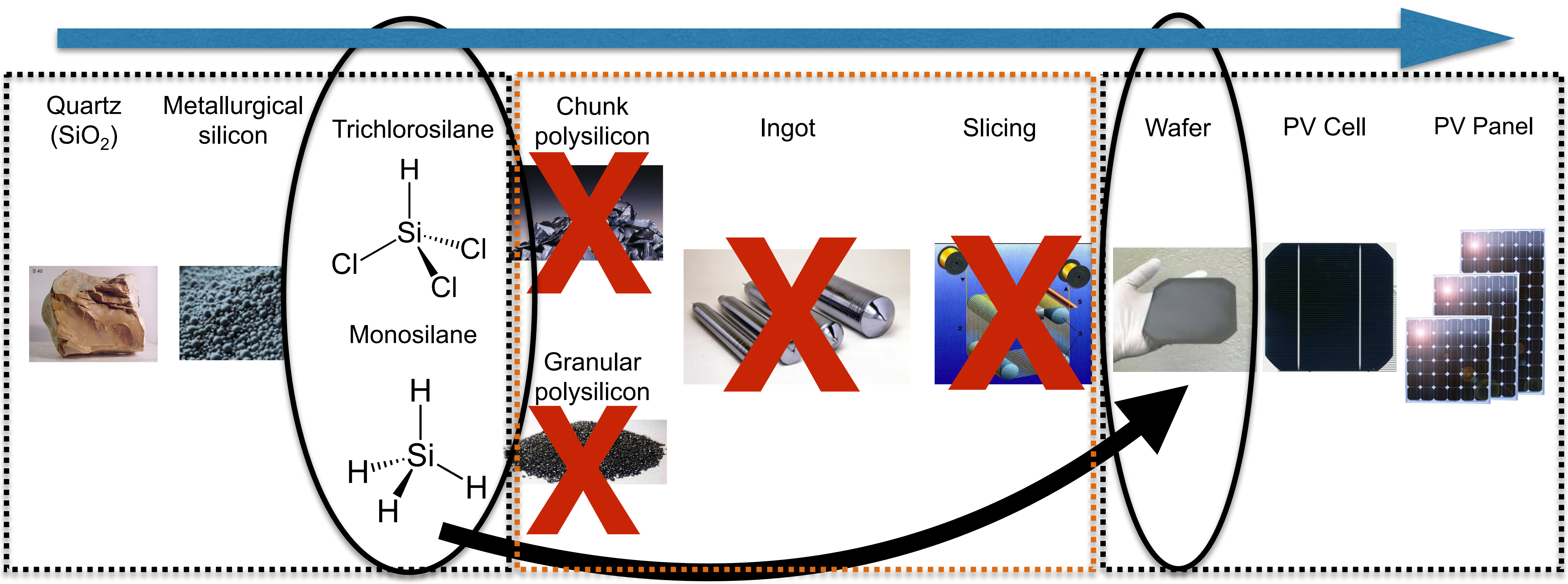
from TCS to ….

direct

mono crystal wafer



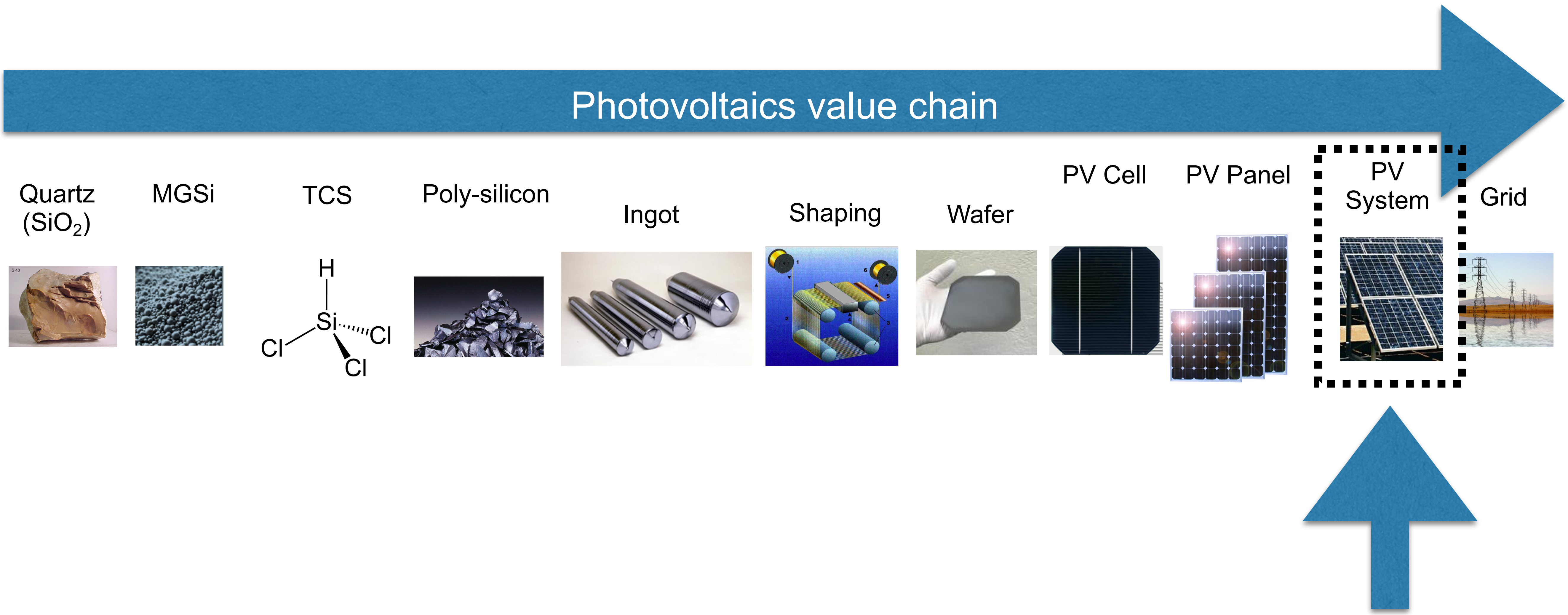
New manufacturing technologies



- **Significant advantages:**
  - lower capex, lower operating costs
  - better performing wafers
  - downstream advantages in cell processing

