Photovoltaics Sustainability: Insights and Perspectives

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Seminar at the UNSW
December 11, 2023

Center for Life Cycle Analysis
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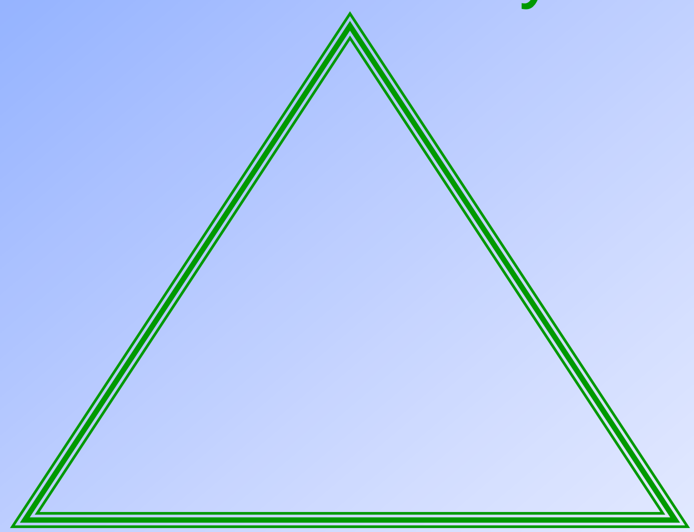
Photovoltaics –Sustainability Criteria

Affordability

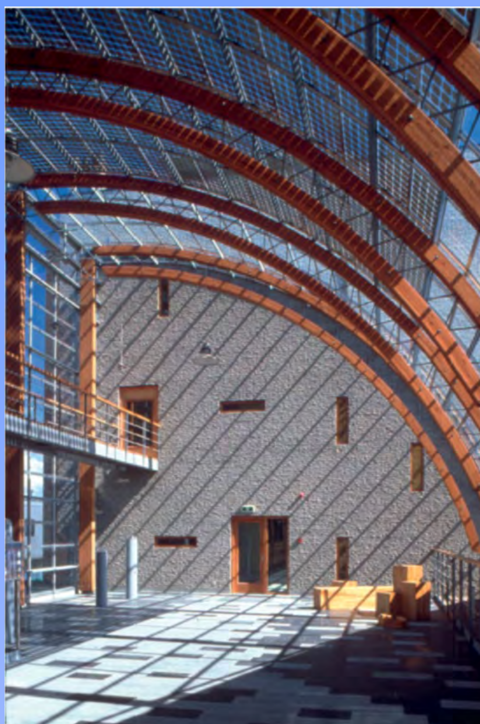


Resource
Availability

Lowest
Environmental Impact

Images from: Fthenakis & Lynn, *Photovoltaic-Systems Integration and Sustainability*, Wiley, 2018

Photovoltaics –Sustainability Criteria: Infancy, Junior, & Adult Examination Levels



-Niche markets

Affordability

Resource Availability

Lowest Environmental Impact

-EH&S R&D facilities & Start-ups

Fthenakis, The sustainability of thin-film PV, Renewable & Sustainable Energy Reviews, 2009

Fthenakis, Mason & Zweibel, The technical, geographical and economic feasibility for solar energy in the US, Energy Policy, 2009

Fthenakis, Sustainability metrics for extending thin-film PV to terawatt levels. MRS Bulletin, 2012

Images from: Fthenakis & Lynn, *Photovoltaic-Systems Integration and Sustainability*, Wiley

Photovoltaics –Sustainability Criteria:
Infancy, Junior (1998-2005), & Adult Examination Levels

- Energy Use

Affordability

-Niche markets

-Peak shaving markets

Resource Availability

Lowest Environmental Impact

-EH&S R&D facilities

-EH&S Standards for Industry

Fthenakis, The sustainability of thin-film PV, Renewable & Sustainable Energy Reviews, 2009
Fthenakis, Mason & Zweibel, The technical, geographical and economic feasibility for solar energy in the US, Energy Policy, 2009
Fthenakis, Sustainability metrics for extending thin-film PV to terawatt levels. MRS Bulletin, 2012
Fthenakis & Lynn, Photovoltaic-Systems Integration and Sustainability, Willey, 2018

Images from: Fthenakis & Lynn, *Photovoltaic-Systems Integration and Sustainability*, Wiley, 2018

Sustainability Criteria for Large Scale PV

Affordability in a competitive world

Low Cost

Te in CdTe
In in CIGS & ITO
Ag in c-Si
Energy Use
Land Use

Resource Availability

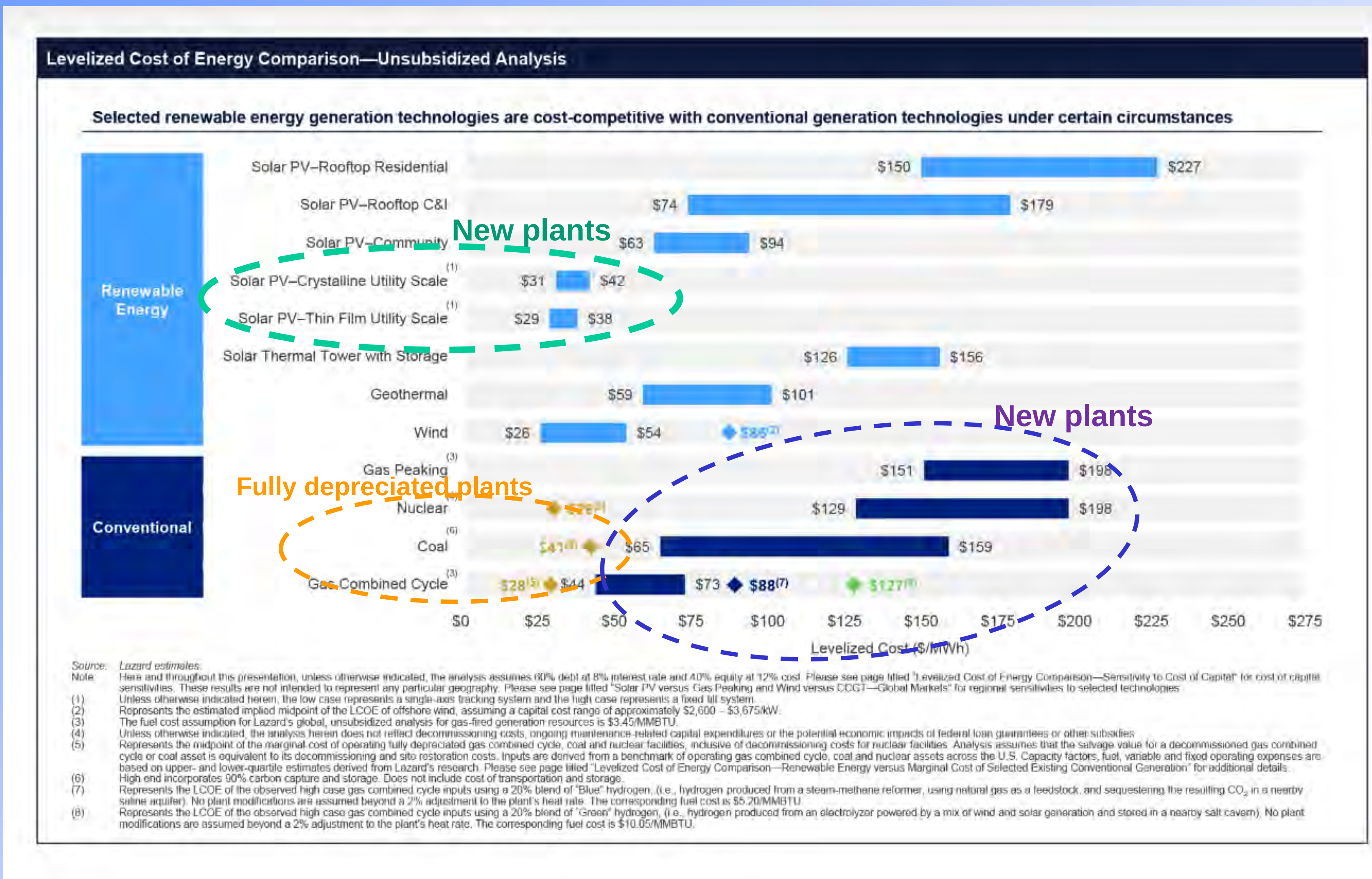
Life cycle impacts & risks lower than alternatives

Lowest Environmental Impact

Zweibel, Mason & Fthenakis, A Solar Grand Plan, Scientific American, 2008
Fthenakis, Mason & Zweibel, The technical, geographical and economic feasibility for solar energy in the US, Energy Policy, 2009
Fthenakis, The sustainability of thin-film PV, Renewable & Sustainable Energy Reviews, 2009
Fthenakis, Sustainability metrics for extending thin-film PV to terawatt levels. MRS Bulletin, 2012

Utility-Scale Solar & Wind: Most Cost-Competitive Forms of New Energy

Levelized Cost of Electricity (LCOE) ($/MWh)



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Addressing Issues and Perceptions on PV Environmental Impact -Proactively

- **PV power plants can pollute the environment**
- **PV growth is constrained by materials availability**
- **PV Energy Return on Energy Investment is too low**
- **PV deployment uses too much land**
- **PV power plants create a Heat Island effect**

Journal peer-review journal and conference publications on Life-Cycle Emissions, Recycling techno-economic feasibility, Energy-Pay-Back Times, Greenhouse Gas emissions, External Costs, Use of Land, Comparisons with Nuclear, Heat Island potential, Material Recovery from Recycling

Lowest Environmental Impact- Effective Dissemination

~800 citations, Google Scholar

SCIENCE NEWS
THE WEEKLY NEWSMAGAZINE OF SCIENCE

Greener Green Energy:
Today's solar cells give more

The New York Times

Photovoltaic Cells Are Still Very Green, Comparative Test Shows *February 26, 2008*

ieee spectrum online
For Tech Insiders

Environmental Science & Technology

Science News
February 6, 2008

New photovoltaics change costs
February 2008

How free is Solar Energy?

The New York Times **Solar Power Lightens Up with Thin-Film Technology**

SCIENTIFIC AMERICAN

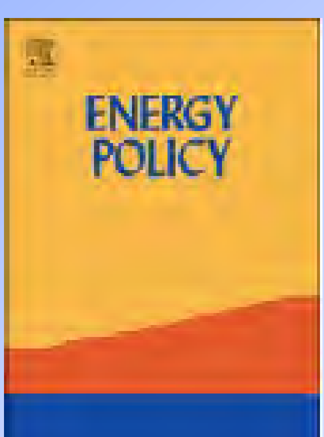
April 25, 2008

Dark Side of Solar Cells Brightens
A life cycle analysis proves that solar cells are cleaner

February 21, 2008

Technical, Geographical and Economic Feasibility for Solar to Supply the U.S. Energy Needs

By 2050 renewable energy to supply 69% of electricity, 35% of total energy needs of the U.S.
Zweibel, Mason, Fthenakis, Jan. 2008



The technical, geographical and economic feasibility for solar energy to supply the energy needs of the U.S.,

Vasilis Fthenakis, James Mason, Ken Zweibel, Energy Policy 37 , 2009

Currently -Photovoltaics Leading the Energy Transition

Images from: Fthenakis & Lynn, *Photovoltaic-Systems Integration and Sustainability*, Wiley, 2018

But some still evoke a debate

energies

MDPI

Review

Through the Eye of a Needle: An Eco-Heterodox Perspective on the Renewable Energy Transition

Megan K. Seibert [1,*] and William E. Rees [1,2]

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Abstract: We add to the emerging body of literature highlighting cracks in the foundation of the mainstream energy transition narrative. We offer a tripartite analysis that re-characterizes the climate crisis within its broader context of ecological overshoot, highlights numerous collectively fatal problems with so-called renewable energy technologies, and suggests alternative solutions that entail a contraction of the human enterprise. This analysis makes clear that the pat notion of "affordable clean energy" views the world through a narrow keyhole that is blind to innumerable economic, ecological, and social costs. These undesirable "externalities" can no longer be ignored.

3. Problems with So-Called Renewables

Here, we holistically examine renewable energy (RE), focusing on the widely overlooked limitations of the RE technologies commonly set forth as solutions (but that do not constitute all possible RE options). This examination shows that RE cannot deliver the same quantity and quality of energy as FFs, that the espoused technologies are not renewable, that their production—from mining to installation—is fossil-energy-intensive, and that producing them—particularly mining their metals and discarding their waste—entails egregious social injustices and significant ecological degradation.

Some still evoke a debate but joint effort brings results

Open Access Comment

Comment on Seibert, M.K.; Rees, W.E. Through the Eye of a Needle: An Eco-Heterodox Perspective on the Renewable Energy Transition. *Energies* 2021, *14*, 4508

by Vasilis Fthenakis [1,2,*], Marco Raugei [1,3,4], Christian Breyer [5], Suby Bhattacharya [6], Michael Carbajales-Dale [7], Michael Ginsberg [1], Arnulf Jäger-Waldau [8], Enrica Leccisi [1], Daniel Lincot [9], David Murphy [10], Marc J. R. Perez [11], Parikhit Sinha [12], Angus Rockett [13], Sascha Sadewasser [14], Billy J. Stanbery [15], Richard M. Swanson [16] and Pierre Verlinden [17,18,19]

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Open Access Editorial

Editorial Note from the EiC

by Enrico Sciubba

Department of Mechanical and Industrial Engineering, Niccolò Cusano University, 00166 Roma, Italy

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The material published in this "Discussion"—and the very reason for which we decided to publish it—requires a clarification on the part of the journal Management; therefore, I advise readers to peruse this foreword before embarking in the task of studying the often polemical statements and counter-statements contained in the Seibert and Rees paper, in the Diesendorf and Fthenakis et al. critique, and in the replies by Seibert and Rees.

Let me first reiterate that at *Energies*, in the over 12 years of my tenure as EiC, we have consistently made every effort to adopt a completely "unbiased publishing policy". This means that any scientific opinion—controversial as it may be—on any topic falling within our journal's scope is peer-reviewed with the utmost attention to its interest for the energy-conversion-systems community, to its scientific merit, to the me... appropriateness of the citations, conclusions, ethics, and academic style. Our rec... a source of great pride for us.

For a series of reasons, the original Seibert and Rees manuscript (S&R in... system in spite of the warning signals given by two of our reviewers: it would be useless to explain the technical reasons of such a mistake here, but as the Editor in Chief, in the end, it is my own responsibility to enforce our publication standards; therefore, I must begin this foreword by asking our readers and our constituency to forgive me for accepting the original manuscript without requiring the authors to make some obvious corrections (that, in light of their response reported below, I believe they would not have accepted).

First of all, the original S&R paper is not a "review paper" but clearly an "opinion paper" (see, for instance, Section 4.3 in the original S&R paper and the last sentence in their response to Diesendorf). We removed the attribute "review paper" from our records as soon as some of our EB members signaled this mistake.

Second, the original Seibert and Rees paper is not only clearly an opinion paper but also a strongly biased one. This emerges from a careful analysis of its original text and of the authors' responses to Diesendorf and Fthenakis et al. I have made a personal list of the inconsistent "technical" statements in their writing but chose not to report them here because this is obviously not—nor should it become—a personal "technical bullfight". One point is, however, noteworthy: the fundamental idea that the overshoot is the only measure of ecological impact is an opinion not substantiated by facts, and presenting it in such a fideistic fashion constitutes a profound lack of respect for the large community of scholars, researchers, and experts that hold a different opinion and propose different environmental indicators. I would also like to signal that S&R's contention that theirs is the only promising approach to the much-needed transition to (pseudo) sustainability is just plain wrong. As for their quoting Kuhn (why not Popper and

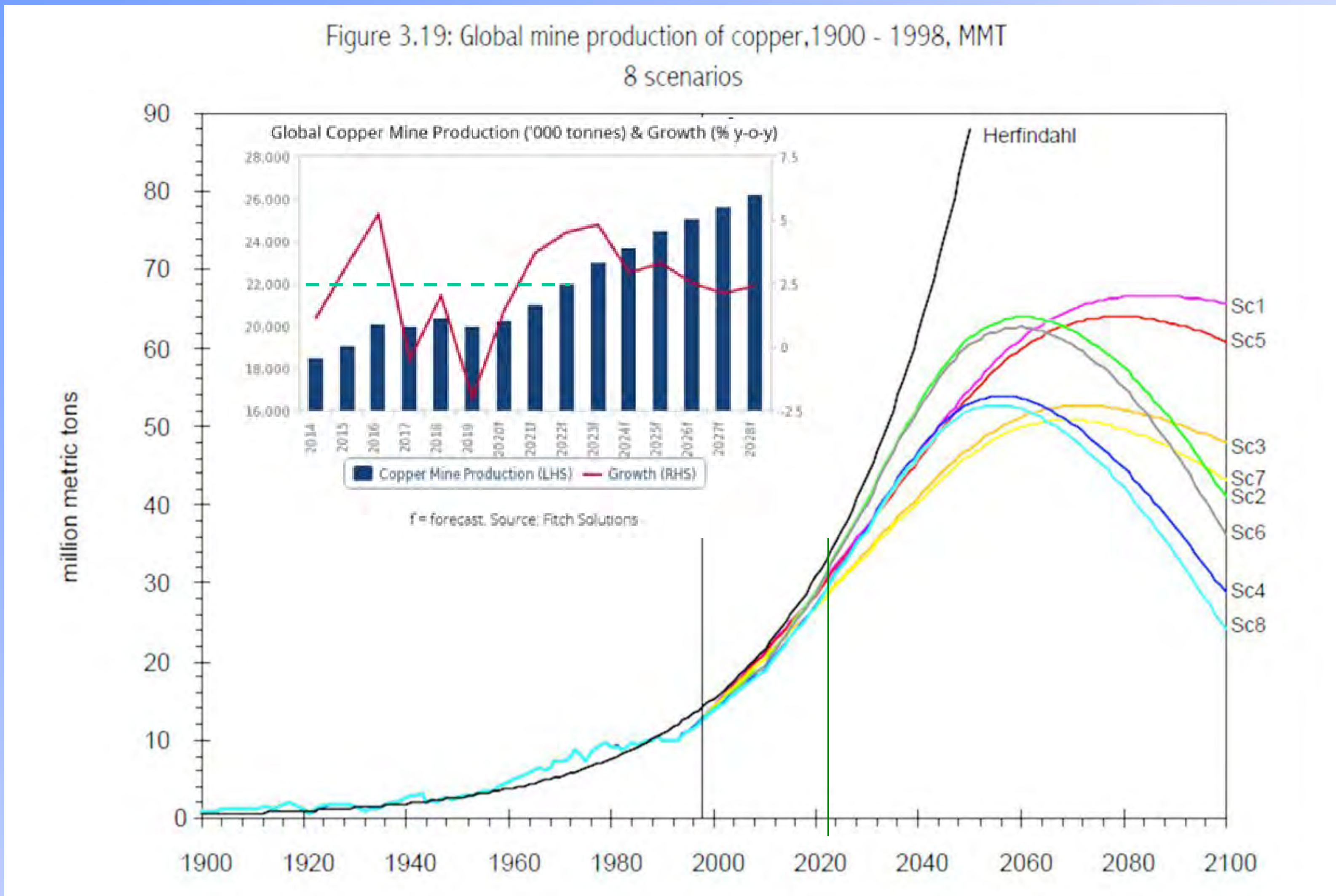
> I must begin this foreword by asking our readers and our constituency to forgive me for accepting the original manuscript

Resource Availability:
Materials Supply and Demand Elasticity

Issues and Solutions

- Supply Increase: Te
- Demand Reduction: In, Ag
- Demand Substitution: Ag

Projection of Primary Cu Production (based on forecasted consumption*)



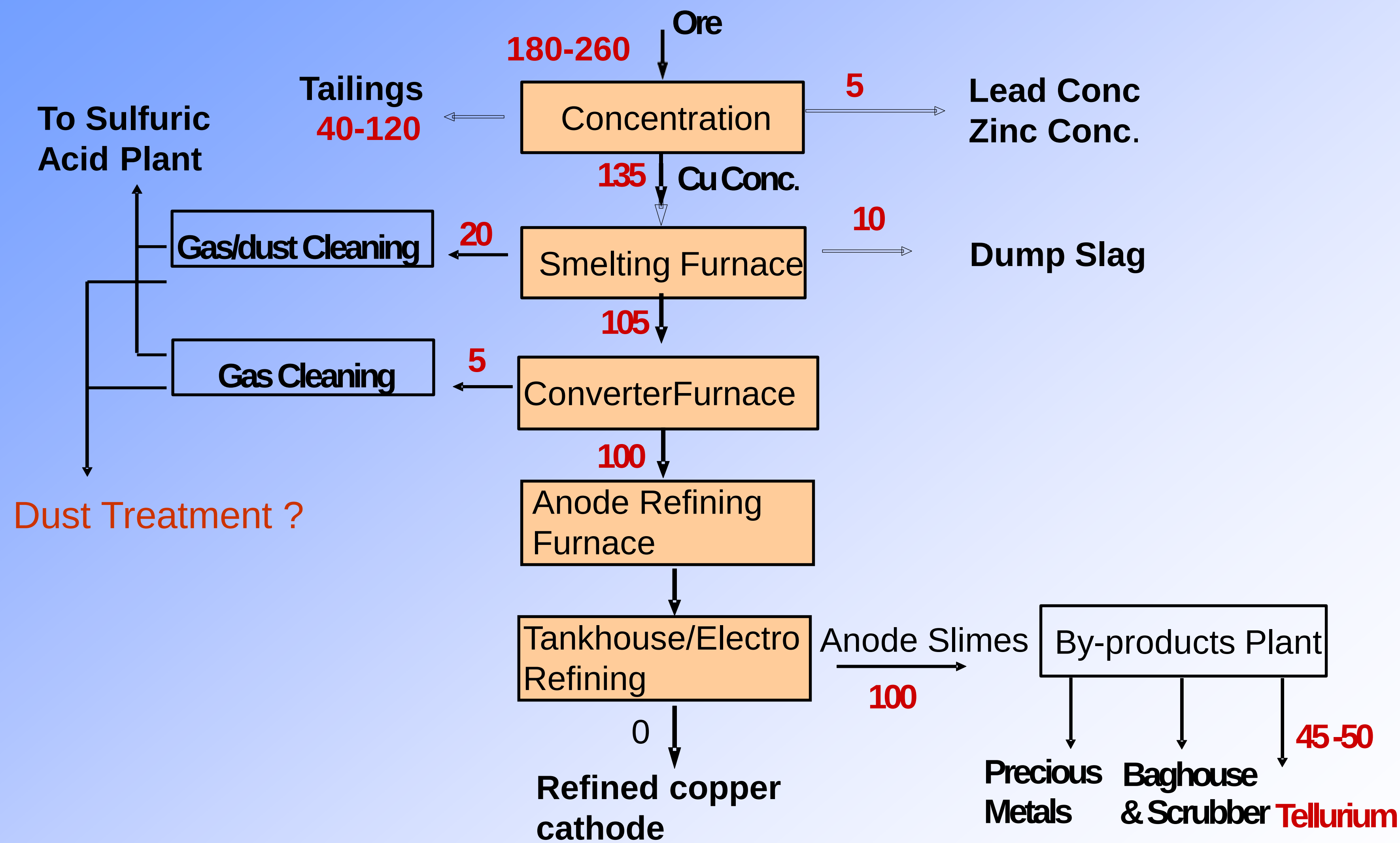
Ayres et al., 2002

* *economic and population growth assuming there are no (environmental) constraints in mining*

Tellurium from Copper Sulfide ores*

Approximate Global Distribution in Copper Circuits

Numbers refer to metric tons of Te from ~0.5 million MT of CuS ores



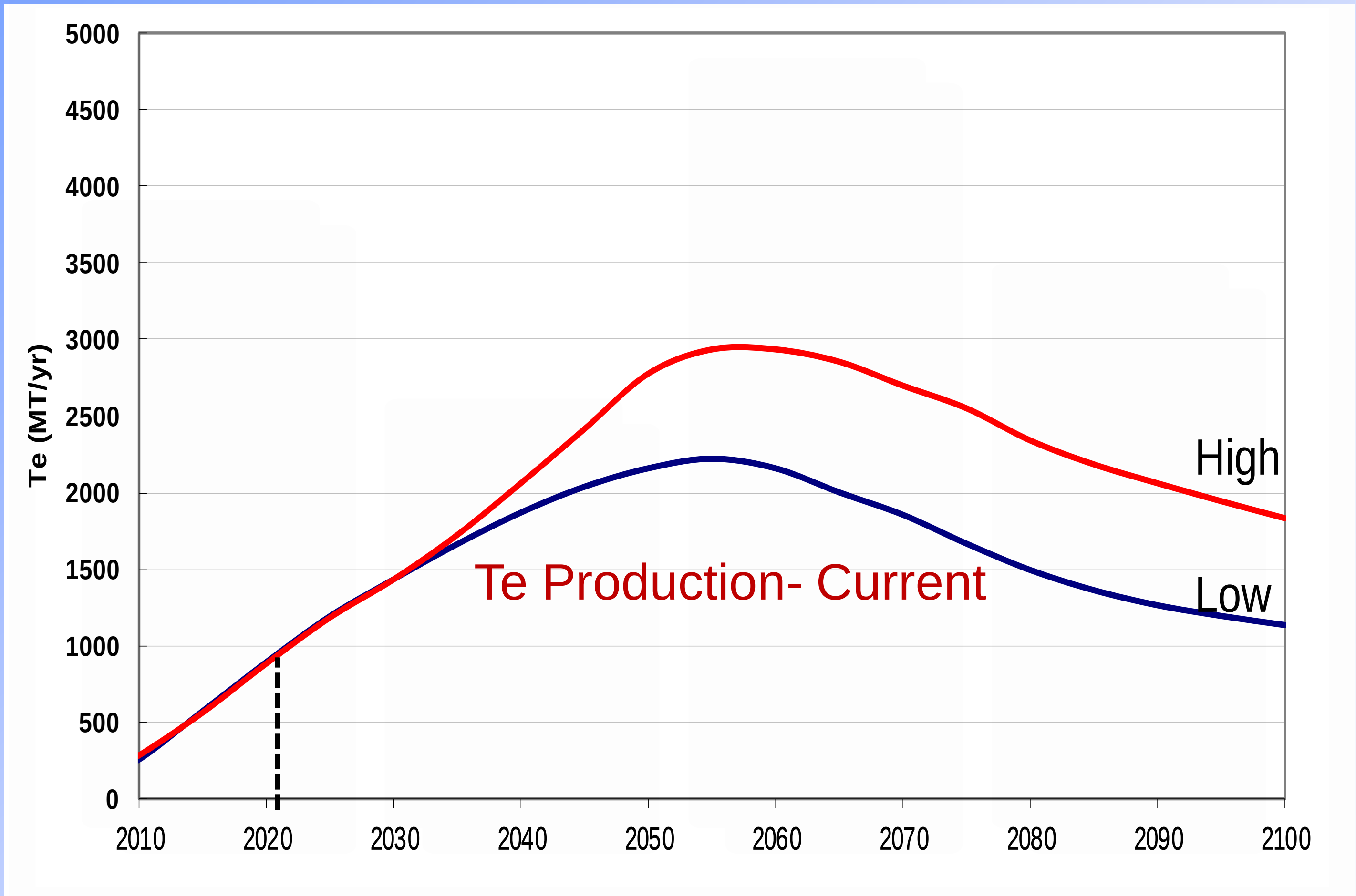
Thus ~2000 MT if co-produced with the currently mined 22 million MT of Cu

*Ojebuoboh, *Proceedings EMC*, 2007; Fthenakis, *MRS*, 2012

Moats, Alagna, Awuah-Offei, *JCP*, 2021

Materials Availability
Case study: Tellurium for PV* from Copper Smelters

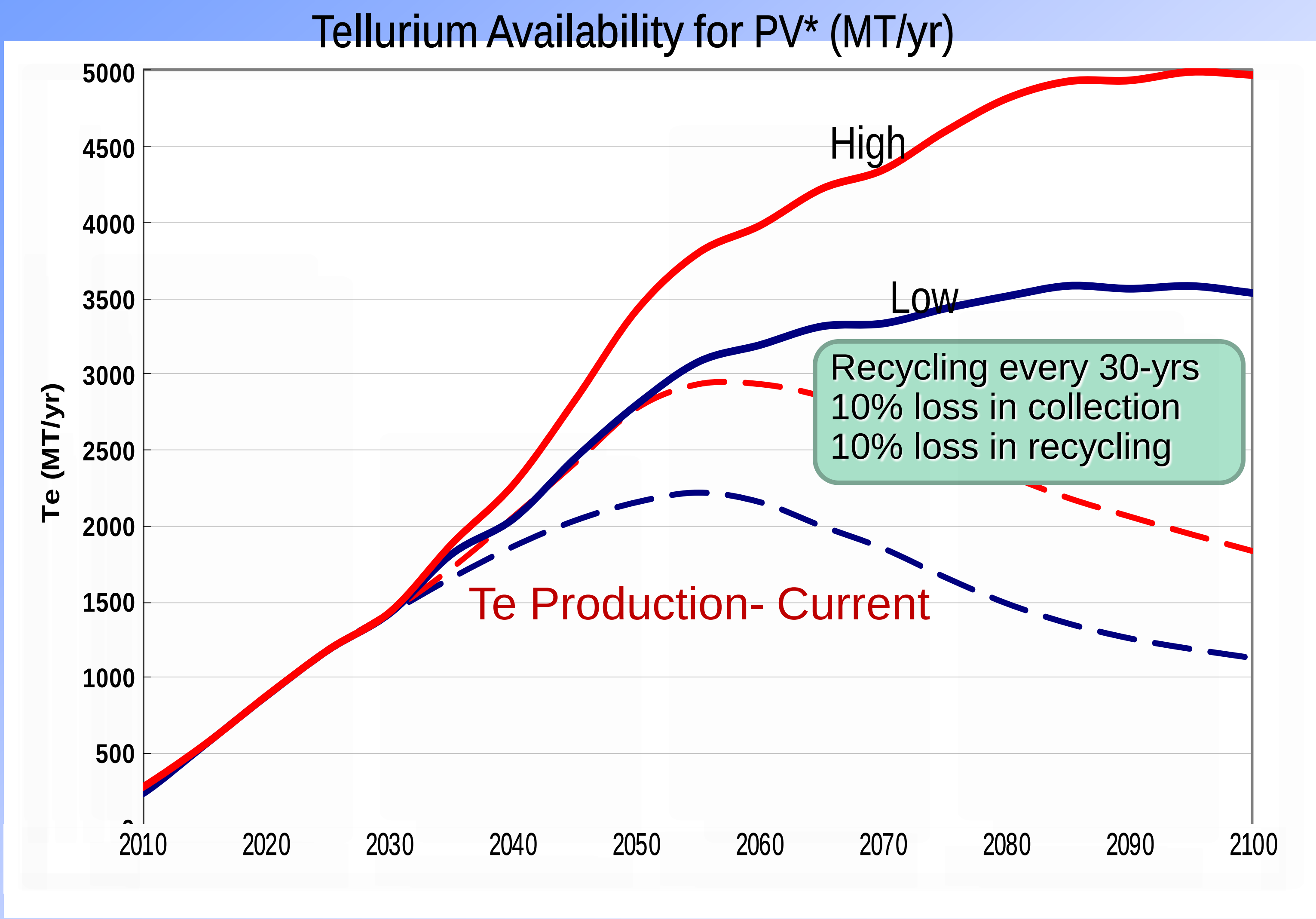
Tellurium Availability for PV* (MT/yr)



•Global Efficiency of Extracting Te from anode slimes increases to 80% by 2030 (low scenario); 90% by 2040 (high scenario)

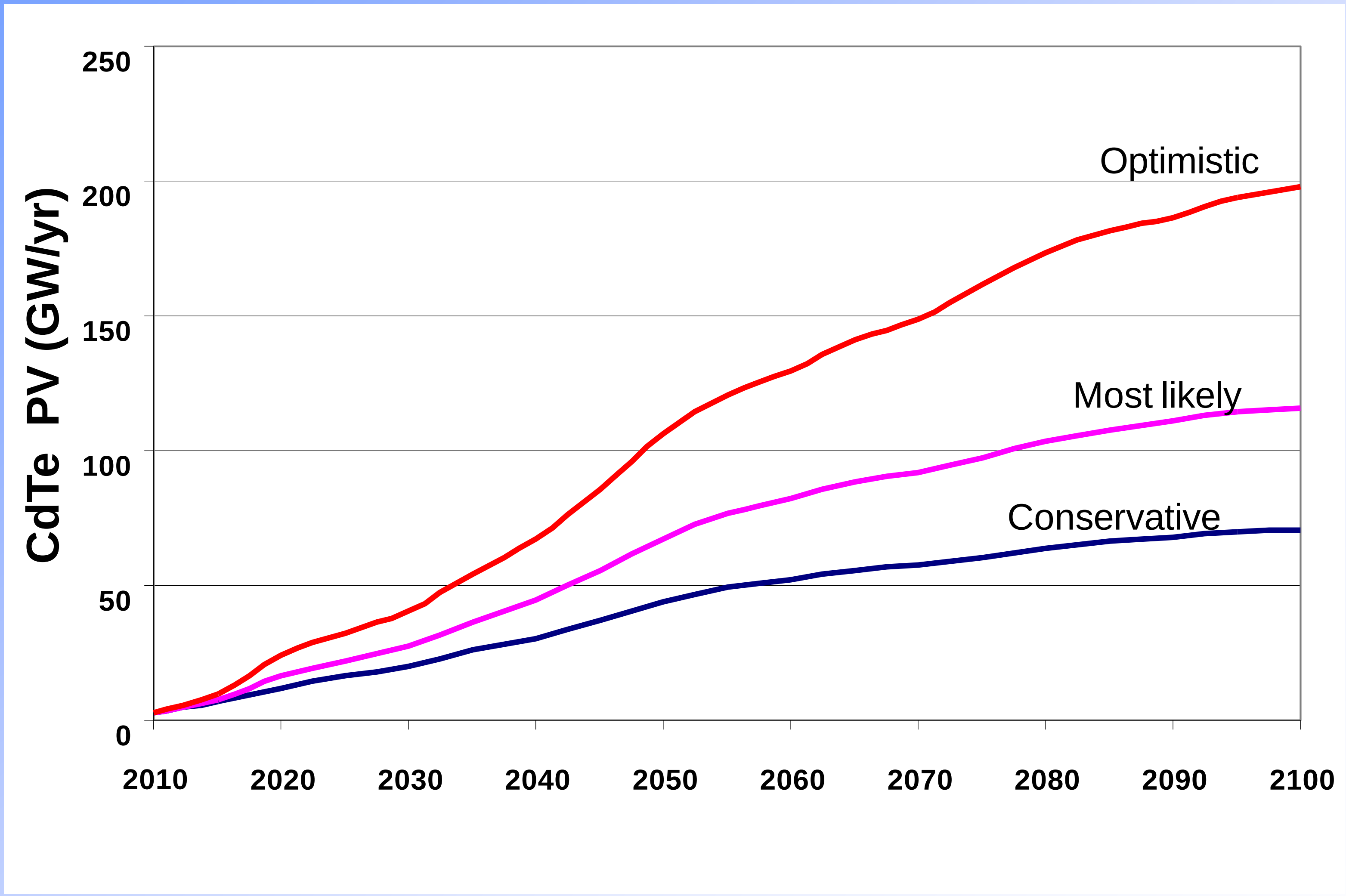
* 322 MT/yr Te demand for other uses has been subtracted
All the future growth in Te production is allocated to PV

Te Availability for PV: Primary + Recycled



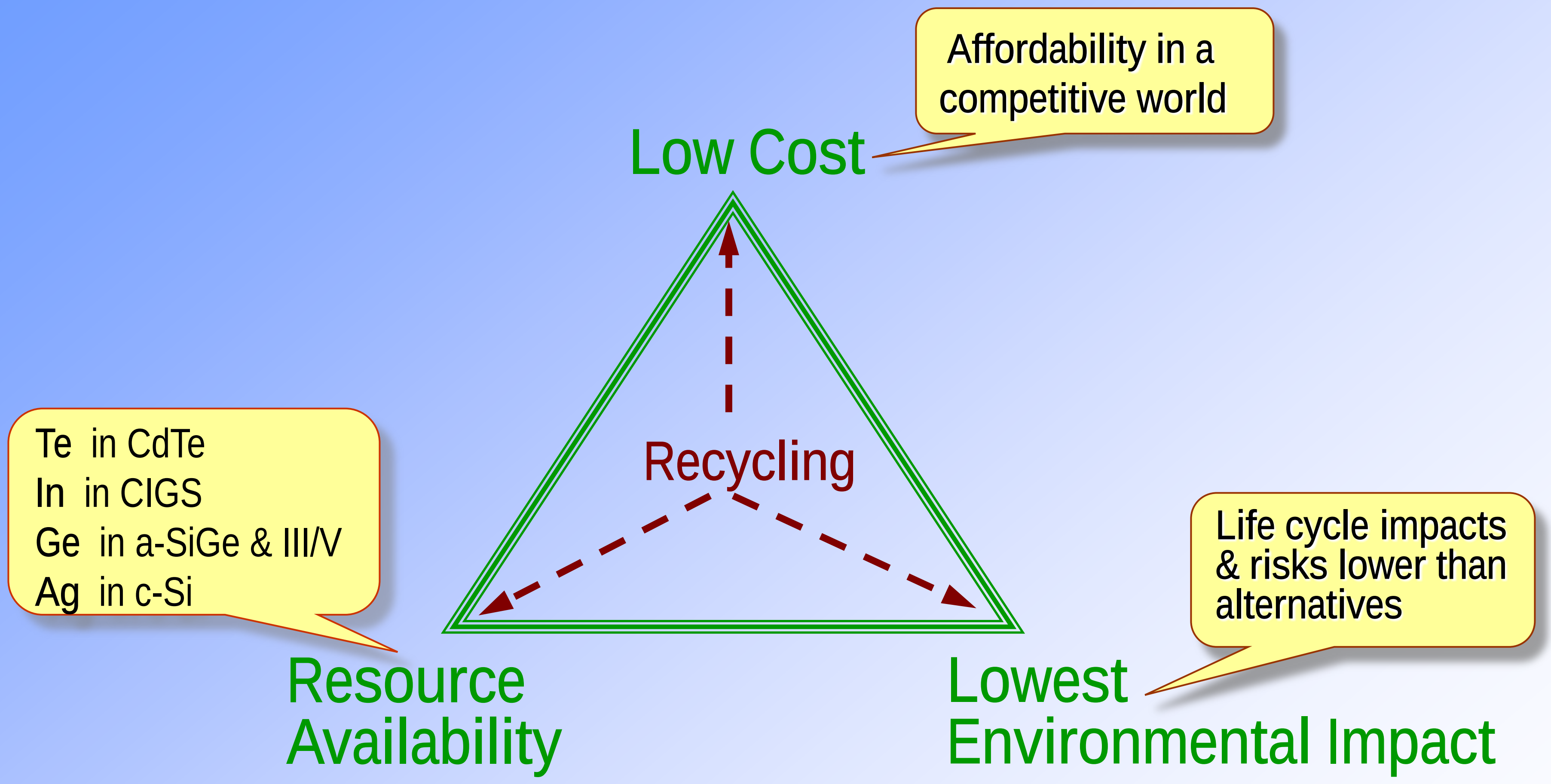
Fthenakis V., Renewable & Sustainable Energy Reviews 13, 2746, 2009
Fthenakis V., MRS Bulletin, 37, 425, 2012

CdTe PV Annual Production Constraints



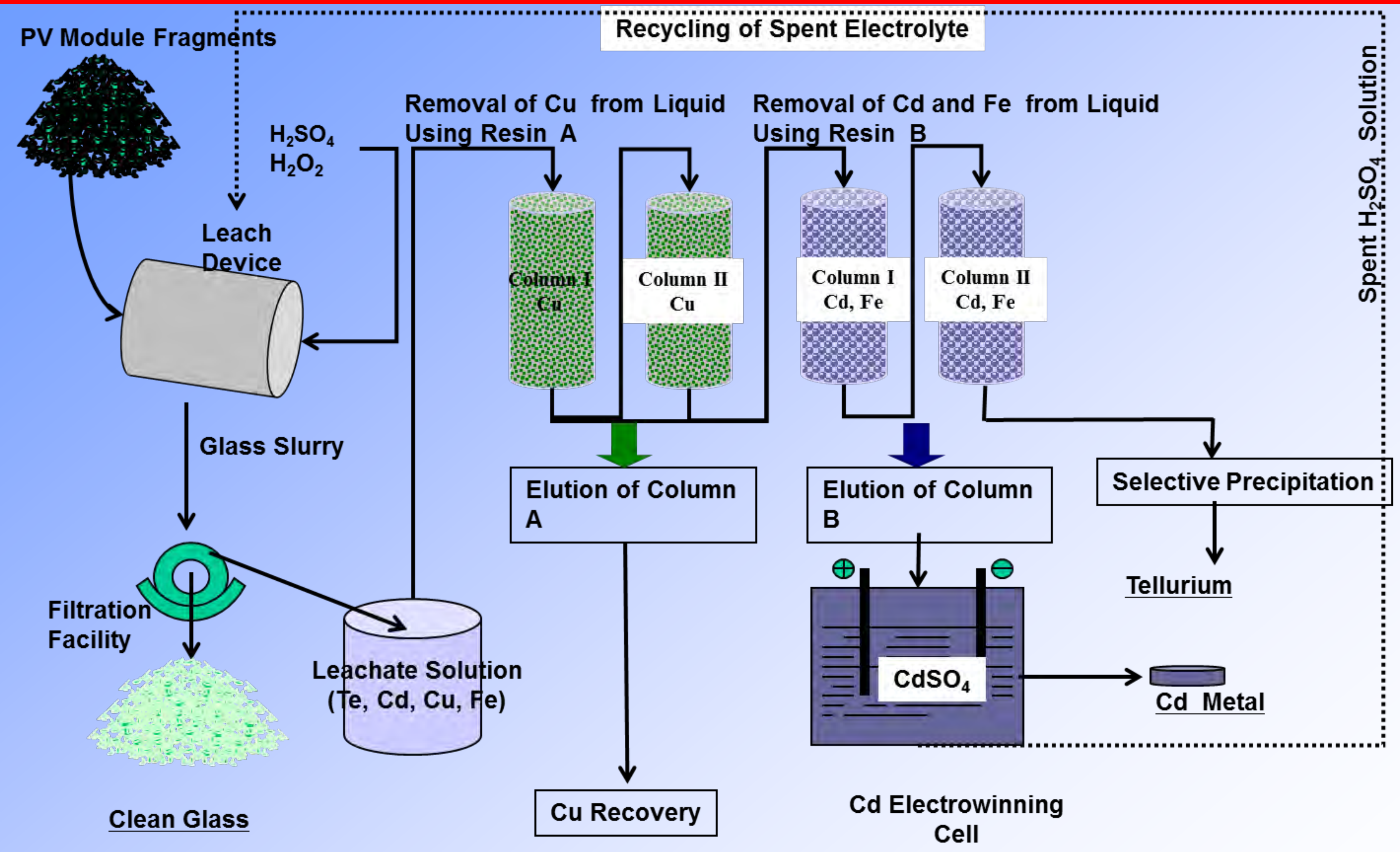
First Solar's Production: 9 GW/yr in 2022; 16 GW/yr in 2024