PV system design and management

PV system design and management

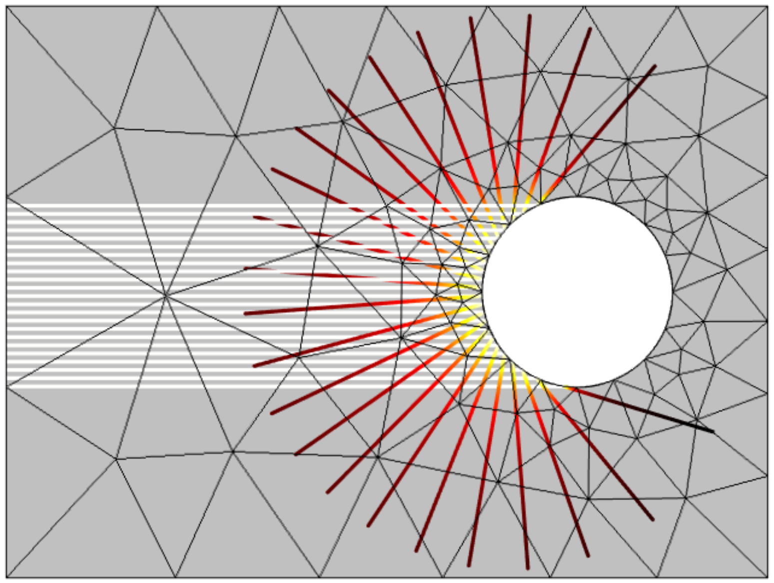


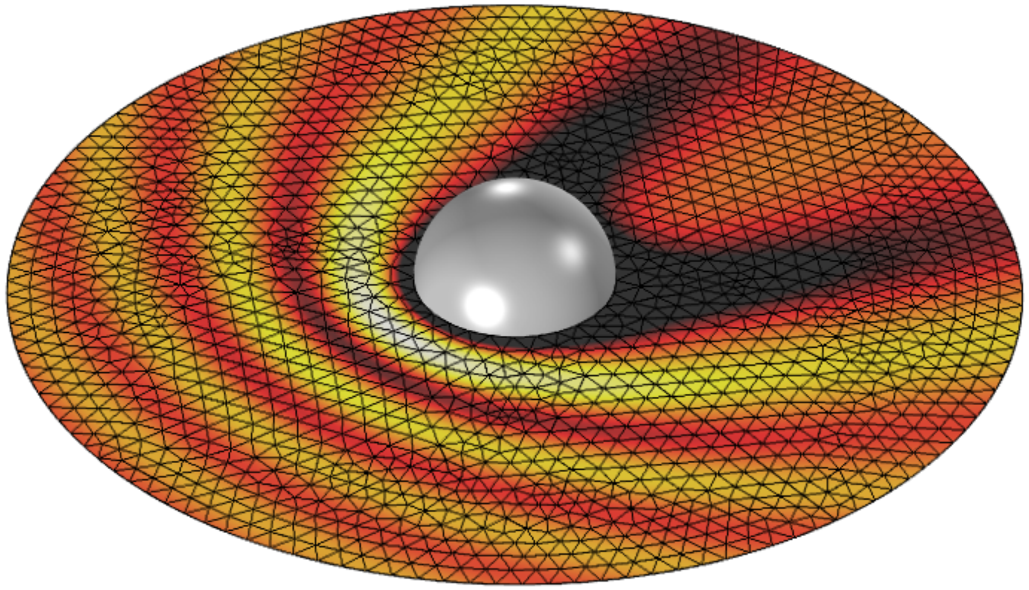
PV system design

- One of the problems for PV system designers is to **optimise the design of a PV system and predict how much energy it can deliver.** This was always a relatively complex non-linear problem.
- Now **significantly more complex** with bifacial PV modules which are now de-facto standard for utility scale systems.
- Unlike front side irradiance, which is relatively easy to model, **rearside irradiance varies significantly** with albedo, position, array design, and near field objects such as combiner boxes and racking.

PV system design

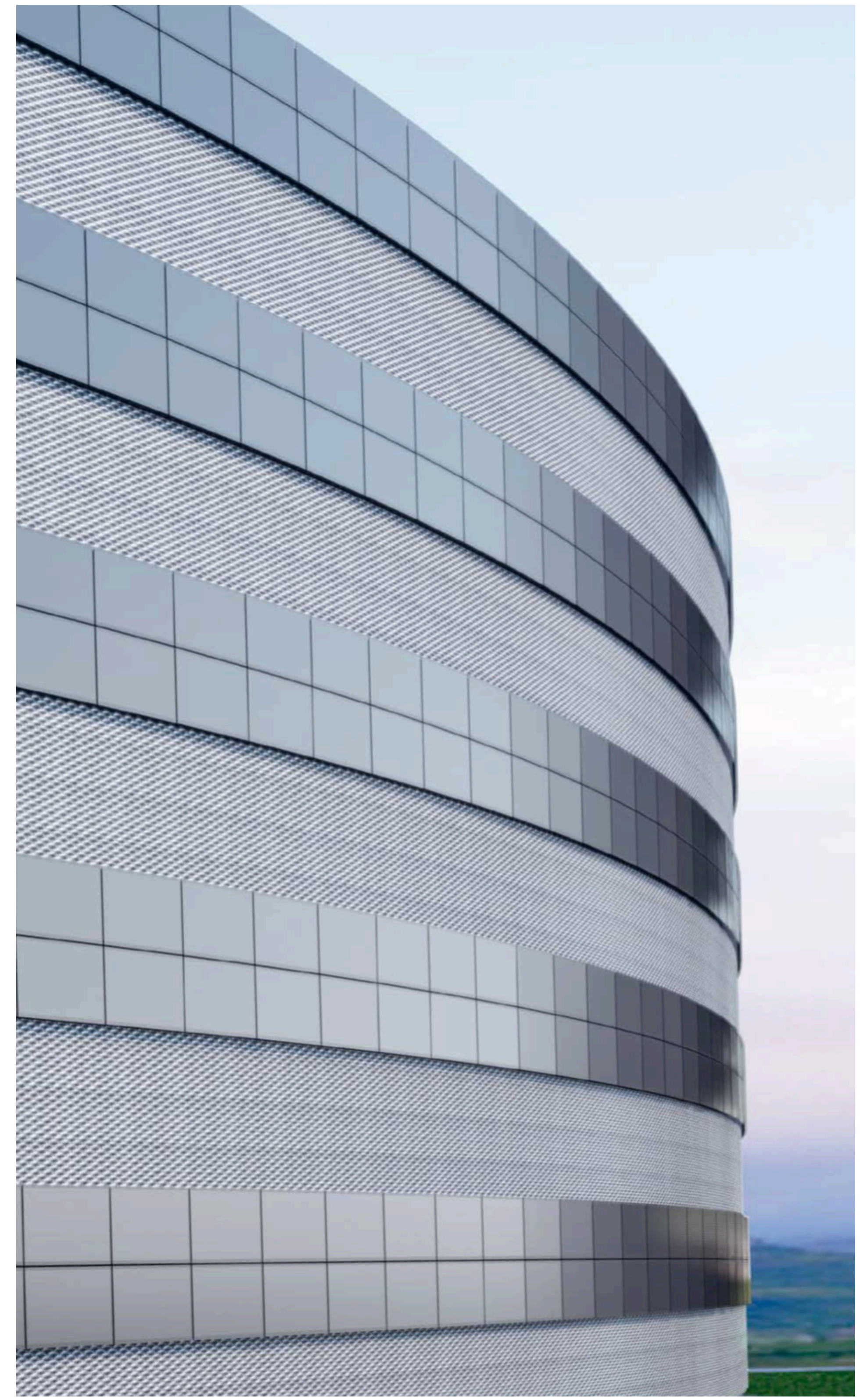
- Several approaches being developed which fundamentally rely on **ray tracing work** done in other fields for example using **a finite element method (FEM) to model electromagnetic wave propagation.**
- Because it is not necessary to resolve the wavelength with a finite element mesh, ray trajectories can be computed over long distances at a low computational cost.
- **Rays can also undergo reflection and refraction** at boundaries between different media.
- **There are other approaches such as View Factor models** …
- Requires new skills not found in traditional PV industry.





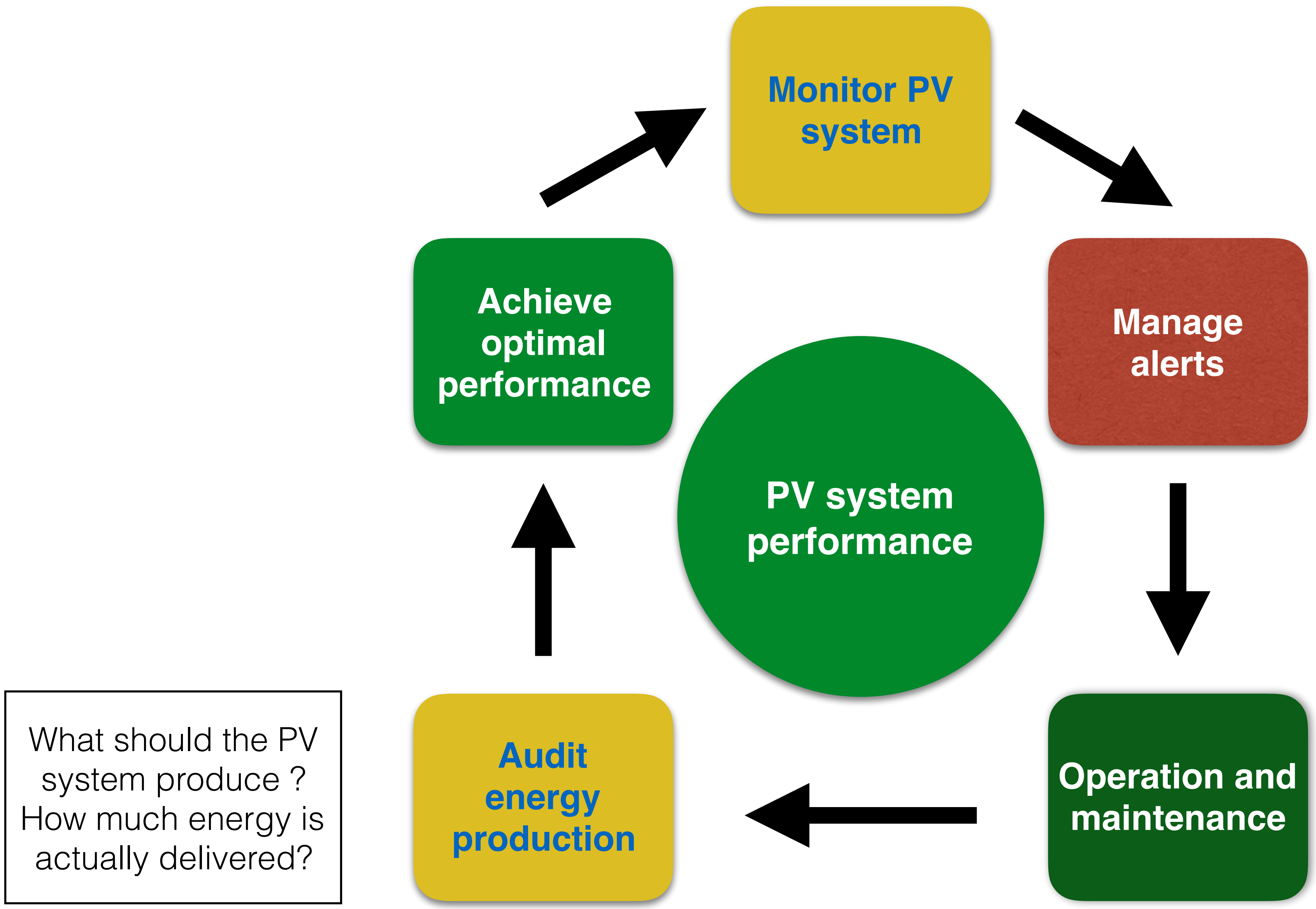
PV system design

- Exciting possibilities for **architectural PV - BIPV** - building-integrated-photovoltaics.
- building envelopes
- windows with variable transparency
- a keystone for **Nearly Zero Energy Buildings** (NZEBs)
- **linking multiple smart buildings** help spread smart grid technology
- **real-time** thermal or lighting regulation



PV system management

- **PV system design and operational management are critical to performance (LCOE)** and some aspects lend themselves to solutions by machine learning using artificial neural networks.
- **AI is finding rapid application in the operations and maintenance (O&M) cycle** which is critical to optimise energy production.



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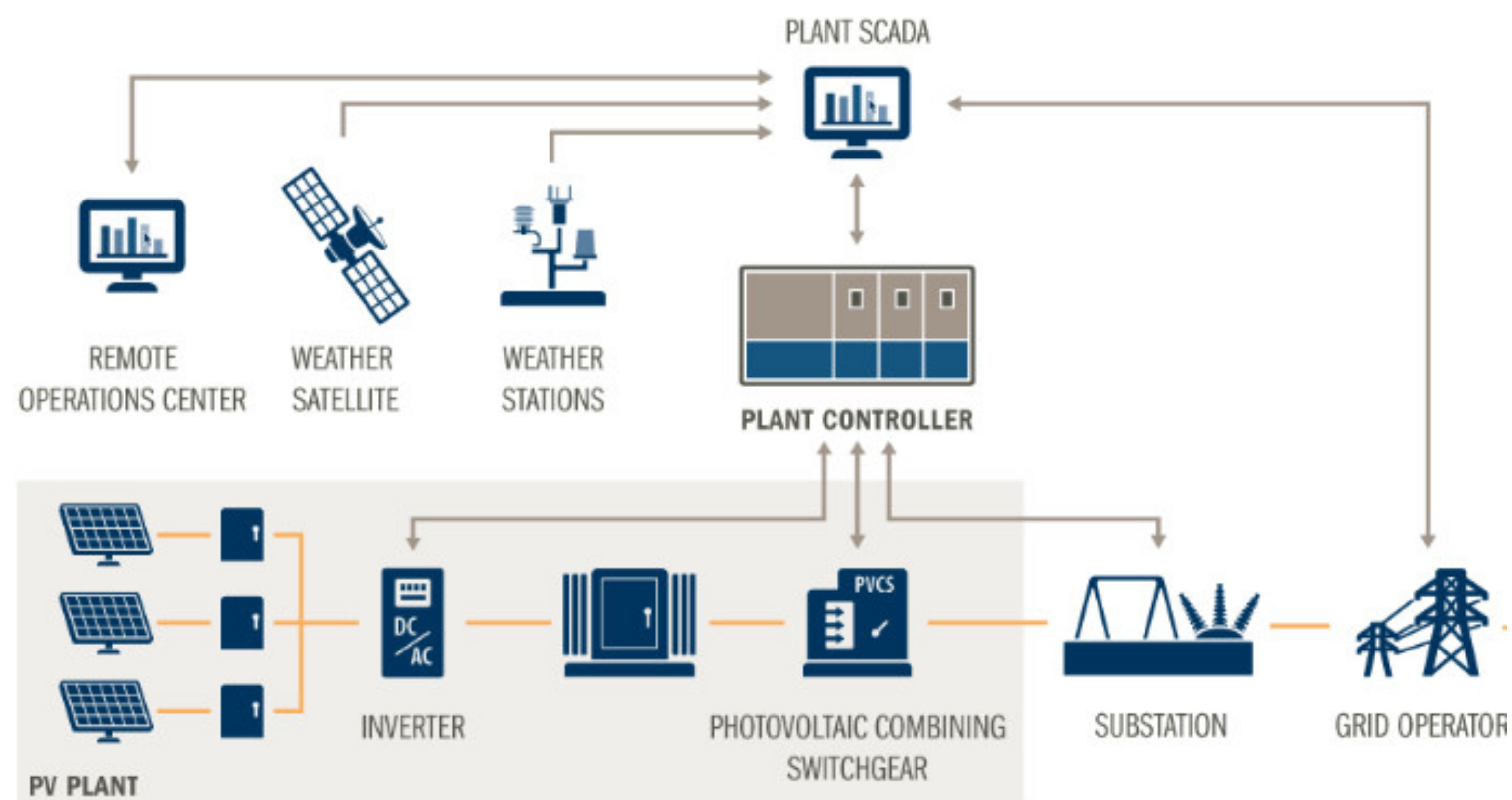
PV system management