Large Scale PV –The Value of Recycling



- Fthenakis, Mason & Zweibel, The technical, geographical and economic feasibility for solar energy in the US, Energy Policy, 2009
- Fthenakis, The sustainability of thin-film PV, Renewable & Sustainable Energy Reviews, 2009
- Fthenakis, Sustainability metrics for extending thin-film PV to terawatt levels. MRS Bulletin, 2012

Recycling R&D: CdTe PV Modules



Fthenakis V. and Wang W., Separating Te from Cd Waste Patent No 7,731,920, June 8, 2010

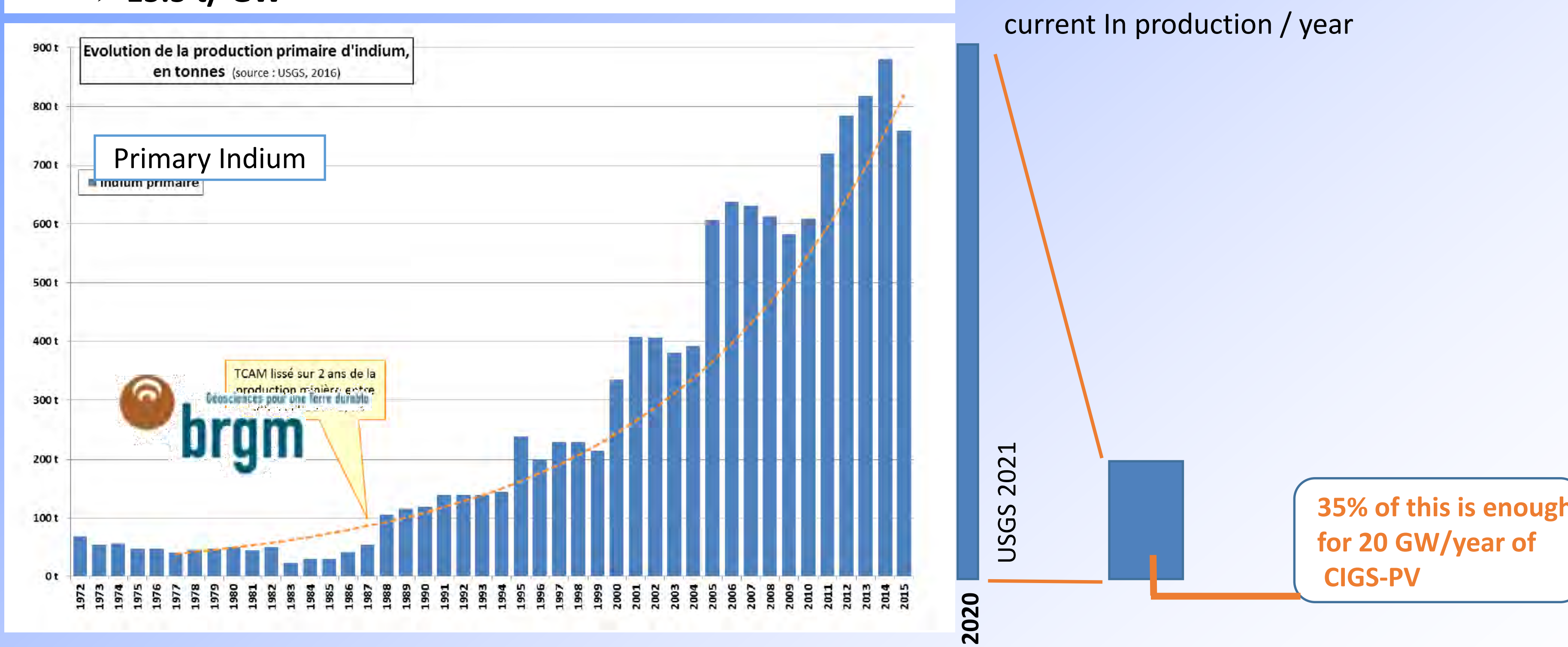
Wang W. and Fthenakis V.M. Kinetics Study on Separation of Cadmium from Tellurium in Acidic Solution Media Using Cation Exchange Resin, Journal of Hazardous Materials, B125, 80-88, 2005

Fthenakis V.M and Wang W., Extraction and Separation of Cd and Te from Cadmium Telluride Photovoltaic Manufacturing Scrap, Progress in Photovoltaics, 14:363-371, 2006.

Indium Availability and Demand in CIGS PV

There is enough Indium for about 20 GW to 100 GW per year production of CIGS-PV with 35% utilization of actual and available resources

- **2 microns CIGS** with In/(In+Ga) = 0.7 need 2.8 g of In by m^2
- with 18% efficiency, 200 W/m^2 0.014 g of In per Watt
  - ➢ **15.5 t/ GW**



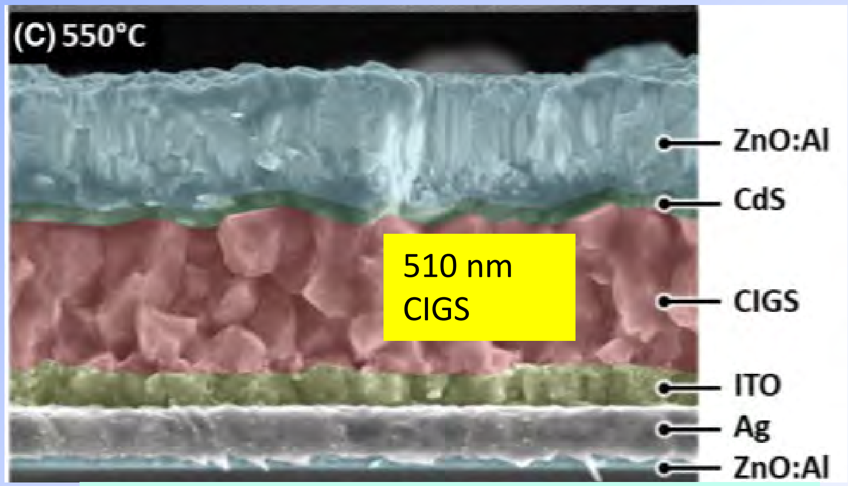
Source: BRGM, criticality study 2017

Source: Werner, Mudd and Jowitt, Ore Geology Reviews, Jan 2017

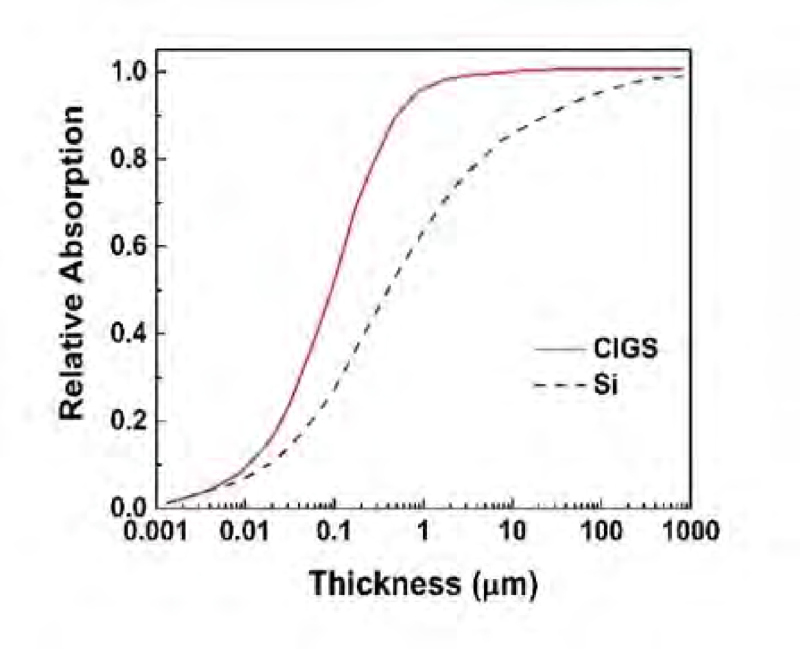
Reduction of CIGS Thickness

Factor of 4 : 400-500 nm → 3-4 tons/ GW

→ 80-100 GW /Year



Prog Photovolt Res Appl. 2021;29:212–221

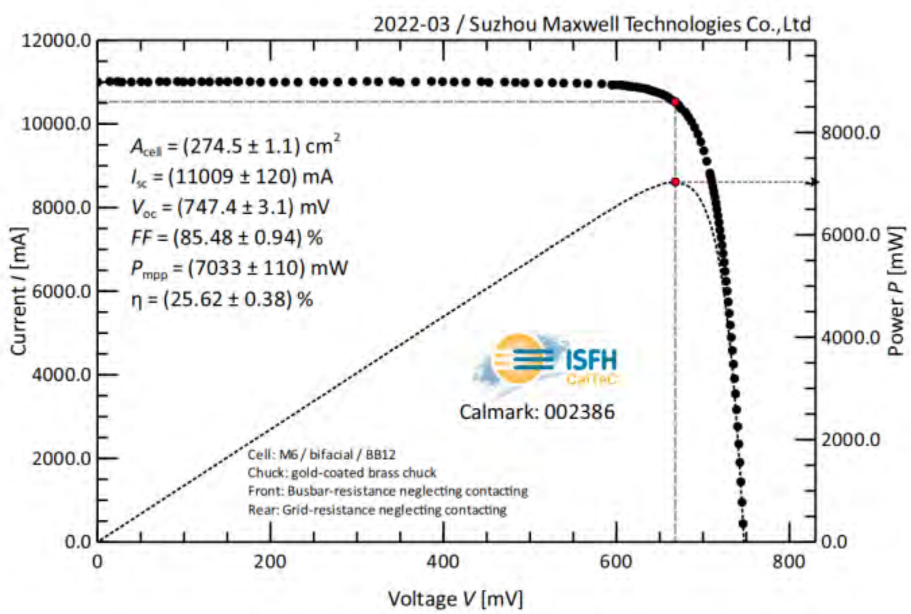


Indium and Silver Use Reduction

25.62%! A New World Record for low indium and low silver HJT Cells Created by Maxwell

APRIL 12, 2022 BY ALEINA IN TECHNOLOGY

PVTIME – Recently, certified by the Institute for Solar Energy Research in Hamelin(ISFH), an authoritative testing institution in Germany, Maxwell has achieved a photoelectric conversion efficiency of 25.62% on full-scale (M6 and 274.5cm²) monocrystalline heterojunction cell via using low indium content transparent conductive oxides (TCO) combined with silver plated copper grids, creating a new world record.



Maxwell reports 25.62% efficiency for monocrystalline silicon HJT solar cells with 50% less indium and using silver coated copper grid wires that reduced Ag use by 55%

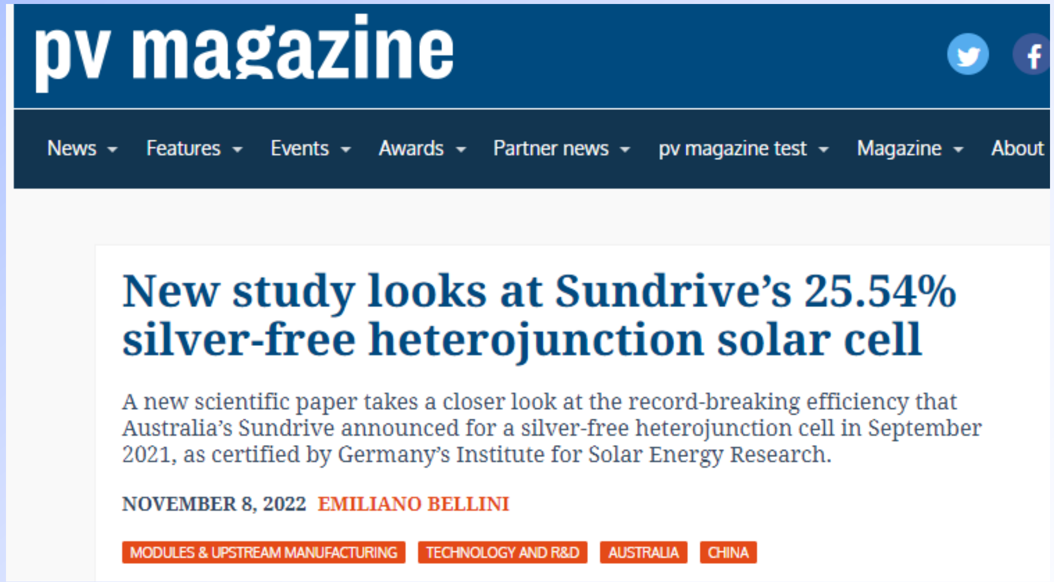
ISFH Validates LONGi Solar's 25.40% Efficiency Claim For Indium-Free Heterojunction Solar Cells

Apr 01, 2022

Silver Replacement

For screen-printed TOPCon cells, silver consumption could be greatly reduced by replacing the silver/Al p-type contact by a pure Al contact, similar to that of PERC.
For SHJ solar cells, the use of copper pastes could greatly reduce silver consumption for both the front and rear contacts.

A potential solution for all technologies is the development and deployment of silver-free metallisation technologies like copper plating, which already exist in laboratories.[54] A recent record by SunDrive Solar at 26.41% efficiency was achieved using copper plating for a large-area SHJ solar cell.


pv magazine

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New study looks at Sundrive's 25.54% silver-free heterojunction solar cell

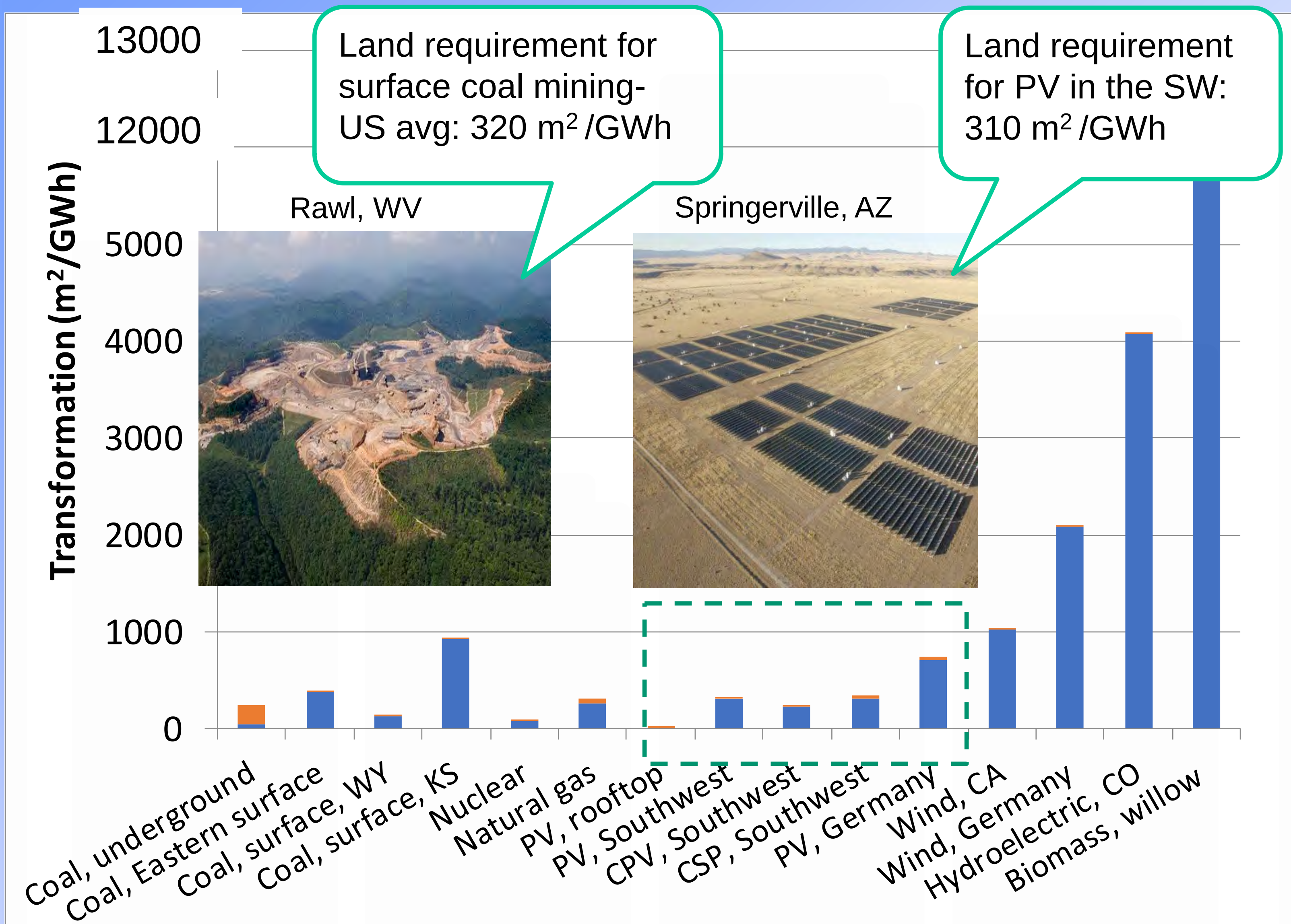
A new scientific paper takes a closer look at the record-breaking efficiency that Australia's Sundrive announced for a silver-free heterojunction cell in September 2021, as certified by Germany's Institute for Solar Energy Research.

NOVEMBER 8, 2022 EMILIANO BELLINI

MODULES & UPSTREAM MANUFACTURING TECHNOLOGY AND R&D AUSTRALIA CHINA

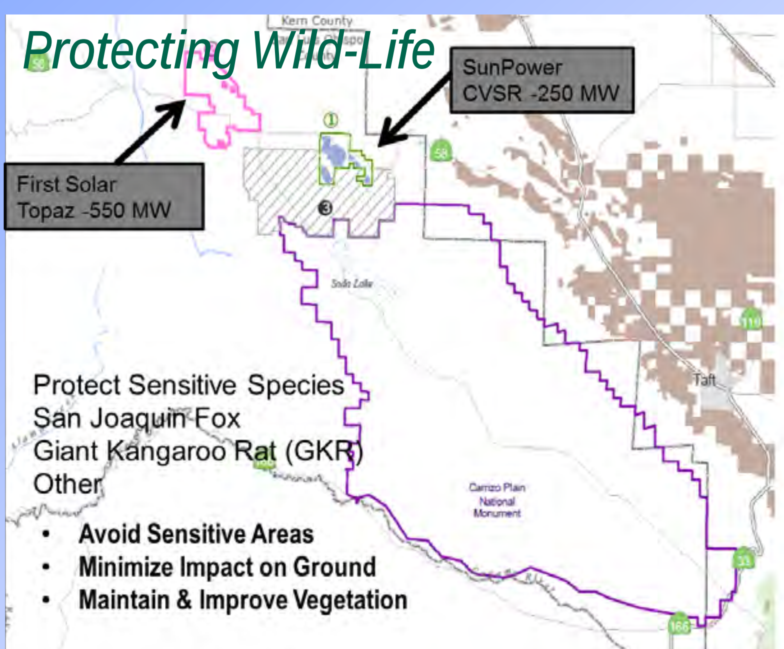
Until is replaced, Ag can be and should be recycled from EoL solar cells
Currently it has the higher recovery value in c-Si PV recycling operations

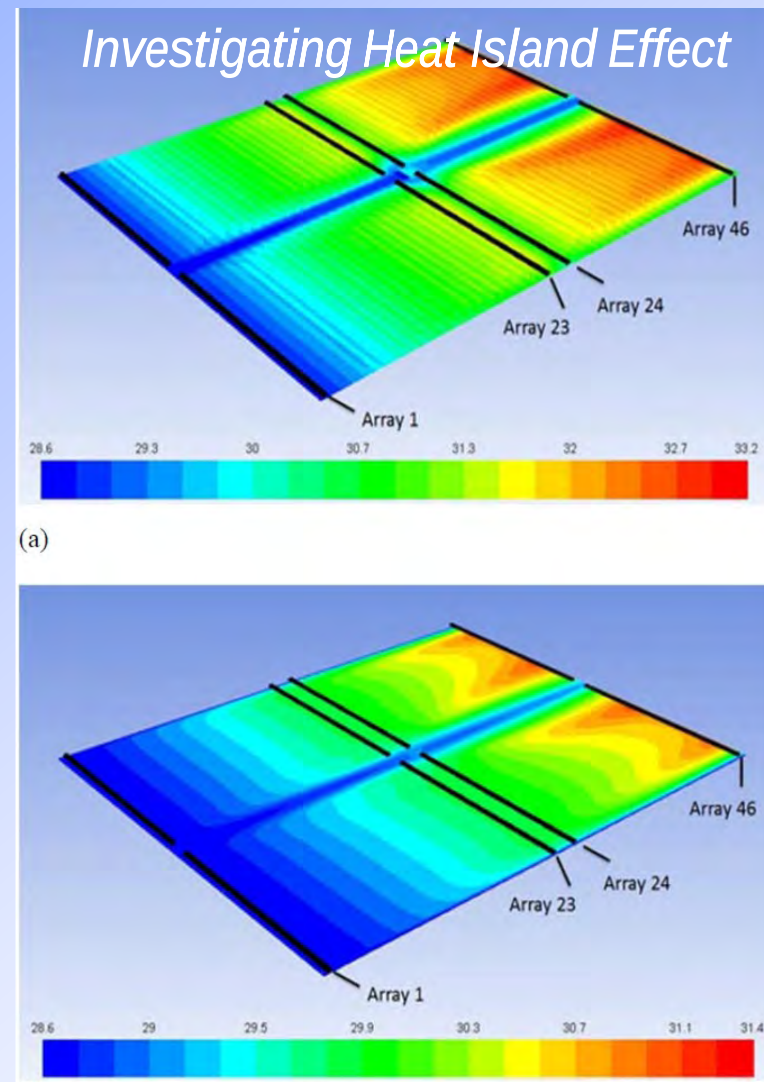
Resource Availability –Land: PV Uses less Land than Coal



Fthenakis and Kim, Renewable and Sustainable Energy Reviews, 2009;
Burkhardt et al (2011)

Use of Land is Environmentally Friendly





(b)
Fig. 11 Air temperatures from 3-D simulations during a sunny day. a) Air temperatures at a height of 1.5 m; b) air temperatures at a height of 2.5 m.

Fthenakis V., Green T., Blunden J. Krueger L., Large Photovoltaic Power Plants: Wildlife Impacts and Benefits, Proceedings 37th IEEE PSC, 2011.

Fthenakis V. and Yu Y., Analysis of the Potential for a Heat Island Effect in Large Solar Farms, Proceedings 39th IEEE PVSC, 2013

Resource Availability: Land
Ecologically Friendly Dual Use of Land and Water

Agrivoltaics

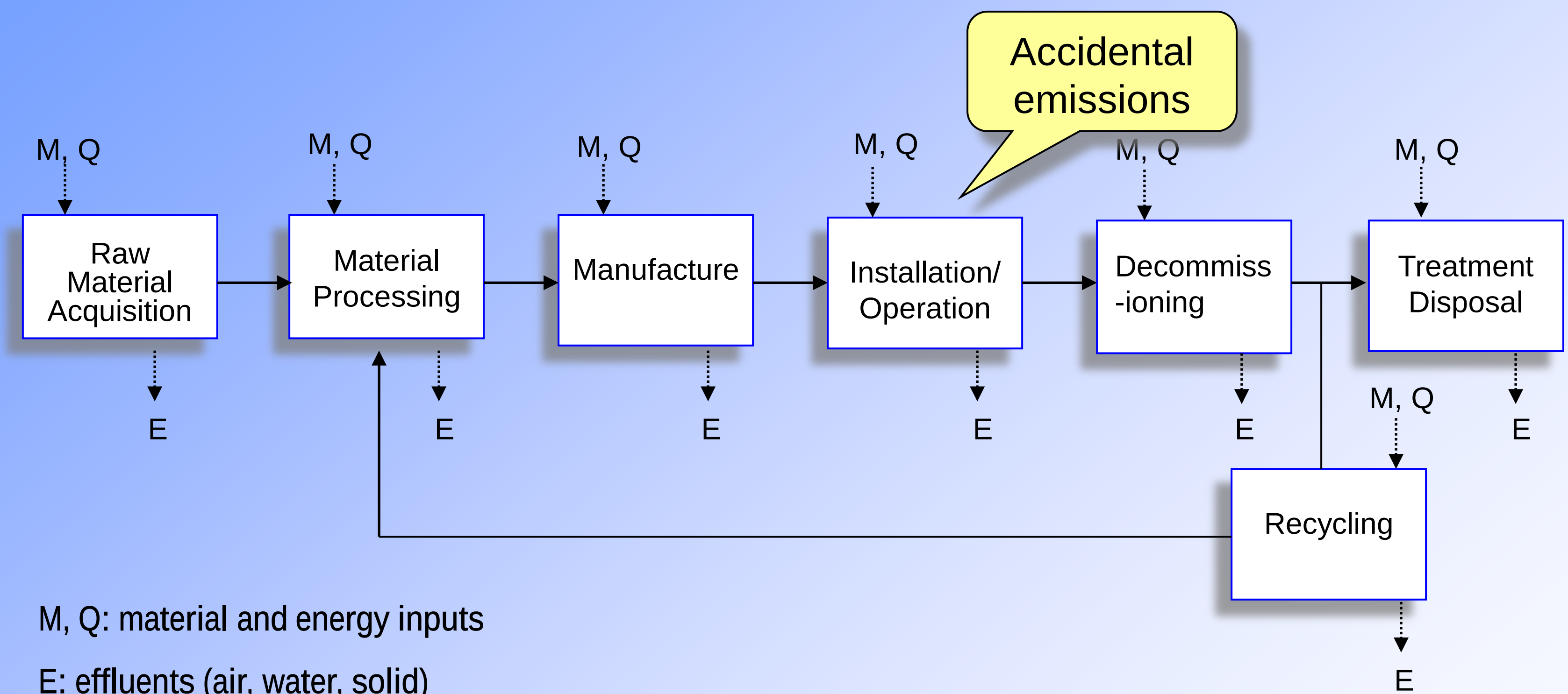
Floating Photovoltaics

Pollinator Solar Farms

Hybrid Solar & Wind Farms

Environmental Impacts-Life Cycle Analysis

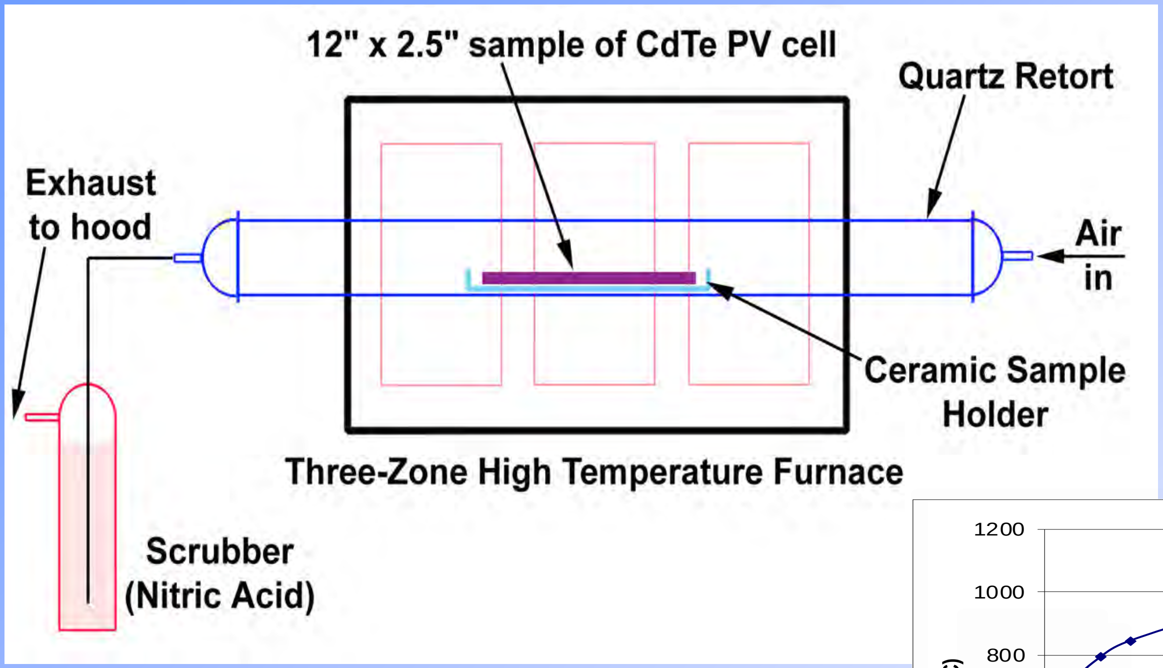
Experimental Research at BNL

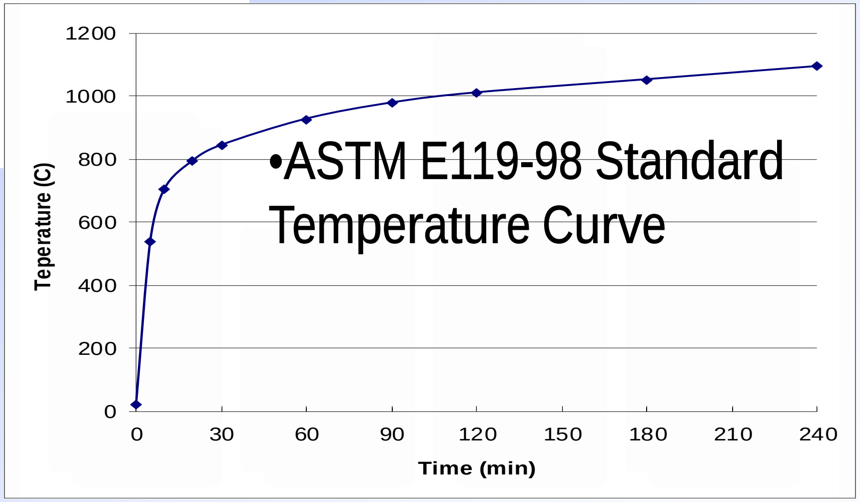


Basic Metrics

- Energy Payback Times (EPBT)
- Greenhouse Gas Emissions
- Toxic Emissions
- Resource Use (materials, water, land)

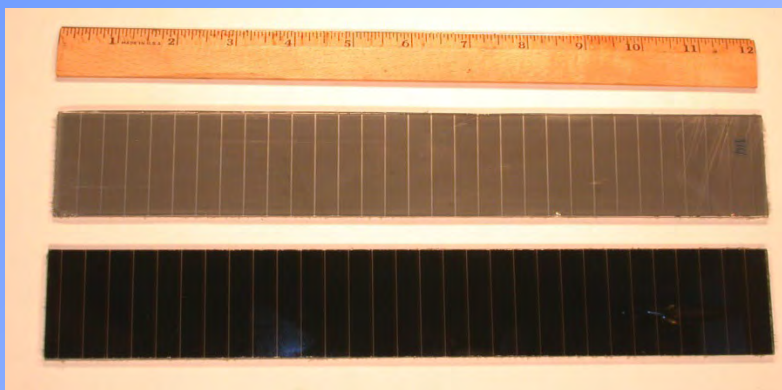
CdTe Module Fire-simulation Experiments





- Weight Loss Measurements
- Inductively Coupled Plasma (ICP) Analysis of Cd & Te Emissions
- X-ray Fluorescence Micro-Spectrometry of Cd in Heated Glass

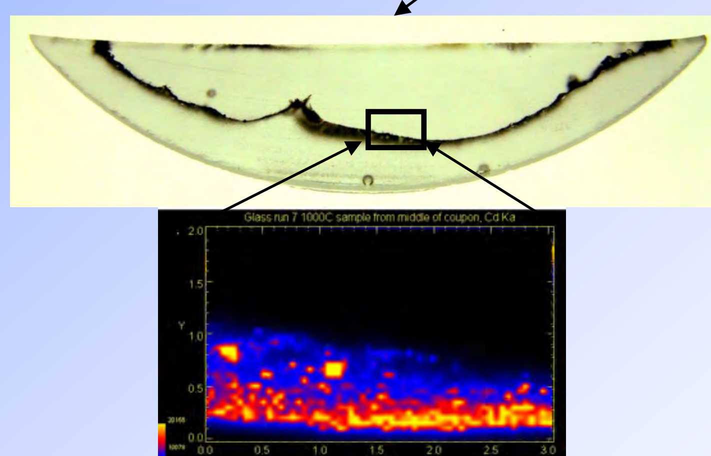
CdTe PV Fire-Simulation Tests: XRF Analysis

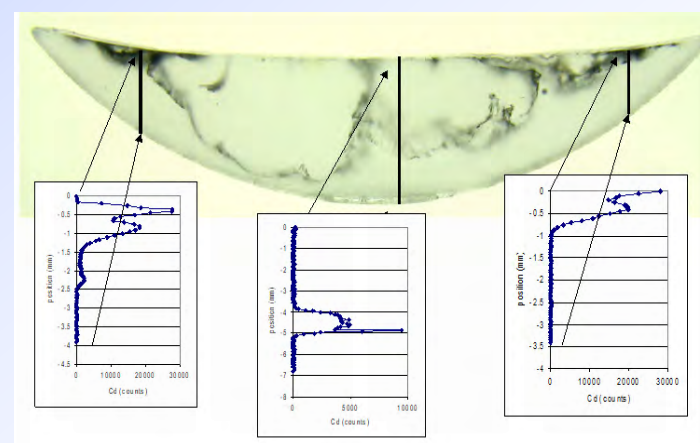


Heat

XRF-micro-spectroscopy -Cd Mapping in PV Glass
1000 °C, Section taken from middle of sample

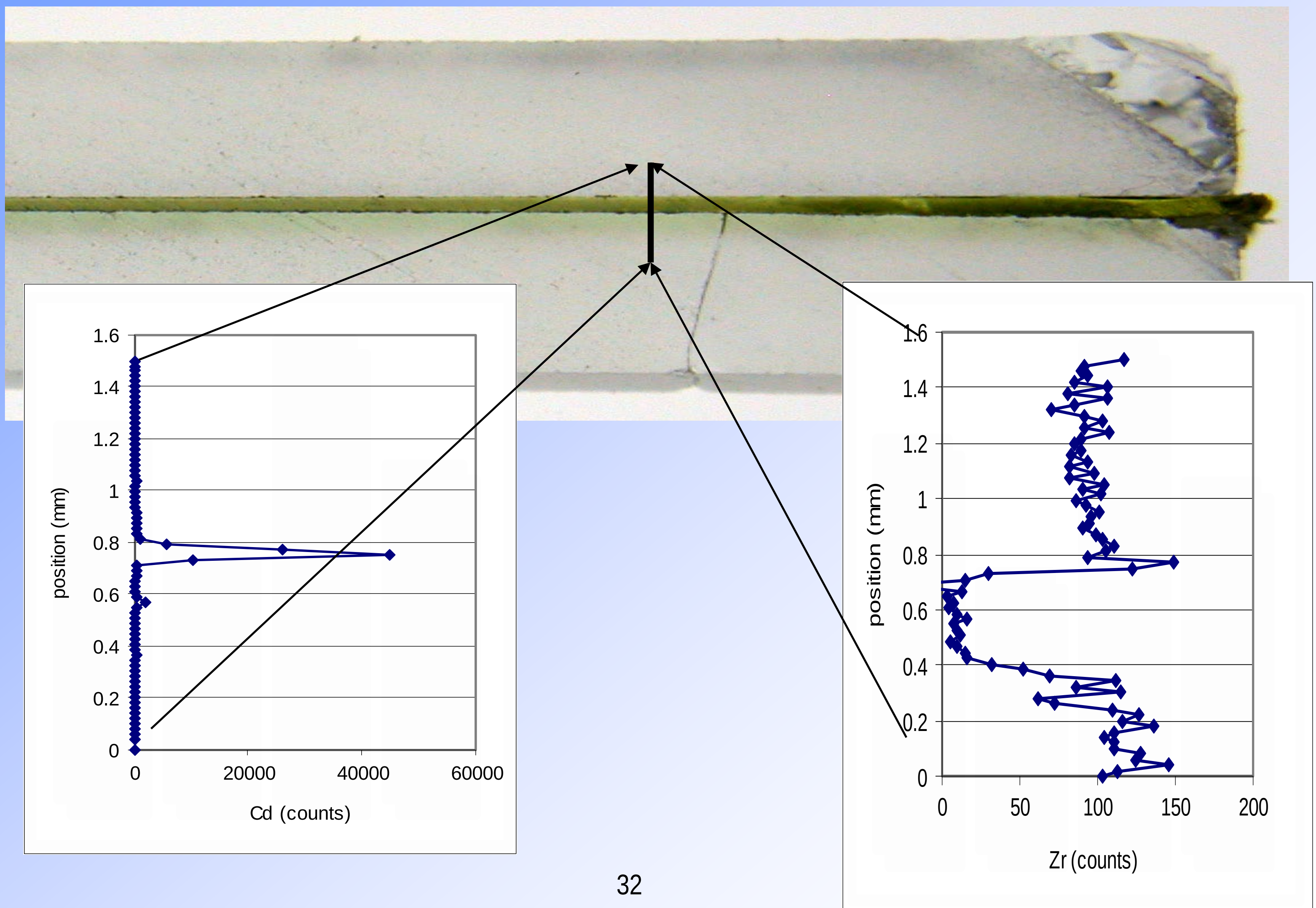
XRF-micro-probing –
Cd Distribution in PV Glass
1000 °C, right end of sample



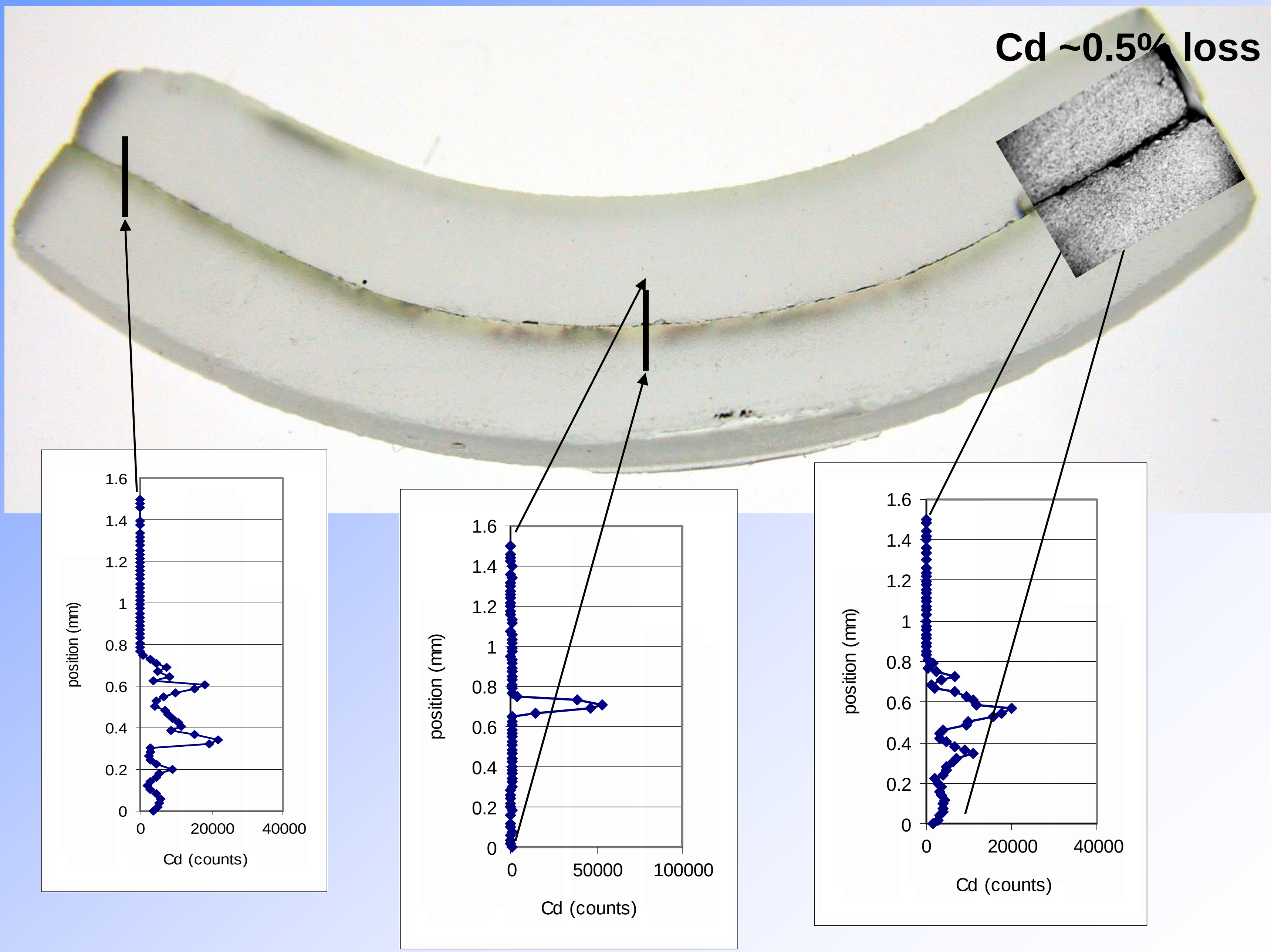


Fthenakis, Fuhrman, Heiser, Lanzirotti, Fitts, Wang, Emissions and Encapsulation of Cadmium in CdTe PV Modules during Fires, *Progress in Photovoltaics, 2005*