The PV management system must be **able to rapidly detect a diverse range of parameters and faults from diverse sources** and offer solutions for rapid problem resolution:



Broken glass	**Soiling**	**Uncontrolled weed growth**	**Shading**	**Hotspots**

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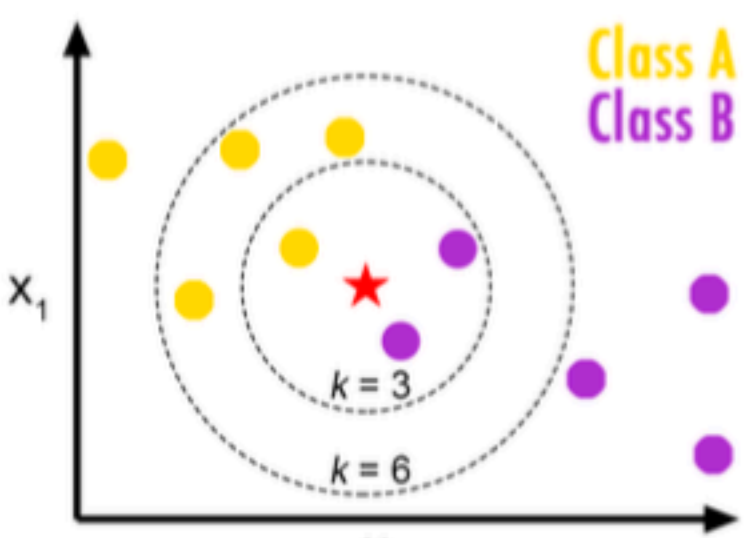
PV system management

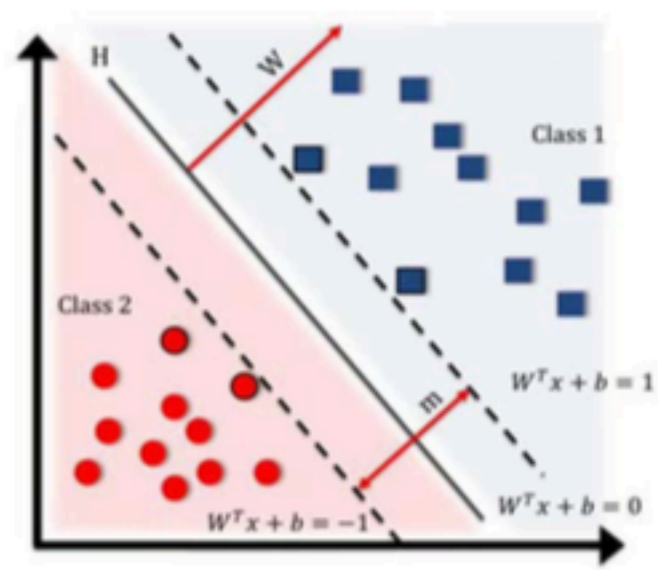
- Systems now take data from a supervisory control and data acquisition (SCADA) platform combined with **algorithms that employ supervised and un-supervised learning to precisely determine faults within the PV array.**

Failure classification stage – Supervised Learning

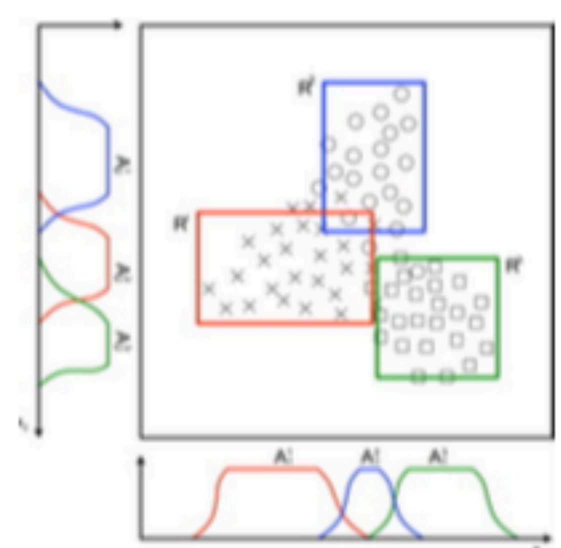
- Supervised learning processes (K-NN, SVM and FIS)
- Accuracy Metric – Binary confusion matrices



k-Nearest Neighbors (k-NN)



Support Vector machine (SVM)



Fuzzy inference Systems (FIS)

Grid integration

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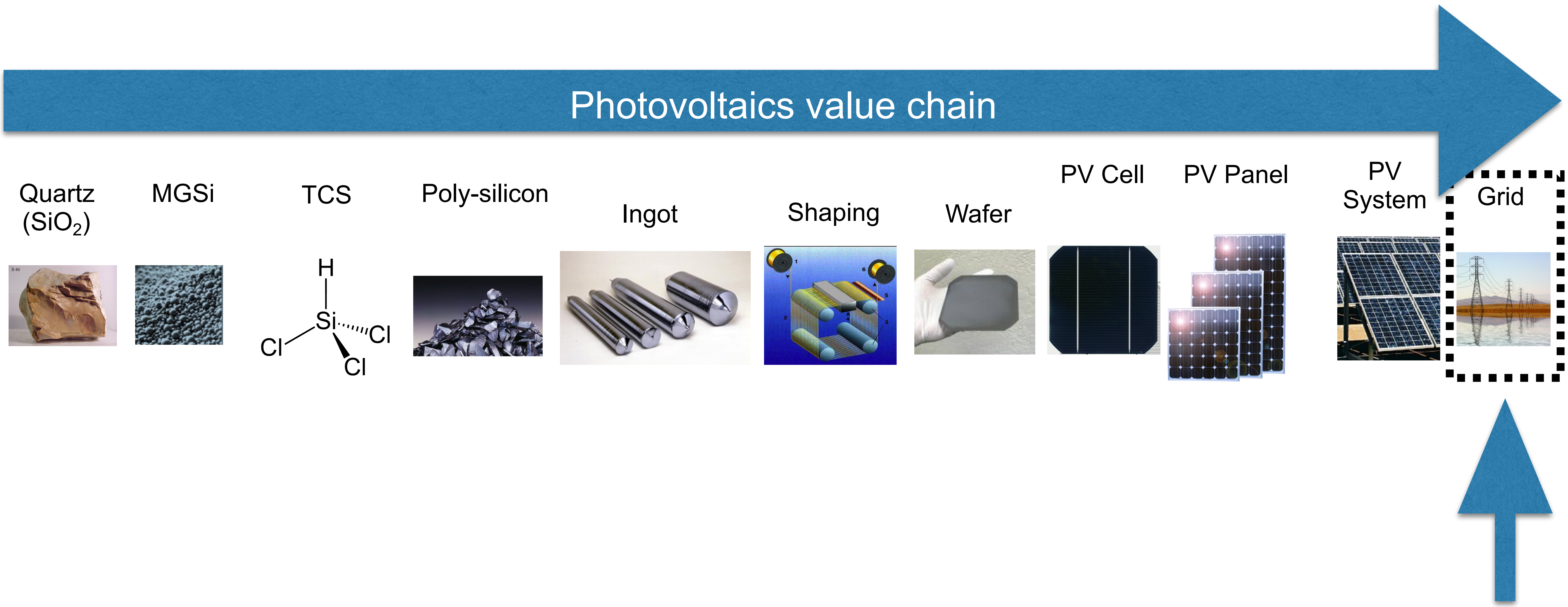
Grid integration