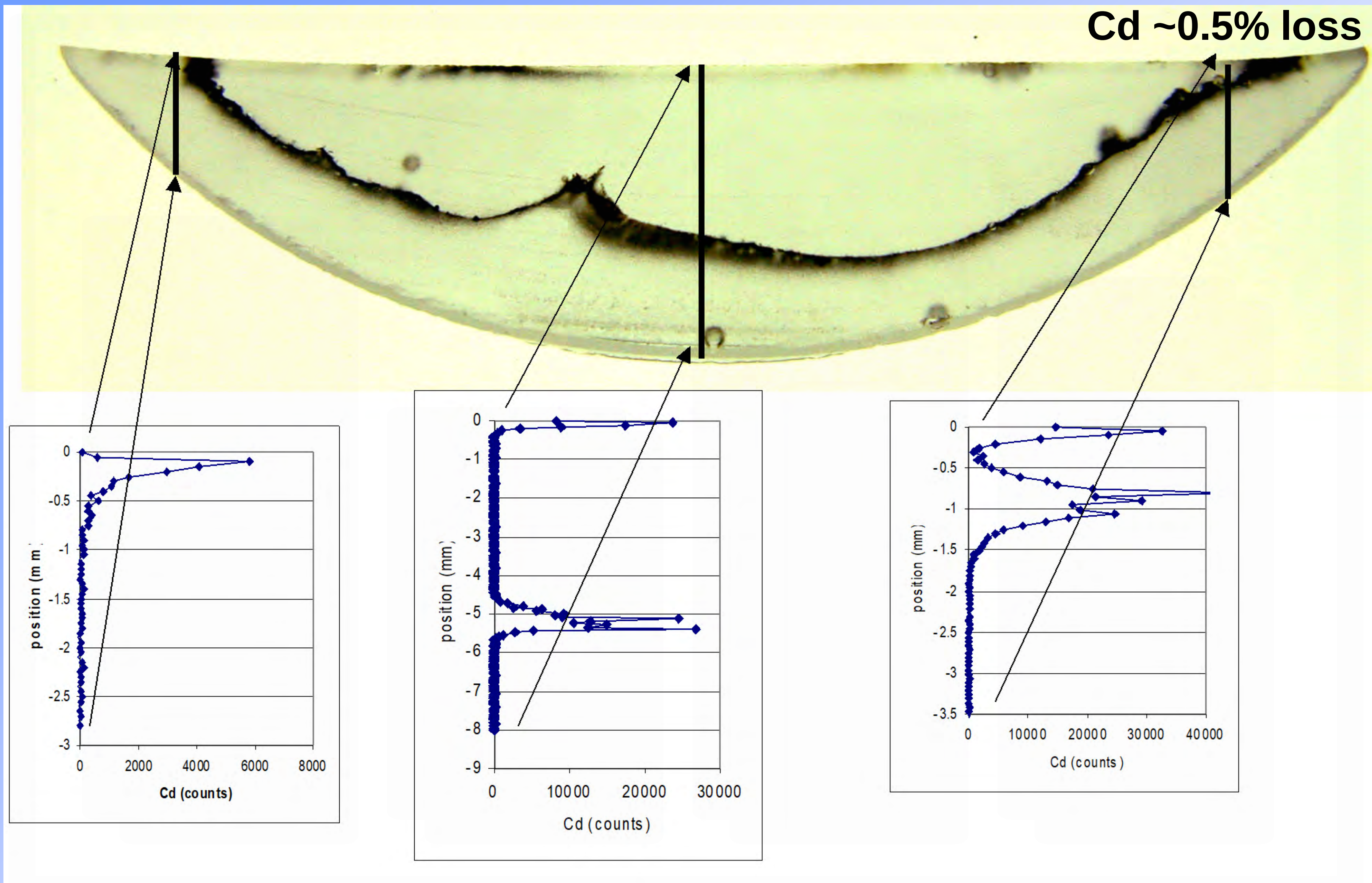
XRF-micro-probing -Cd & Zr distribution in PV sample
Unheated Sample -Vertical Cross Section



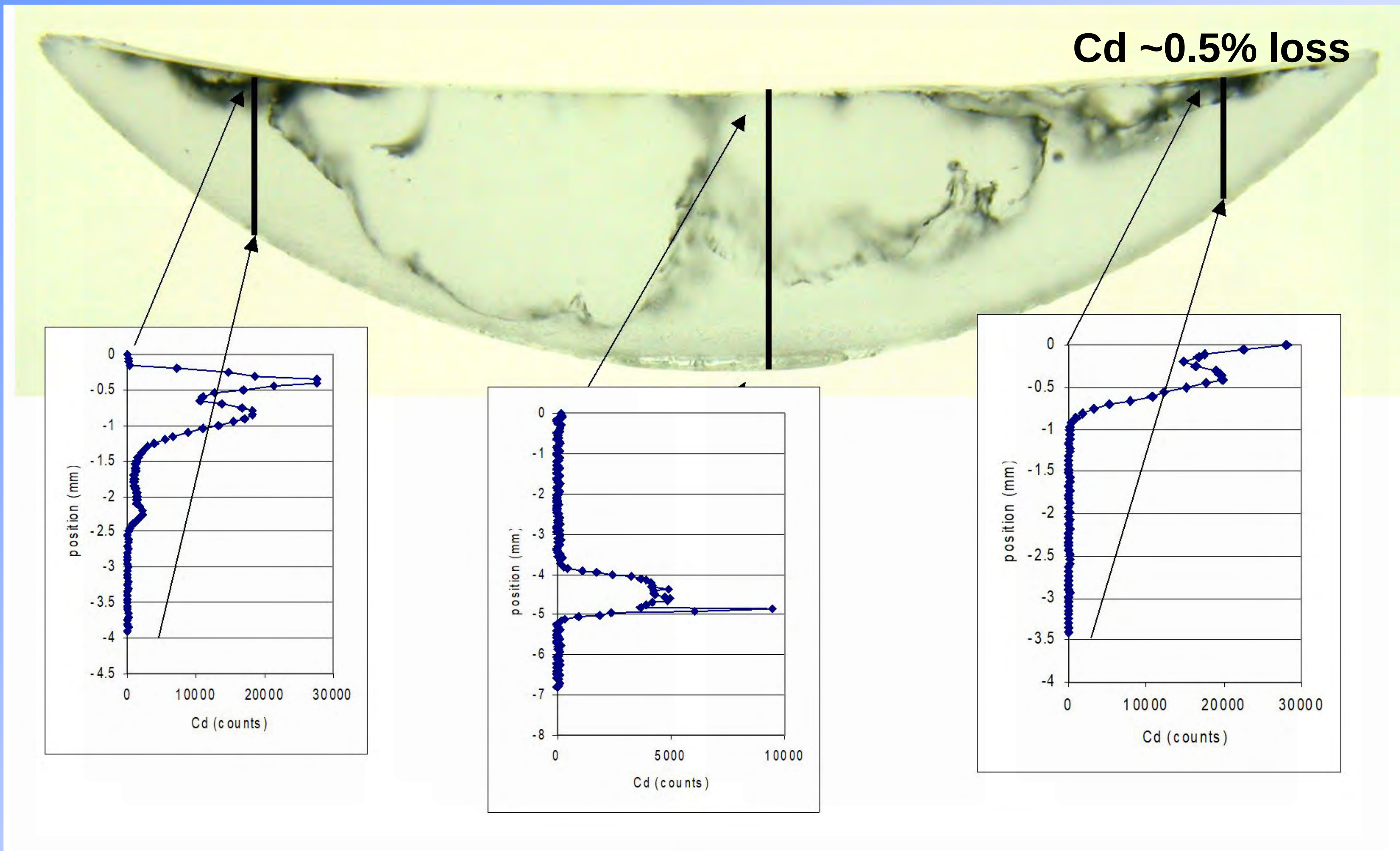
XRF-micro-probe -Cd distribution in PV sample 760 ^{o}C, Section taken from middle of sample



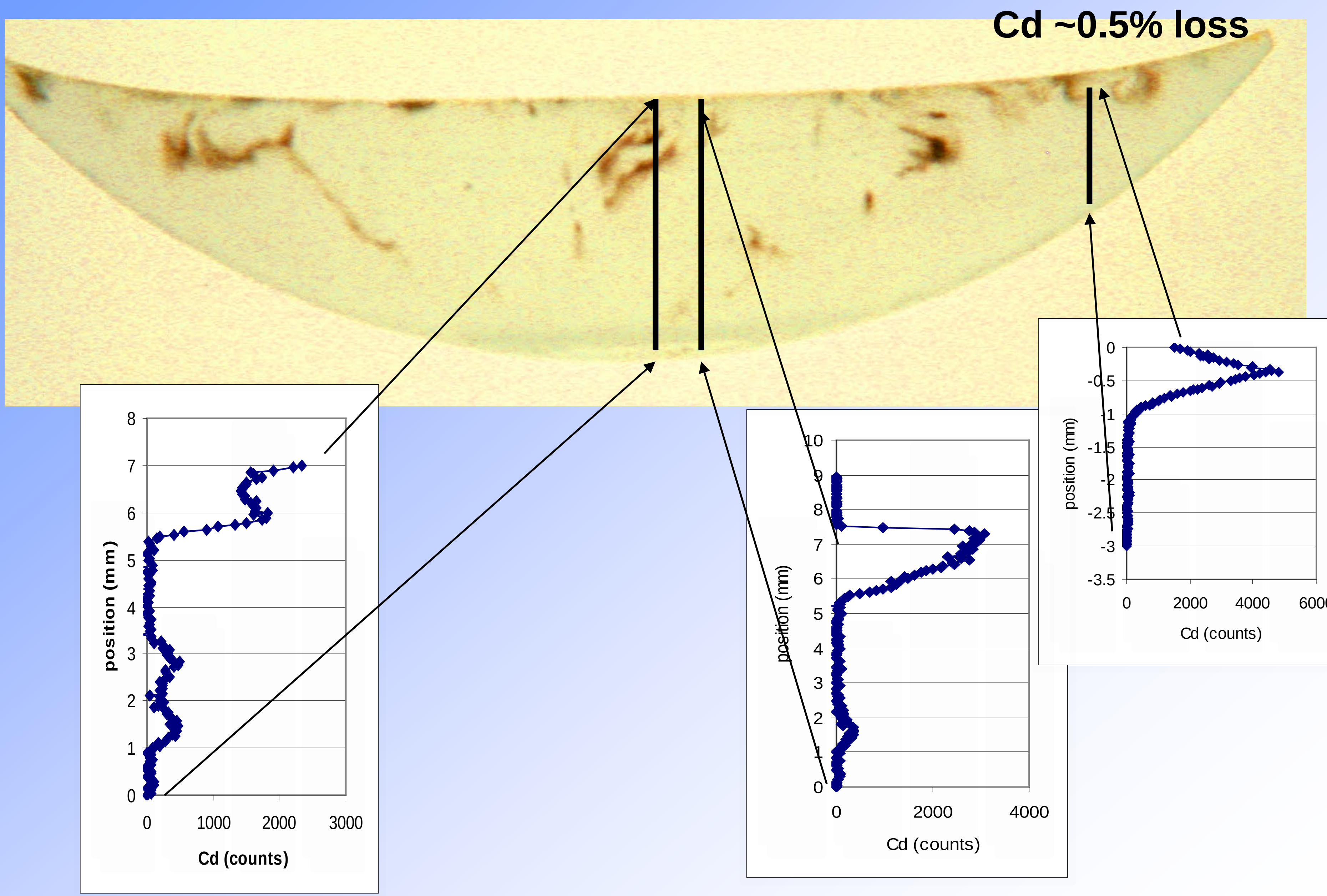
XRF-micro-probe -Cd distribution in PV sample 1000 °C, Section taken from middle of sample



XRF-micro-probing -Cd distribution in PV sample 1000 °C, Section taken from right side of sample



XRF-micro-probing -Cd distribution in PV sample 1100 ^{o}C, Section taken from middle of sample



Atmospheric Cd emissions from the Life-Cycle of CdTe PV Modules –Direct Emissions

Process	Cd Emissions (g /GWh)
1. Mining/Smelting of Zn	3.2×10^{-4}
2. Purification/CdTe Production	1.5×10^{-2}
3. Module Manufacturing	3.9×10^{-3}
4. Operation (accidents)	6.0×10^{-5}
5. Recycling	-
TOTAL Life-Cycle Emissions	0.02

These emissions are 100-360 times lower than those of the best equipped coal-firing power plants in the United States.

Fthenakis, Renewable and Sustainable Energy Reviews, 2004

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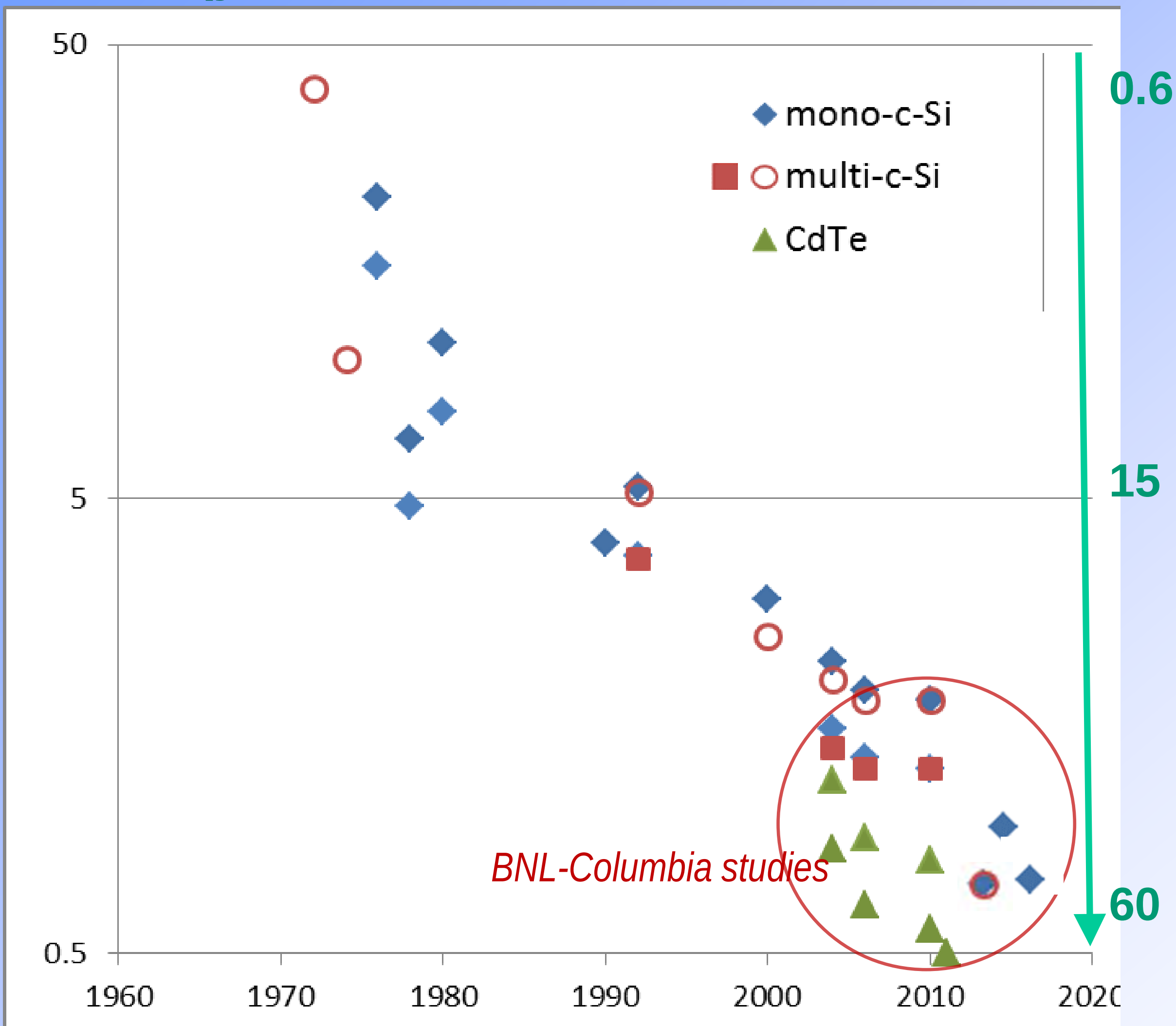
Energy Payback Times & Energy Return on Energy Investment Historical Evolution

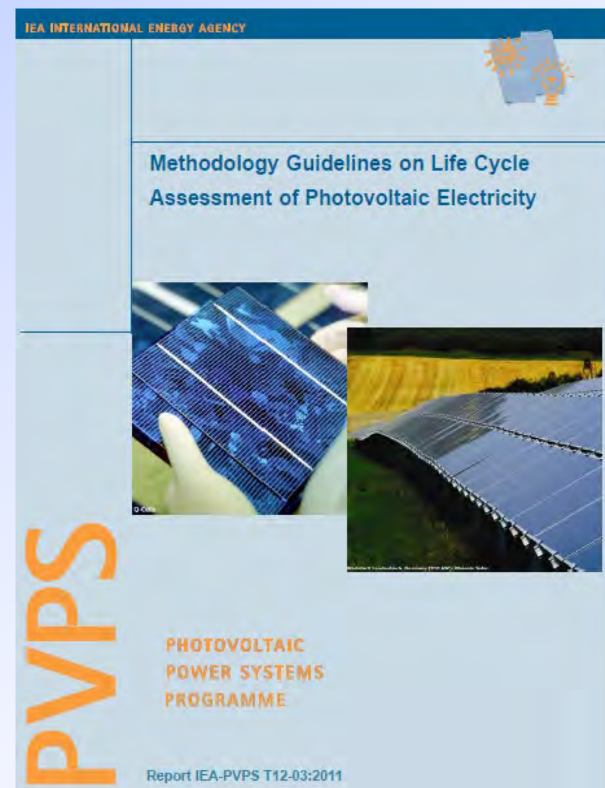
EPBT (years) EROI



Irradiation of 1700 and 2400 kWh/m^2/yr

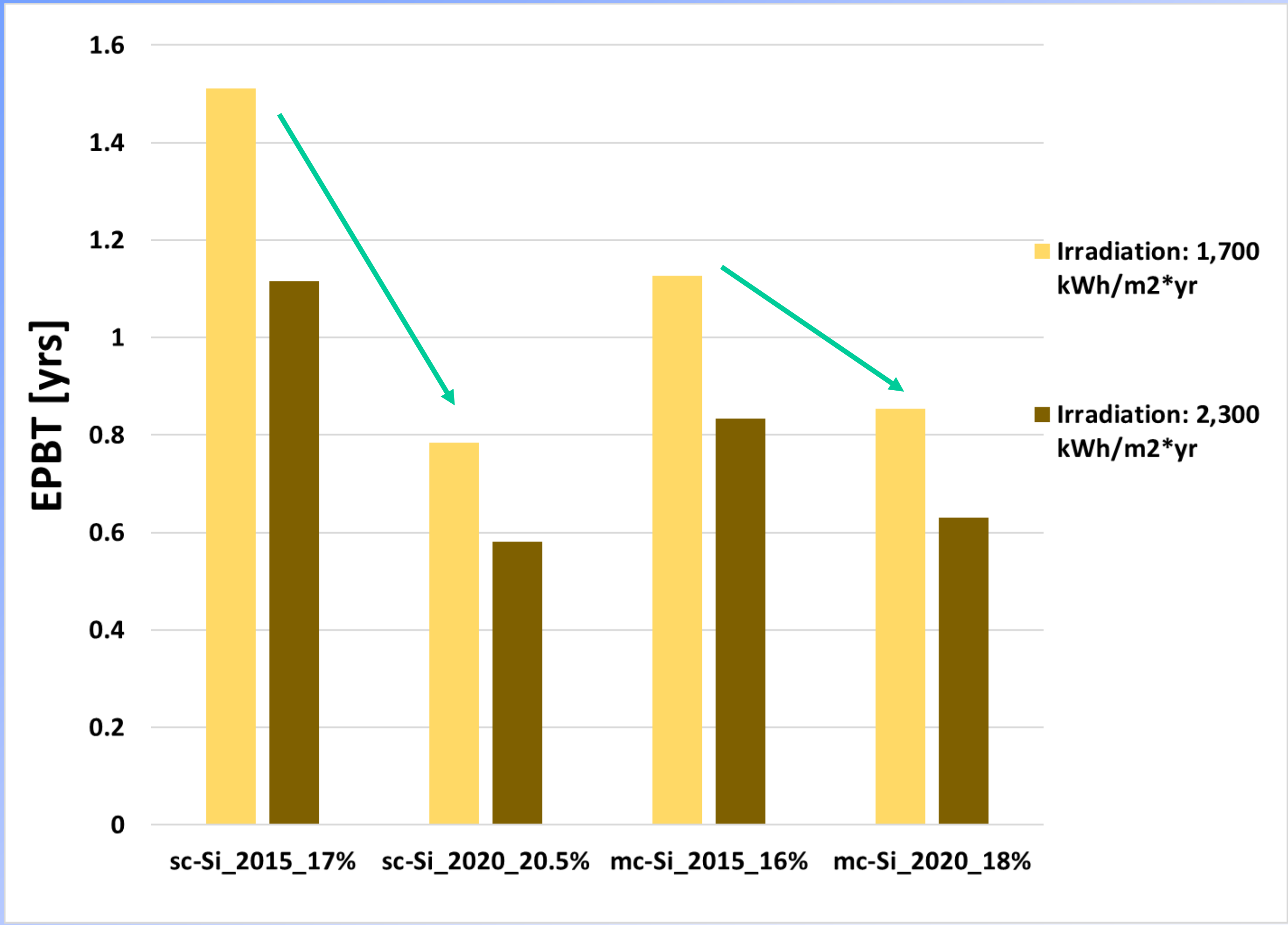
Divergence between studies due to:

1. LCA Methodology
2. Age of Data
3. Treatment of Intermittency
4. Real-world Performance Assumptions



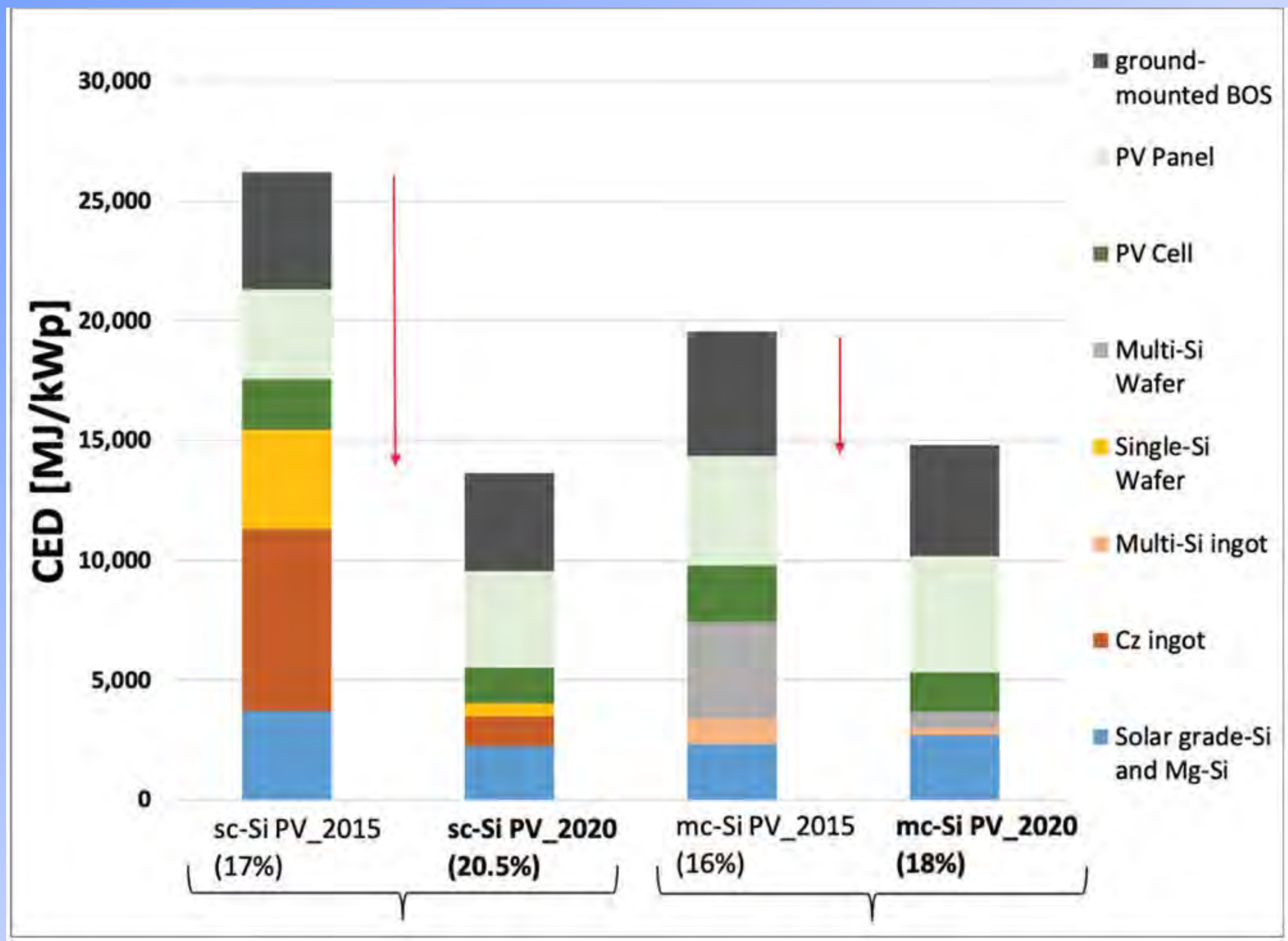
- Fthenakis V., PV Energy ROI Tracks Efficiency Gains, ASES Solar Today, 2012
- Fthenakis V., PV Total Cost of Electricity from Sunlight, Proceedings of IEEE, 2015

The Evolution Continues with Established Technologies

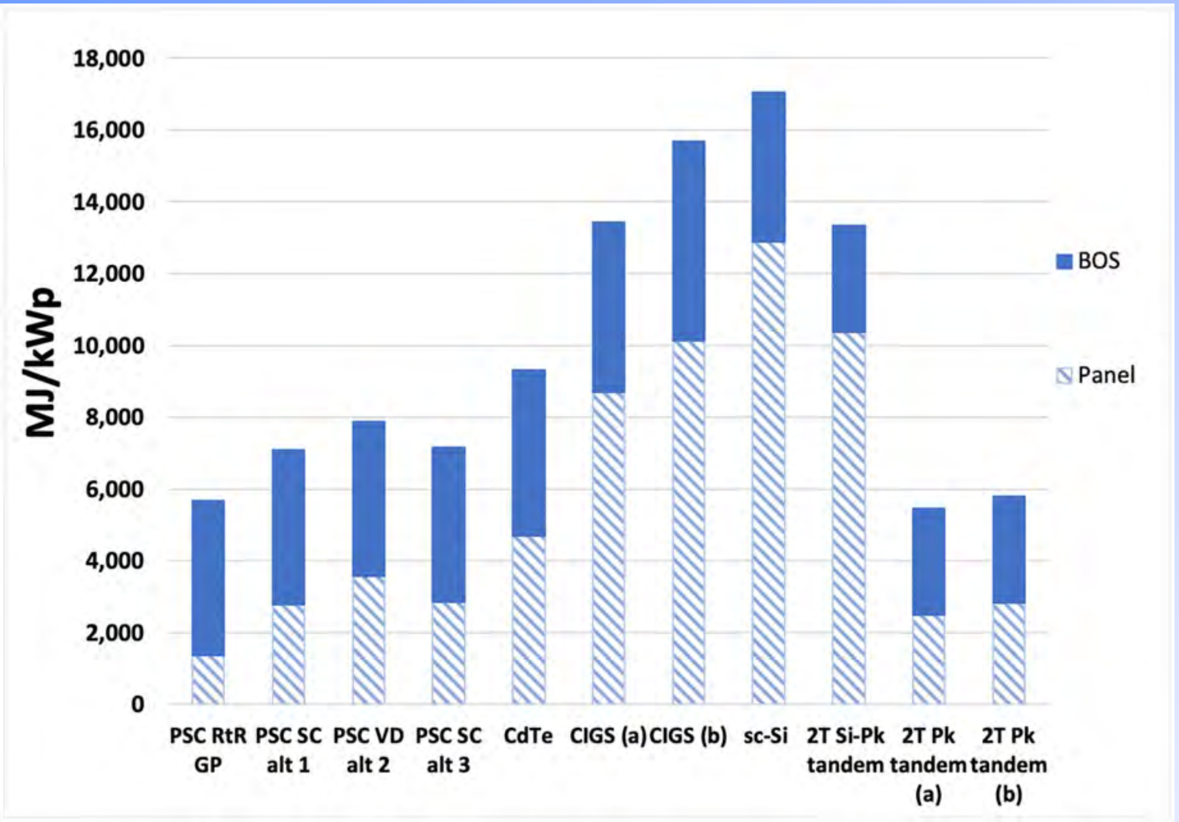


Fthenakis, V. and Leccisi, E., 2021. Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends. *Progress in Photovoltaics: Research and Applications*, *29*(10), pp.1068-1077.

Improvements in Conventional c-Si PV



and PV continues to improve with emerging Perovskite technologies



PV module	Reference efficiency [%]
PSC RtR GP	19.3
PSC SC alt 1	19.3
PSC VD alt 2	19.3
PSC SC alt 3	19.3
CdTe	18
CIGS (a)[a]	17.5[a]
CIGS (b)[b]	15[b]
sc-Si	20
2T Si-Pk tandem	28
2T Pk tandem (a)	28
2T Pk tandem (b)	28

Single-junction and Tandem Perovskite architectures

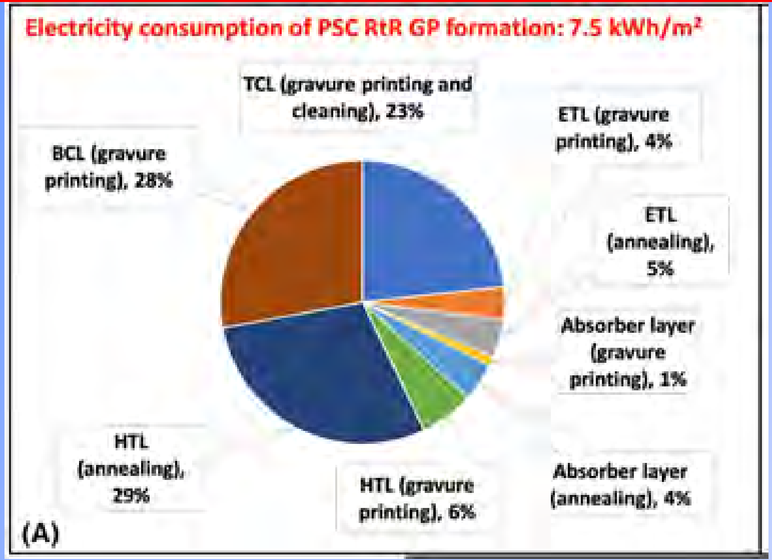
PSC Layer	PSC RtR GP, Encapsulation: Glass-PET		PSC SC alt 1, Encapsulation: Glass-Glass		PSC VD alt 2, Encapsulation: Glass-Glass		PSC SC alt 3, Encapsulation: Glass-Glass	
	Materials and thickness	Processes	Materials and thickness	Processes	Materials and thickness	Processes	Materials and thickness	Processes
TCL	FTO 500 nm	gravure printing cleaning	FTO 500 nm	oxygen plasma	ITO 110 nm	ultrasonication	FTO 500nm	oxygen plasma treatment
ETL	SnO2 60 nm	gravure printing annealing	SnO2 60 nm	spray coating annealing	SnO2 60 nm	spray coating annealing	PCBM 50 nm	spray coating annealing
Absorber	MAPbI3 300 nm	gravure printing annealing	MAPbI3 300 nm	spray coating annealing	MAPbI3 300 nm	evaporation vacuum	MAPbI3 300 nm	spray coating annealing
HTL	CuSCN 700 nm	gravure printing annealing	CuSCN 700 nm	spray coating annealing	CuSCN 700 nm	spray coating annealing	NiOx 60 nm	spray coating annealing
BCL	MoOx/ Al 100 nm	gravure printing annealing	MoOx/ Al 100 nm	evaporation vacuum	MoOx/ Al 100 nm	evaporation vacuum	Ag 100 nm	evaporation vacuum

Materials and thickness	Processes
Ag wires	Thermal evaporation
Indium Tin Oxide (ITO) 50 nm	Sputtering
SnO2 20 nm	Atomic layer deposition
PCBM 10 nm	Spray coating
LiF 1 nm	Thermal evaporation
$Cs_{0.17}FA_{0.83}Pb(Br_{0.17}I_{0.83})_3$ 350 nm	Spray deposition
PFN 1 nm	Thermal evaporation
Poly-TDP $(C_{22}H_{21}N)_n$ 5 nm	spray coating
NiOx 20 nm	spray coating
Indium Tin Oxide (ITO) 20 nm	Sputtering
i a-Si 5 nm / p a-Si 10 nm	Plasma-enhanced CVD
Si 0.18 mm	Czochralski
i a-Si 5 nm / p a-Si 10 nm	Plasma-enhanced CVD
ITO 80 nm	Sputtering
Ag 100 nm	Thermal evaporation

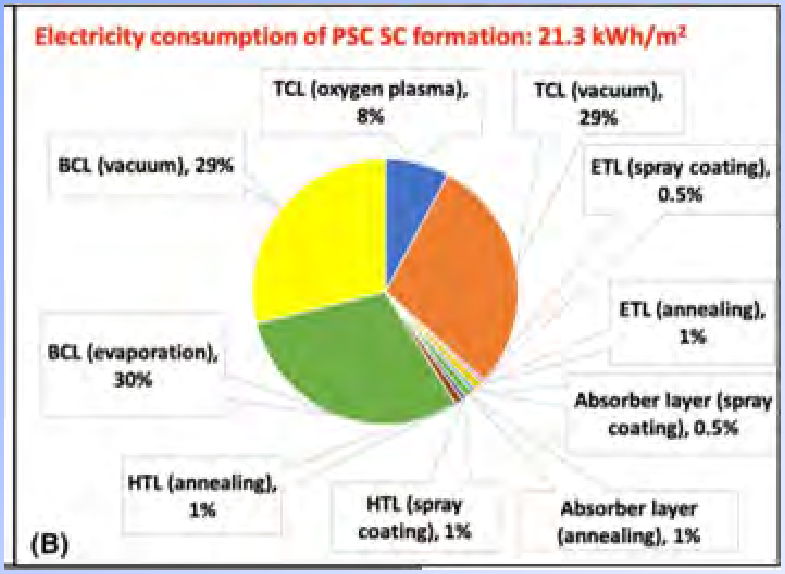
Materials and thickness	Processes
ITO 110 nm	Sonication and ozone treating
Poly-TDP $(C_{22}H_{21}N)_n$ 5 nm	Spray coating
PFN-Br $(C_{56}H_{80}N_2.Br_2)_n$ 1 nm	Spray coating
$FA_{0.6}Cs_{0.3}DMA_{0.1}PbI_{2.4}Br_{0.6}$ 300 nm	Spray coating
Lithium fluoride (LiF) 1 nm	Thermal evaporation
C_{60} 30 nm	Thermal evaporation
Polyethylenimine 1 nm	Spray coating
Aluminum-doped zinc oxide 25 nm	Atomic layer deposition
Indium Tin Oxide 5 nm	Sputtering
PEDOT:PSS 20 nm	Spray coating
$FA_{0.75}Cs_{0.25}Sn_{0.5}Pb_{0.5}I_3$ 850 nm	Spray coating
C_{60} 30 nm	Thermal evaporation
Bathocuproine (BCP) 6 nm	Thermal evaporation
Ag 100 nm	Thermal evaporation

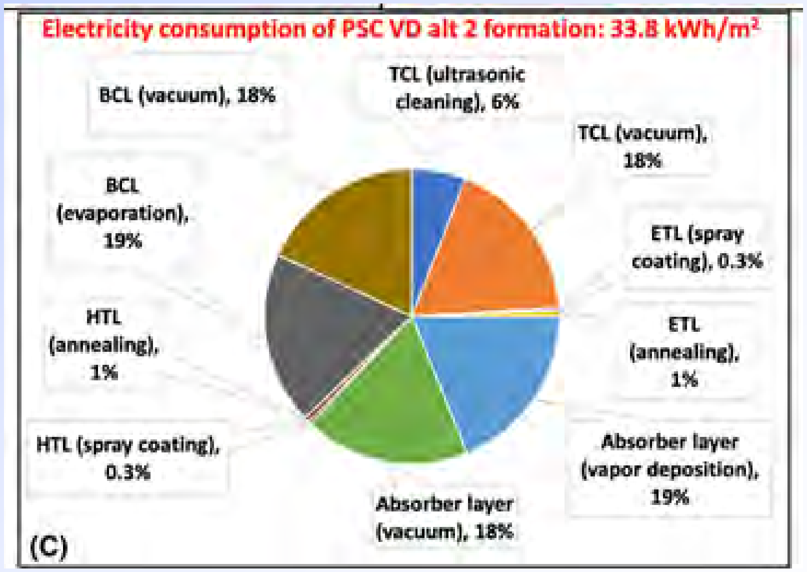
Lecissi, Fthenakis, Progress in Photovoltaics, 2021

Electricity Consumption of Single-junction Perovskite Solar Cell Formation



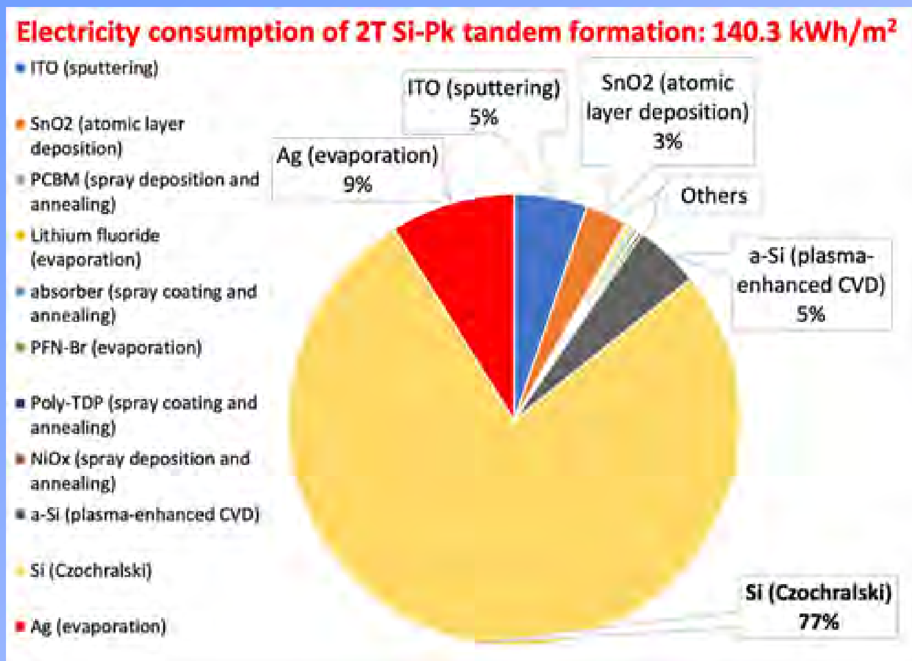
Energy data on RtR gravure printing (GP) were derived from commercial 8-station RtR photosensitive film printing tools running at 30 m/min. Data correspond to producing 45 m2/min of perovskite PV with a 1.5 m wide web.