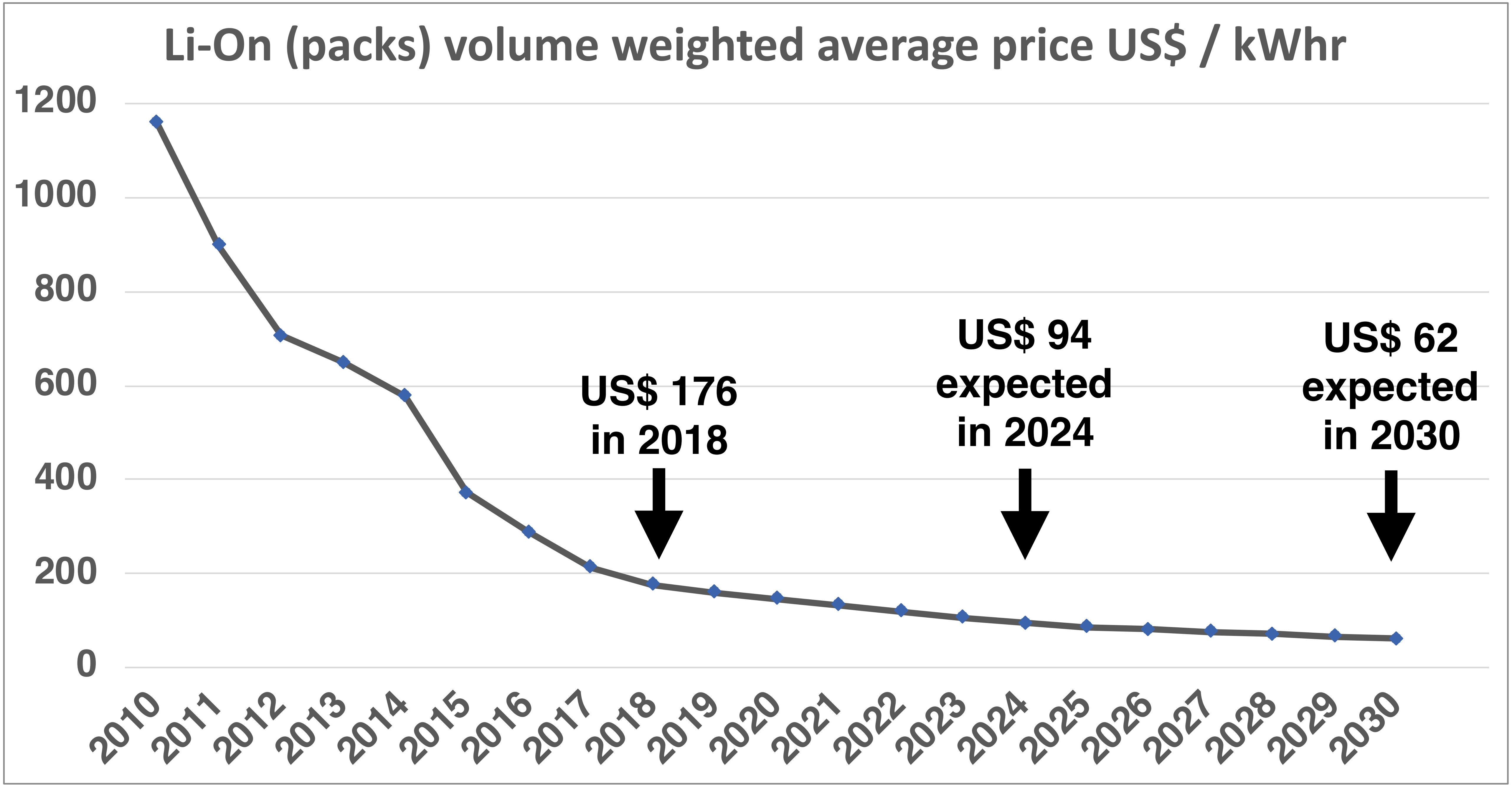
Grid integration

- Renewables and PV in particular are the quintessential **enablers of the grid of the future.**
- Clean, distributed generation matches distributed demand.
- **PV is scalable** from a 300W panel to multi-GW.
- Compatible with **a future smart, peer-to-peer, energy system.**

Grid integration

- A system with high % of RE offers many opportunities.
  Grid management issues - classical and new:
  - Supply & demand management
  - Metering, billing, security
  - Frequency regulation
  - Spinning/Non-spinning reserves
  - Resource adequacy and reserve management
  - Peer-to-peer energy trading
  - Energy arbitrage
  - Green certificates & Carbon trading
  - Integration with growing EV infrastructure …
- Many tools now … smart-grids, **storage, blockchain, AI, machine learning, IoT, smart-devices,** …

Li-on battery packs falling in price by virtue of increased production scale, incremental innovation:



Source: Bloomberg New Energy Finance

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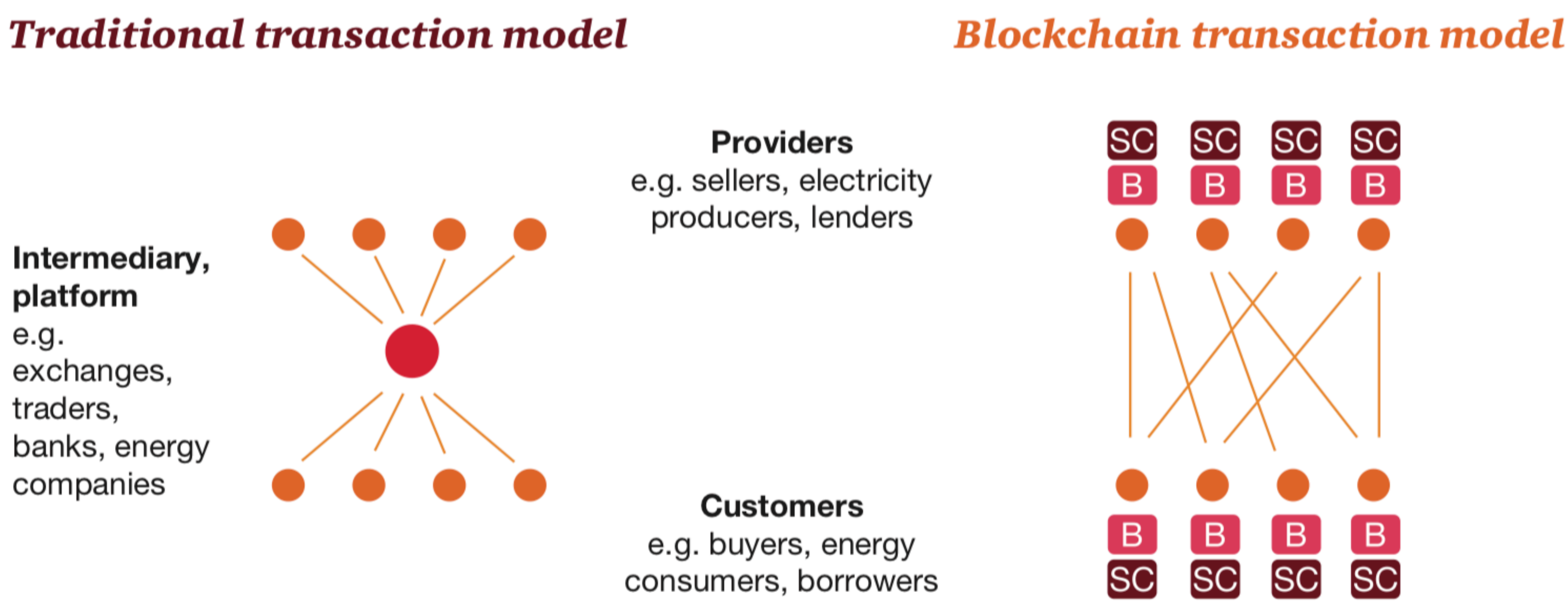
Grid integration

- **Over 140 blockchain** initiatives in the energy sector.
- **Well matched with PV** given inherent decentralised generation, enabling peer-to-peer energy exchanges.



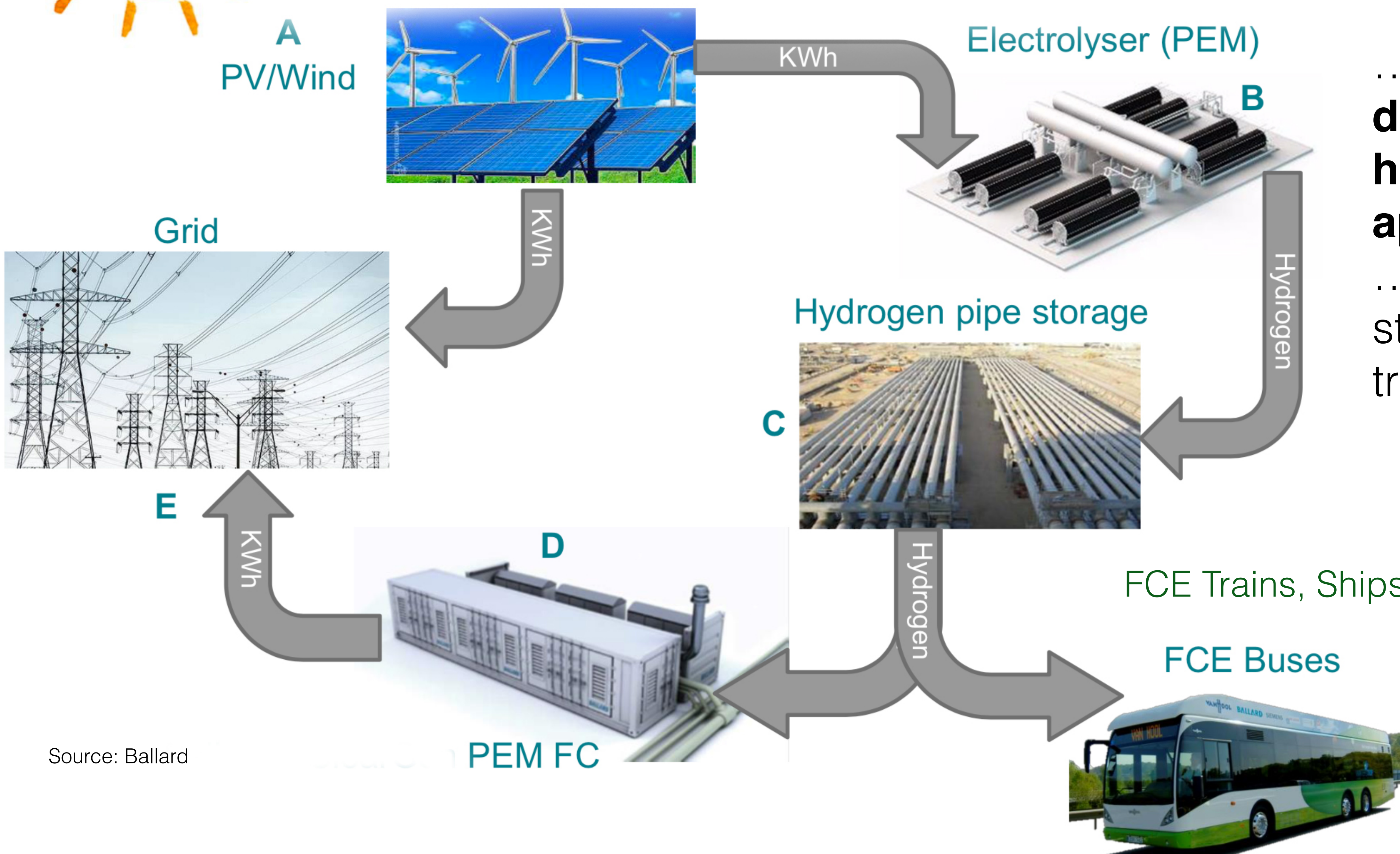
Grid integration

In future plentiful supplies of cheap, green hydrogen from **near zero marginal cost renewable energy.**

Source: Ballard

Grid integration

Beyond batteries … **the solar-hydrogen economy** … because hydrogen is a large scale, ideal, energy vector.