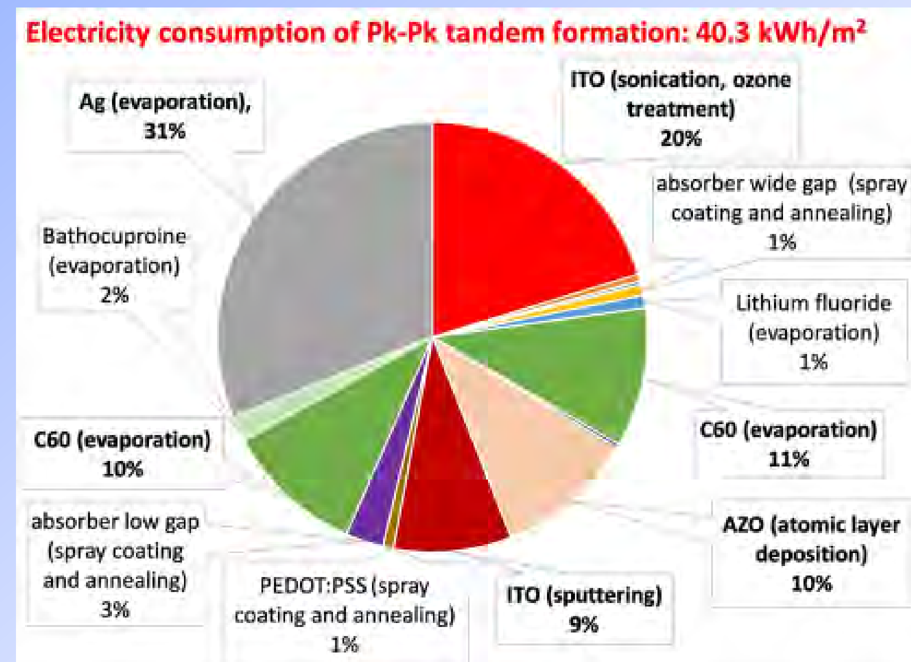




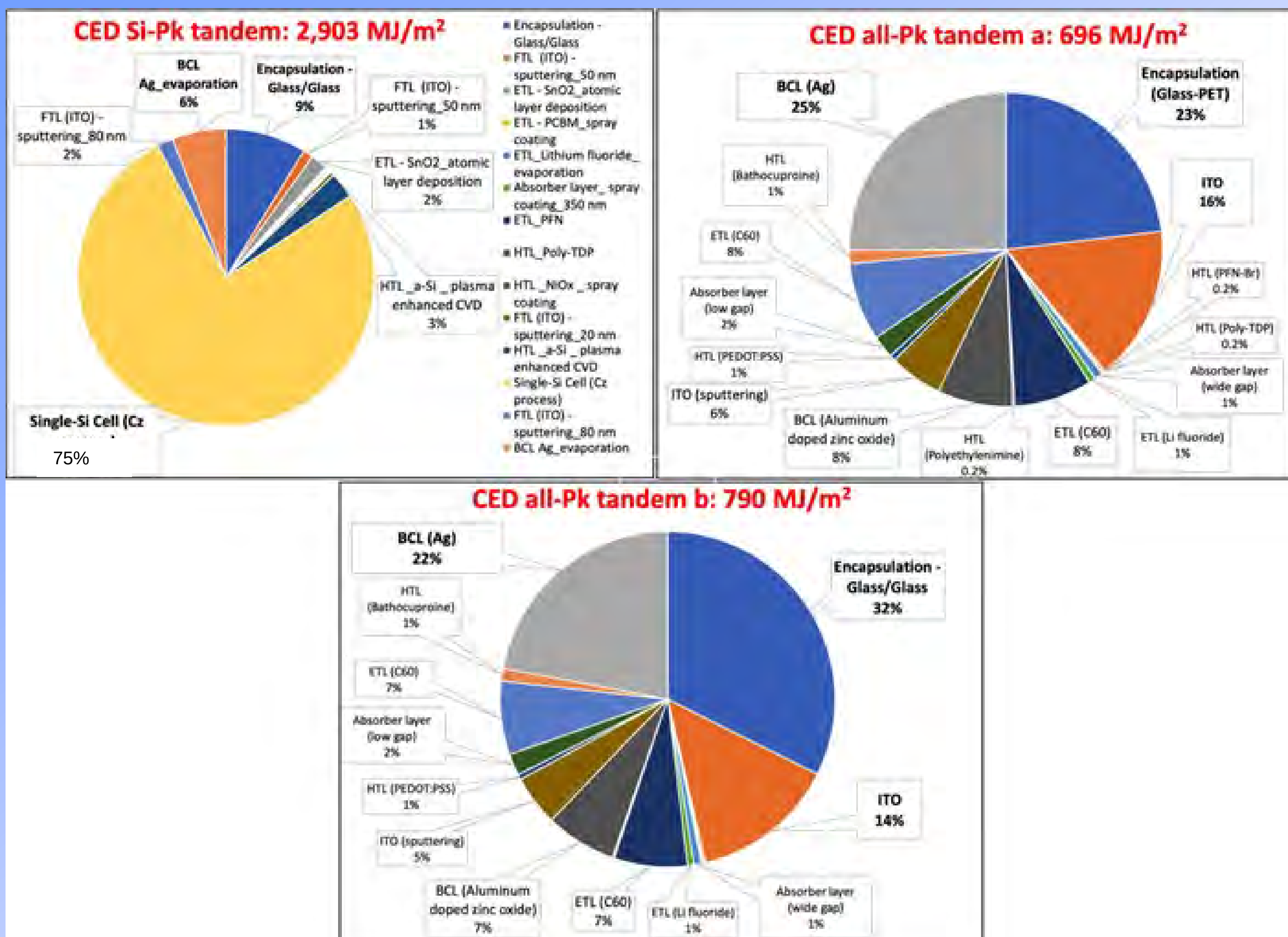
Electricity consumption of PSC SC was estimated for scaling the lab measurements to industrial scales, based on equipment power rating, associated processing time and energy use factor

Electricity Consumption of Tandem Si-Perovskite and All-Perovskite Solar Cells

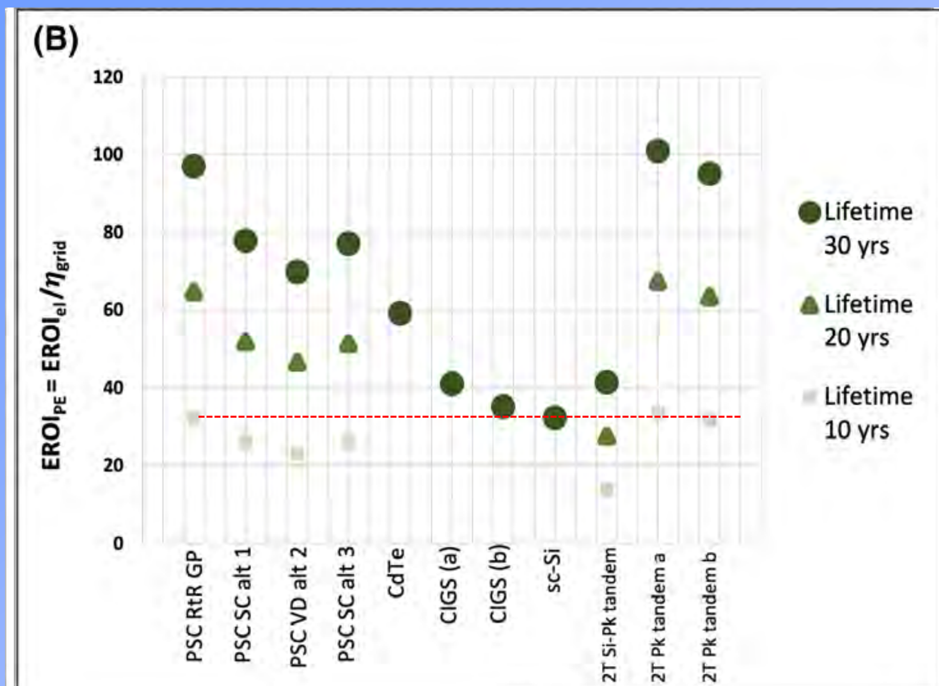


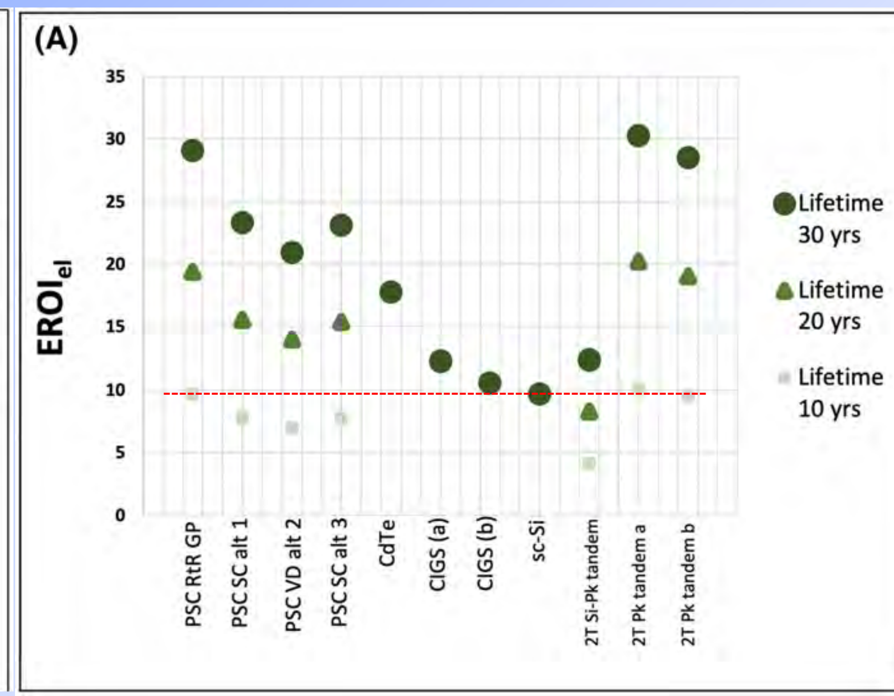


Cumulative Energy Demand (CED) of Tandem Perovskite Panels



Energy Return on Energy Investment (EROI) of PV Systems: Irradiation 1800 $kWh/m^2/yr$





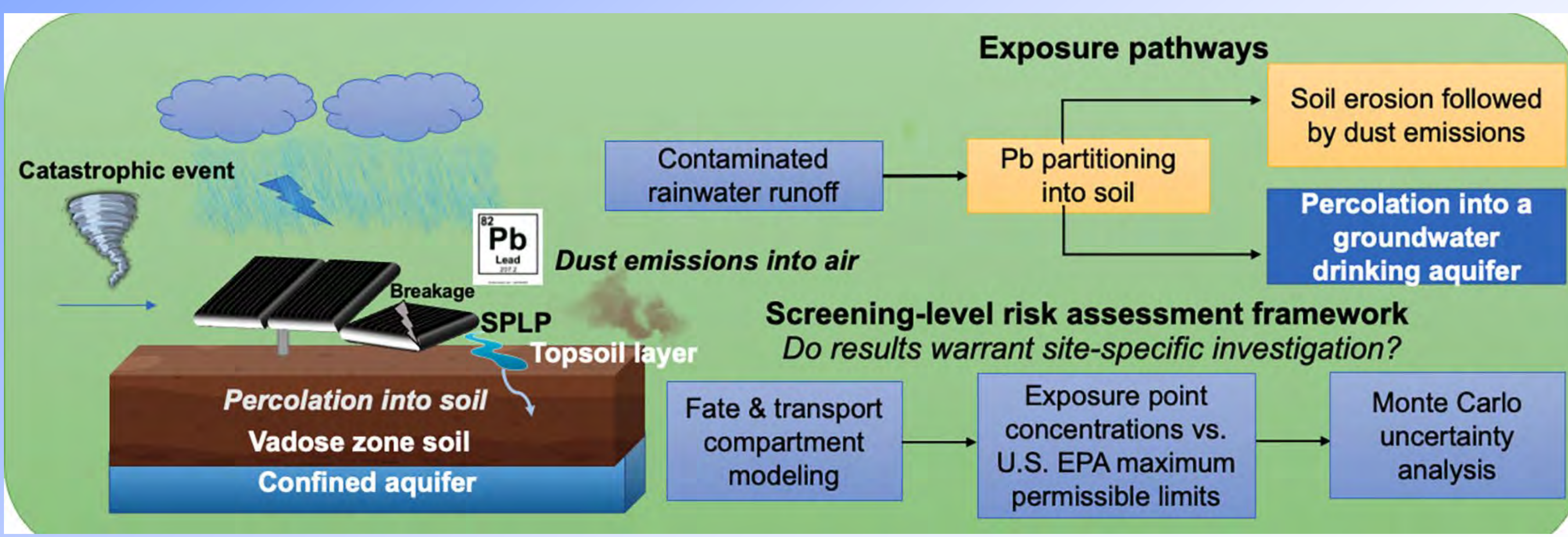
Fossil-fuel dominated grid
Primary energy to electricity conversion n_{grid}=0.3

100% renewable energy grid

Fate & Exposure Assessment of Pb Leachate from Broken Perovskite Modules

While today's efforts are focused on stability and scalability of lead-halide perovskite (LPH) photovoltaics, the toxicity of lead remains a major challenge to their large-scale commercialization.
The amount of Pb in LPH PV is small (0.42 g Pb/m2 in 300 nm MAPbI3 layer), but LPH films degrade to very highly soluble PbI2.

We started an investigation of associated risks by using a screening-level, EPA-compliant model of fate and transport of Pb leachate in groundwater, soil and air, following hypothetical catastrophic breakage of LHP modules in conceptual utility-scale sites



Fate & Exposure Assessment of Pb Leachate from Broken Perovskite Modules

Scenarios & associated Pb releases

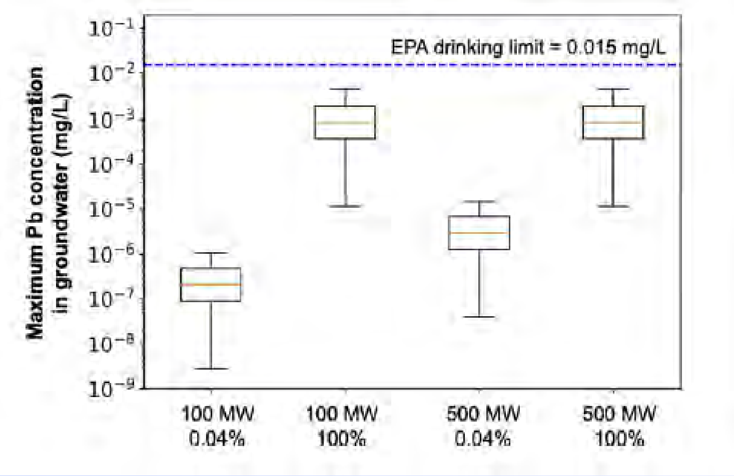
scenario	capacity (MWp)	module breakage rate	maximum Pb released from impacted area (kg)
	PV site parameter		
scenario A	100	0.04%[a]	0.228
scenario B	100	100%	569
scenario C	500	0.04%[a]	1.14
scenario D	500	100%	2,848

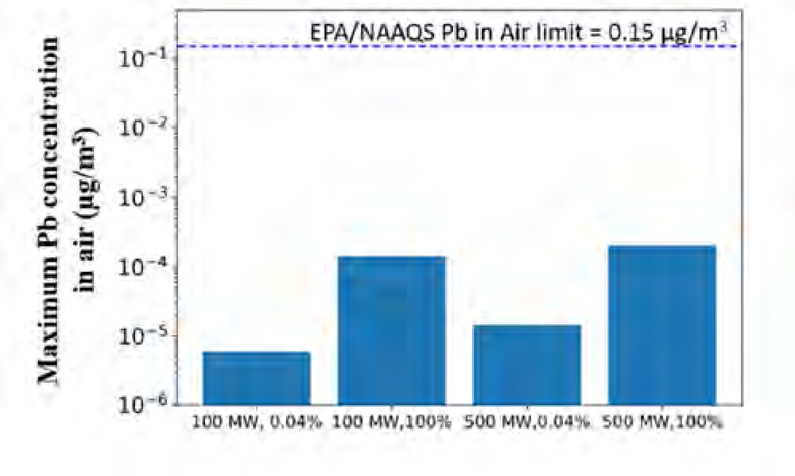
Methodologies Used

- ✓ EPA Soil partition coefficient model
- ✓ Dilution Attenuation Factors
- ✓ SCREEN3 Gaussian plume dispersion

Tentative Results

Pb concentration in groundwater in all scenarios fall below EPA regulatory limits.
This is ascribed to the strong binding of Pb to soil under the assumption of equilibrium of Pb compounds between soil and soil pore water





Study Limitations: Absence of Pb leachate concentration data from SPLP testing of commercial modules. We used TCLP of a lab mini-module as approximation.

Remaining Challenges and New Opportunties

- **Photovoltaics End-of-Life Management/ Recycling Implementation**
- **Dual Use of Land:**
  - **Agriphotovoltaics**
  - **Ecosystem Services from solar facilities**

- **Variable Renewable Energy Systems Integration**
- **Addressing Problems of Humanity: Solutions enabled by abundant low-cost solar energy**

The Future: Problems awaiting Solutions

Top 10 problems of Humanity for the next 50 years
Richard Smalley (1943- 2005)

1. Energy
2. Water
3. Food
4. Environment
5. Poverty
6. Terrorism & War
7. Disease
8. Education
9. Democracy
10. Population

Problems and Integrated Solutions

Top 10 problems of Humanity for the next 50 years

Richard Smalley (1943- 2005)

1. Energy
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Solar Water Desalination & Electrolysis
New Partnerships - New Markets

What is common between water desalination and electrolytic production of hydrogen?

- **They both use water and currently use fossil energy**
- **Water desalination emits 2-20 kg $CO_{2(eq)}$ per m^3 H_2O produced**
- **H_2 from Natural Gas Steam Methane Reforming (SMR) generates 11.8 kg $CO_{2(eq)}$ per kg H_2 produced**
- **The cost of energy is the major cost contributor in both**

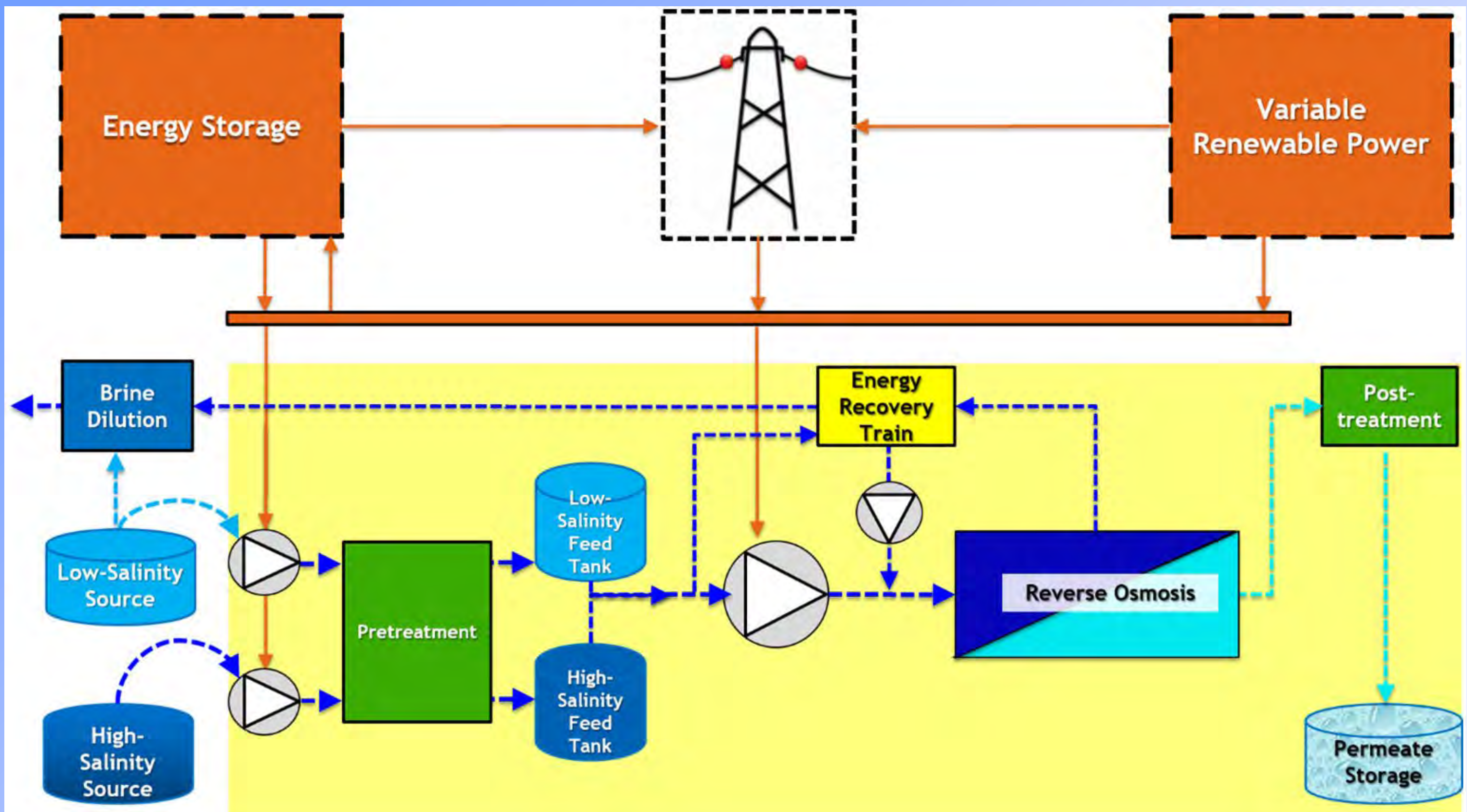
Solar Desalination

- **PV-RO-Flexible Desalination Design** (Winner US-Israel Design Challenge, 2017-2018)
- **Solar Thermal Advanced Desalination Designs** (with Plataforma Solar de Almeria, Spain, 2018-2021 and NREL 2022-2024)

Solar Hydrogen

- **Dynamic Operation for time-of-use electricity pricing** (with Dan Esposito, Chem Eng)

Active-salinity-control reverse osmosis (ASCRO) desalination as a flexible load resource

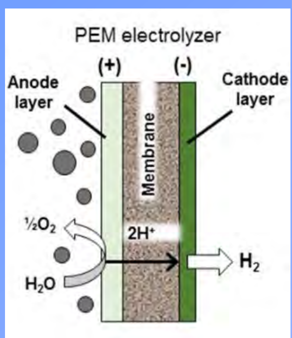


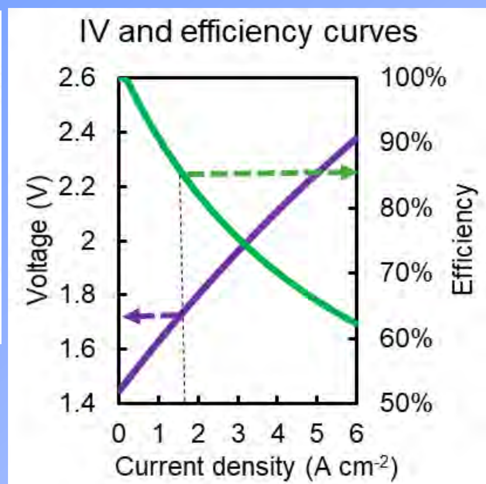
- ASCRO dynamically controls energy consumption by operating across a range of feed salinity, allowing it to shift over a wide range of pump feed flows and pressures.
- Enabling a dynamic power consumption, it can improve the integration of solar by responding to power fluctuations without compromising permeate production.