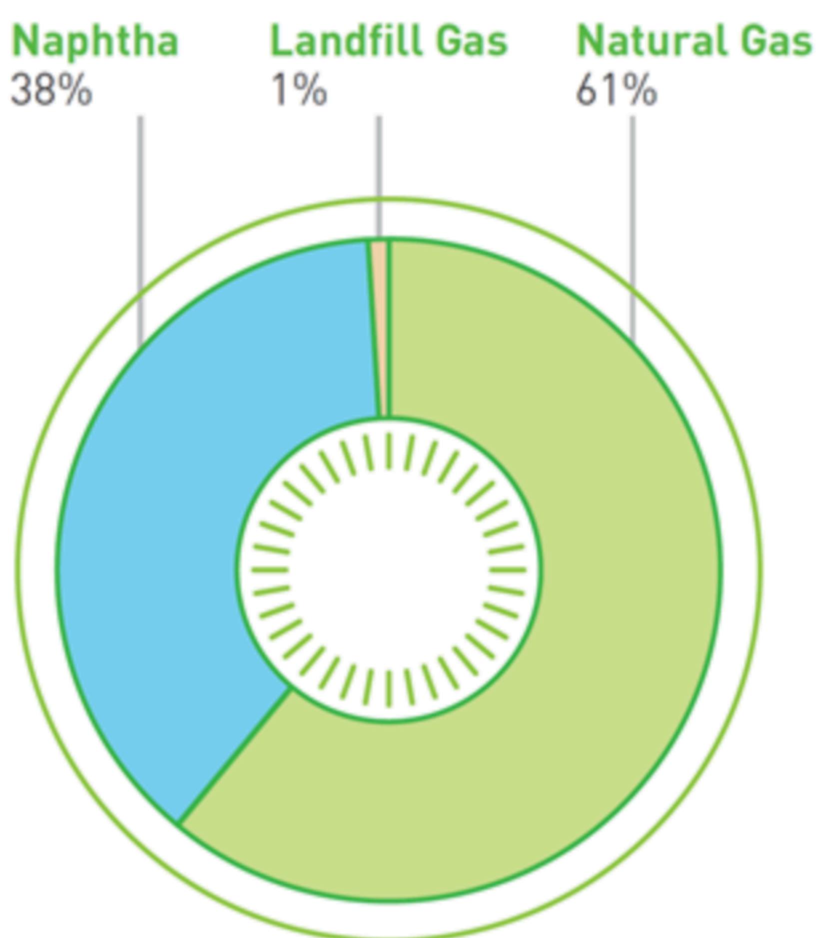
… essential **to decarbonise heavy duty applications**: … large scale storage, tranportation.

Source: Ballard

Grid integration

Many H_2 applications … for example … in Hong Kong **Towngas already contains 51% hydrogen**, and is synthesised from Natural Gas and Naphta. **Easy switch to green hydrogen could decarbonise 50% of H.K.'s gas energy sector.**

Fuel Mix for Town Gas Production



Chemical Composition

Carbon Dioxide	16.3% – 19.9%
Carbon Monoxide	1.0% – 3.1%
Methane	28.2% – 30.7%
Hydrogen	46.3% – 51.8%
Nitrogen and Oxygen	0% – 3.3%

Source: Towngas website

Summary
The future of PV at a glance

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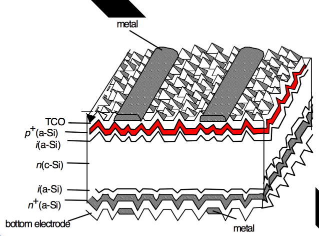
The future of PV at a glance

PV device architectures



New materials

Manufacturing tech and scale

Storage, AI, ML, P2P, blockchain

Politics ? Fossil fuel oligopolies ?

Factors driving average global 24h PV LCOE, likely < US$ 0.01 / kWh by 2030

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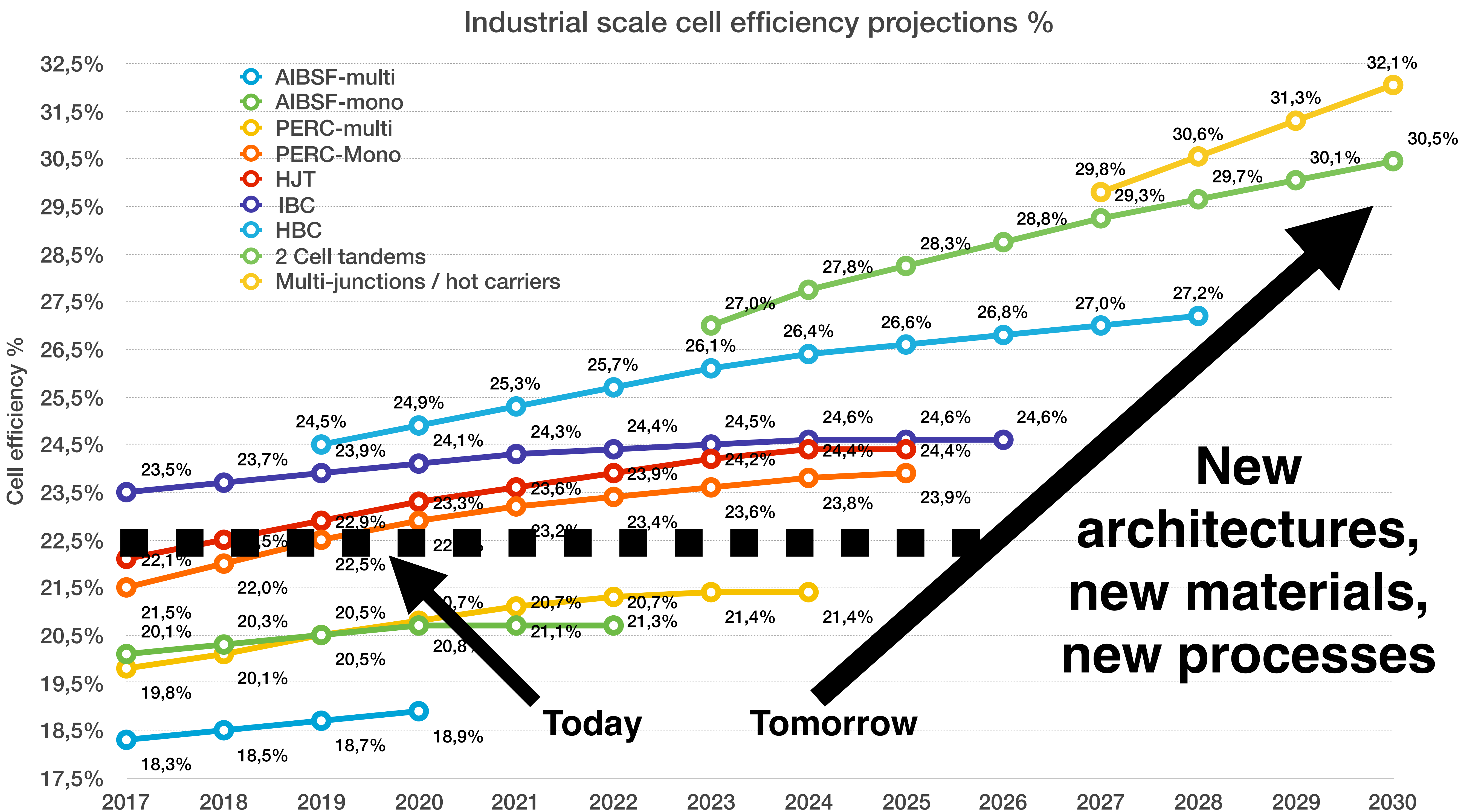
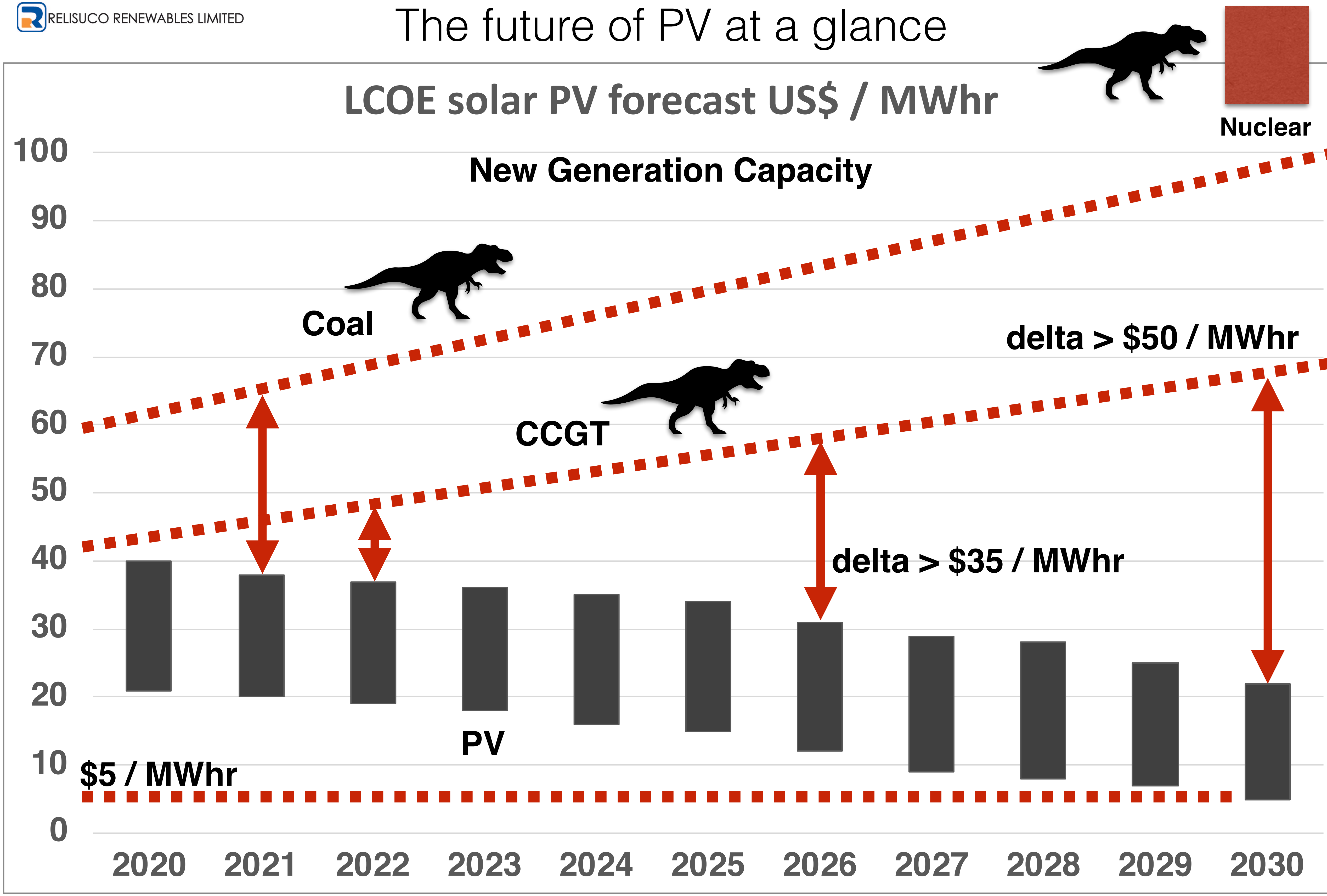
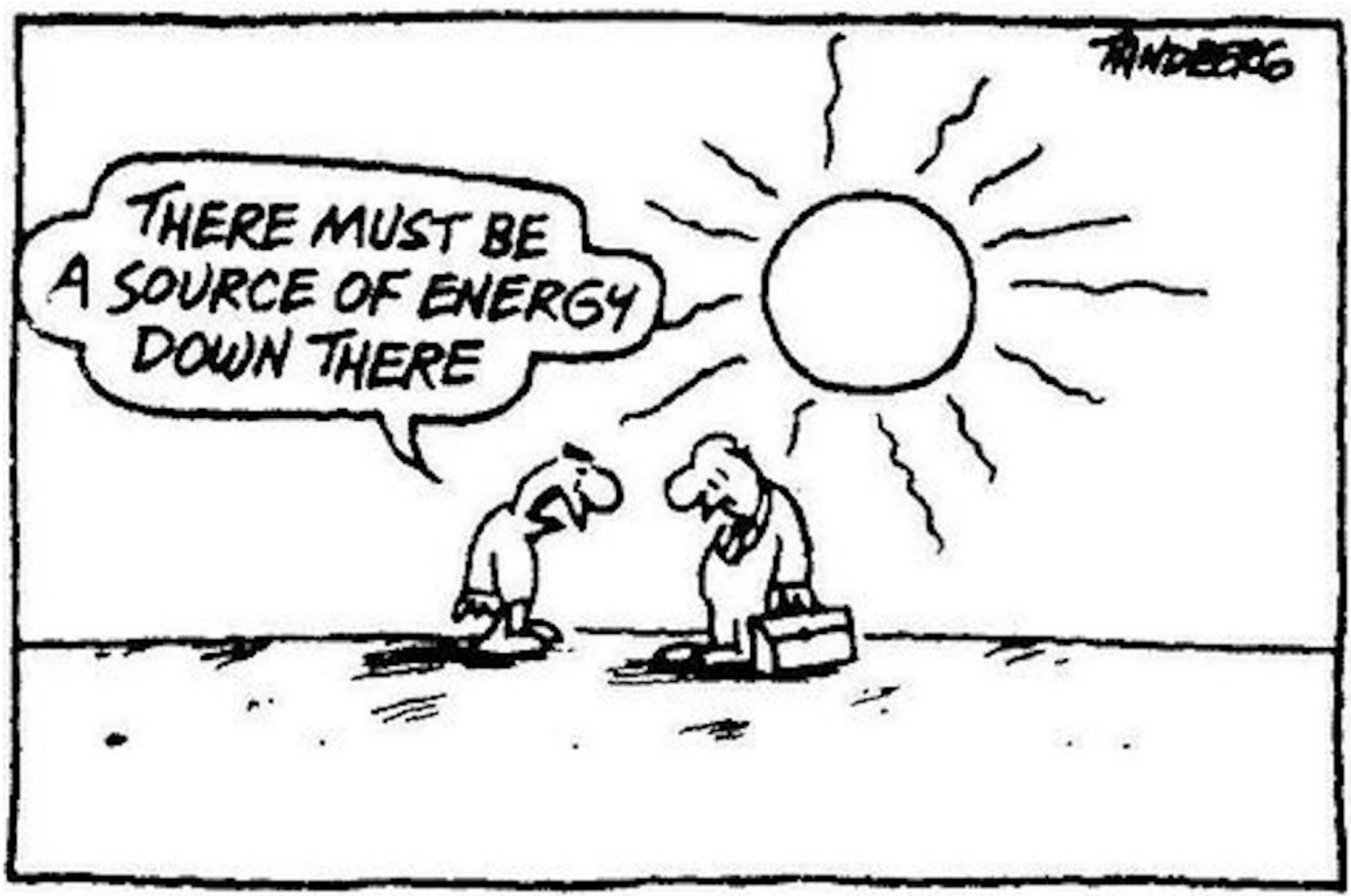
The future of PV at a glance

Likely **evolution of solar cell efficiencies to 2030** …



The future of PV at a glance




THERE MUST BE A SOURCE OF ENERGY DOWN THERE
TANDBERG

Thank you.

Michele Bina
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