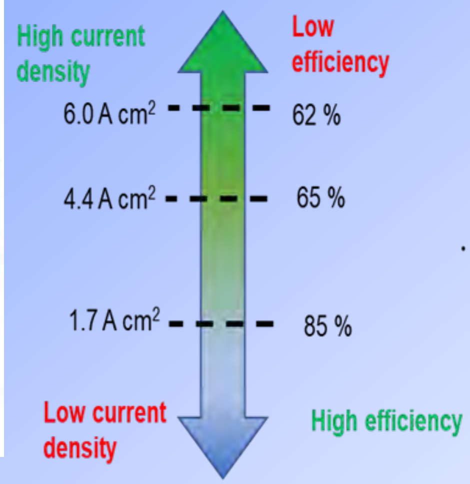
Atia A., Fthenakis V.M., Active-salinity-control reverse osmosis desalination as a flexible load resource, Desalination, 468, 114062, 2019
Winner US-Israel Desalination Design Challenge, 2017-2018

Water Electrolysis with Variable Energy

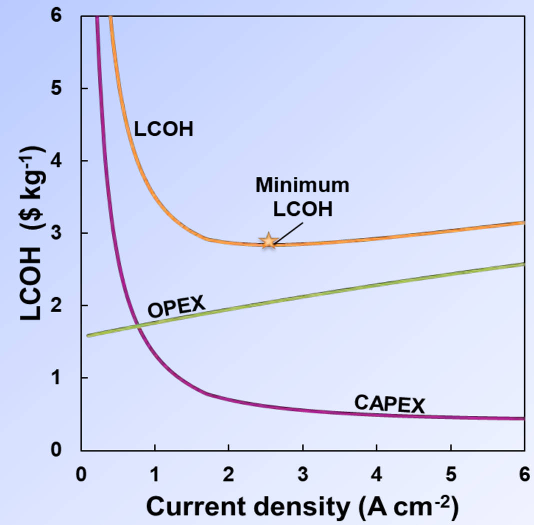
Efficiency vs. Current Density in PEM electrolyzers



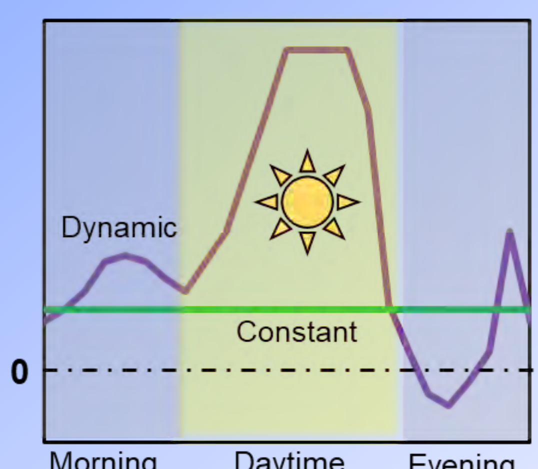


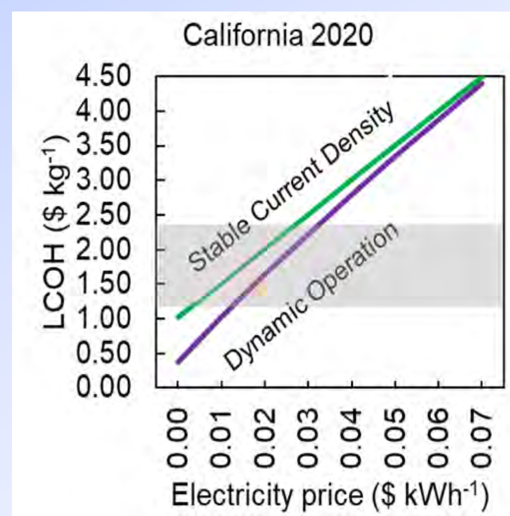


Levelized Cost of H2 (LCOH)



Current density & H2 production



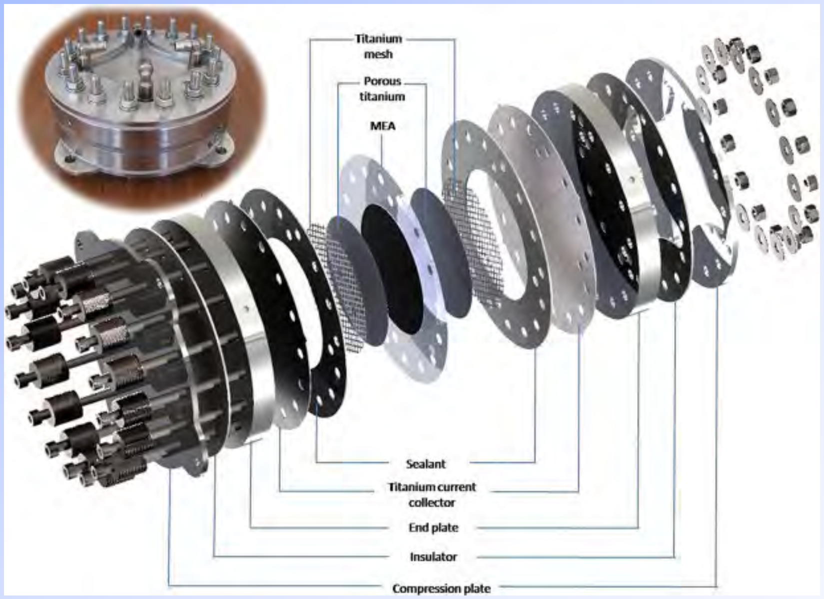


H_2 from SMR;
NG \$3-10/MBtu

-Ginsberg G.,Venkatraman M., Esposito D., Fthenakis V, Minimizing the Cost of Green Hydrogen Production through Dynamic Polymer Electrolyte Membrane Electrolyzer Operation, Cell Reports Physical Science, 3(6), 100935, 2022
-Ginsberg M., Esposito D., Fthenakis V, Designing Off-Grid Green Hydrogen Plants Using Dynamic Polymer Electrolyte Membrane Electrolyzers to Minimize the Cost of Hydrogen Production, Cell Reports Physical Science, 4(10), 101625, 2023

Impact of High and Variable Current Density on Degradation and Useful Life

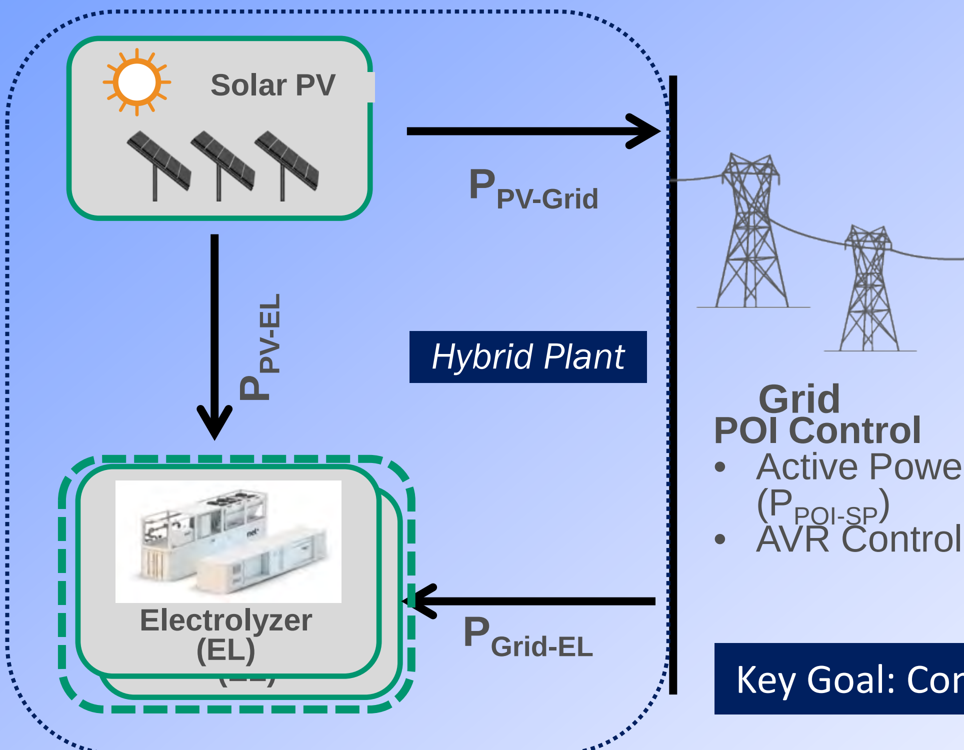
- High cell voltages result in the formation of **low conductivity oxides** on the surface of the titanium current collector, resulting in larger ohmic drops during operation.
- **Membrane thinning** - gradual chemical attack of the membrane accompanied by release of fluoride ions in the case of perfluorosulfonic acid (PFSA)-based membranes such as Nafion.
- **Hotspots and gas crossover** or permeation, which becomes a safety concern below 20 µm.
- **Accumulation of oxygen gas bubbles** in the pore bodies of the porous transport layer, which increases mass transport overpotentials.
- Higher production rate may lead to **large localized pressures**, as H2 must escape through small channels in the gas diffusion electrode in order to be released.

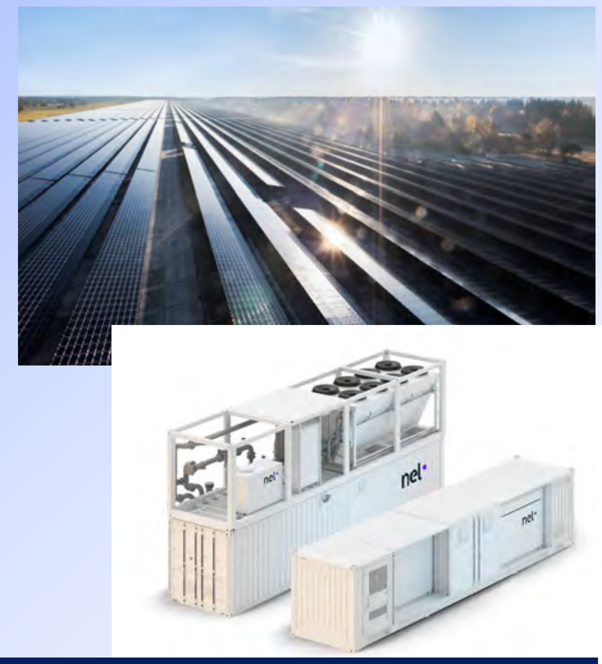


Mitigation strategies

-Nanostructured and conductive antimony-doped tin oxide reduce Ir loadings
-Protective Pt coatings over PTLs and bipolar plates minimize formation of the resistive TiO2
- Superhydrophilic surface treatment of a sintered titanium PTL prevent runaway voltage

Power Flow in a PV+Electrolyzer Hybrid Plant (Simplified)



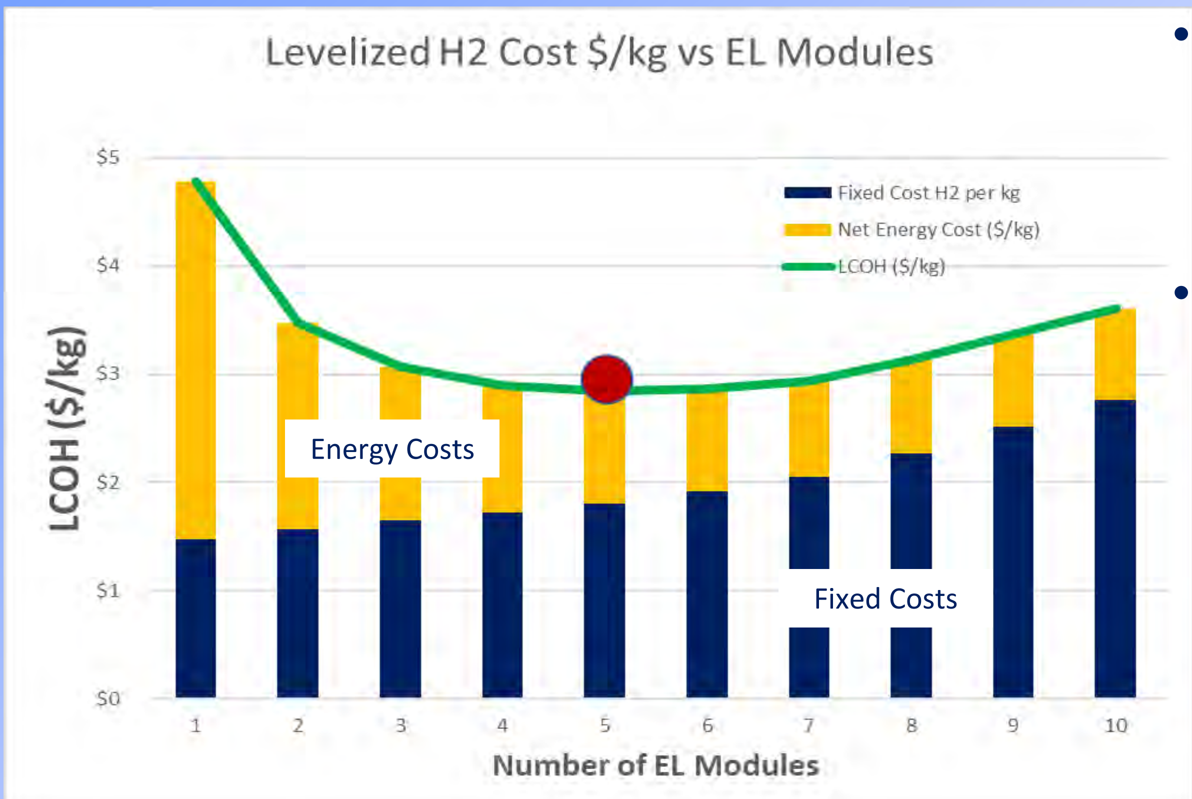


Key Goal: Configure Hybrid Plant to Reduce LCOH

LCOH: Levelized Cost of Hydrogen

Courtesy Mahesh Morjaria, Terabase Energy Inc.

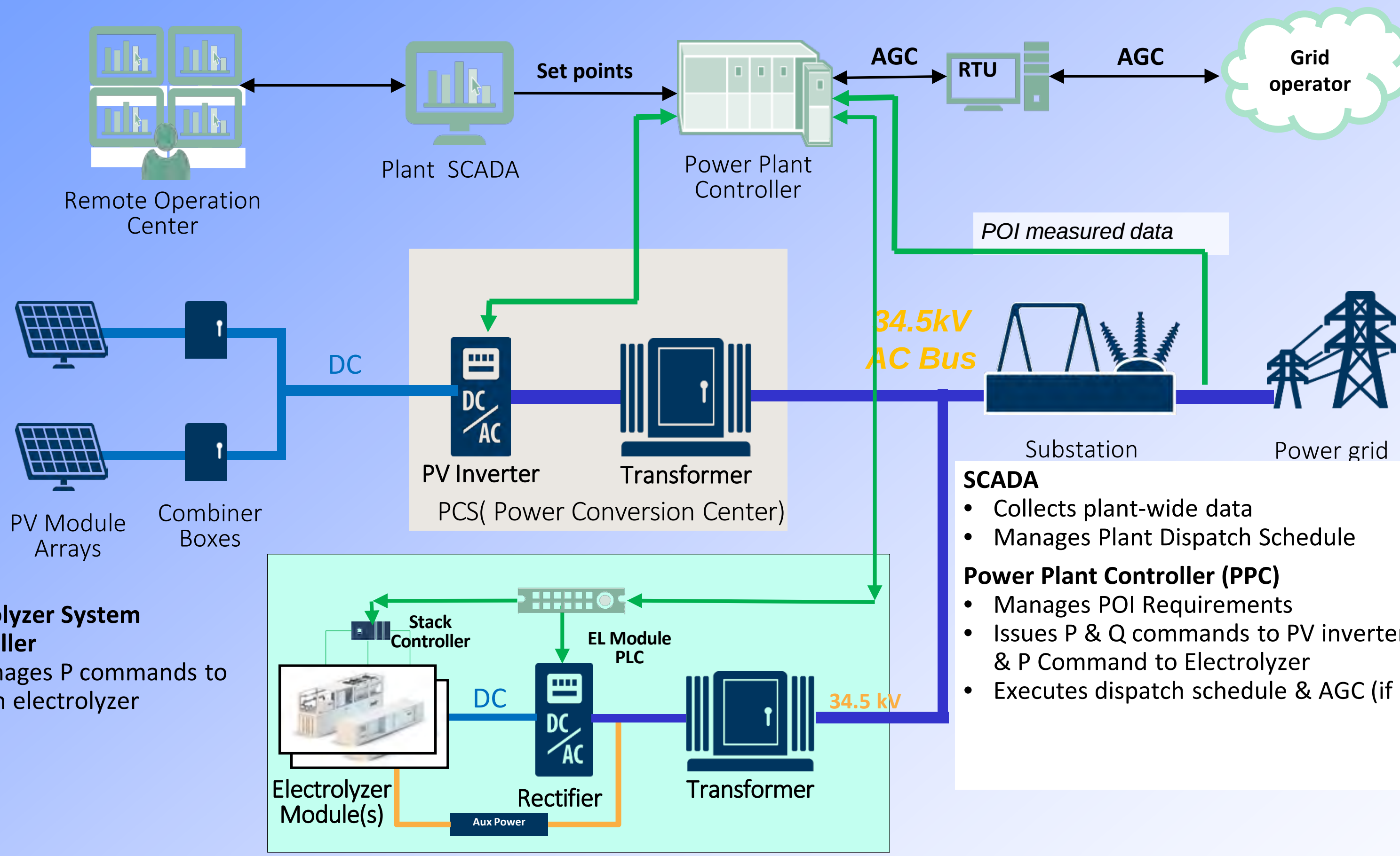
Key Goal: Optimize Hybrid Plant Design to Reduce Levelized Cost of Hydrogen (LCOH)



- Increasing EL capacity more fully utilizes the PV electricity …reducing energy costs
- However, increasing EL capacity increases fixed capital while decreasing their capacity factor

Courtesy Mahesh Morjaria, Terabase Energy Inc

Plant Controls & SCADA System Architecture



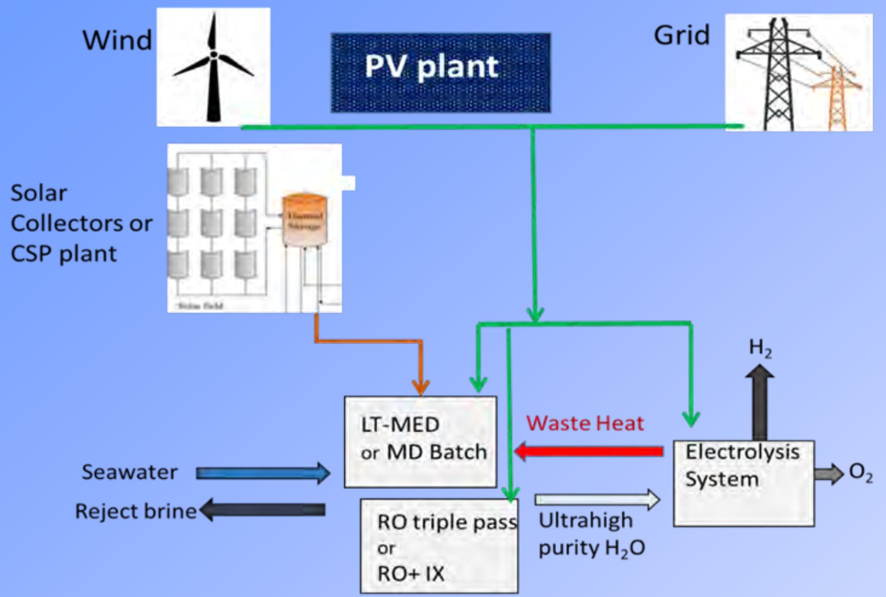
Electrolyzer System Controller
- Manages P commands to each electrolyzer

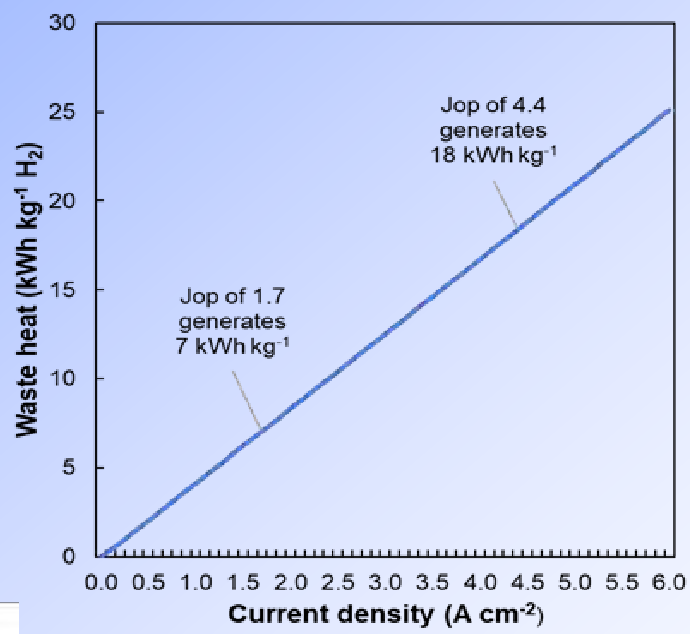
SCADA
- Collects plant-wide data
- Manages Plant Dispatch Schedule

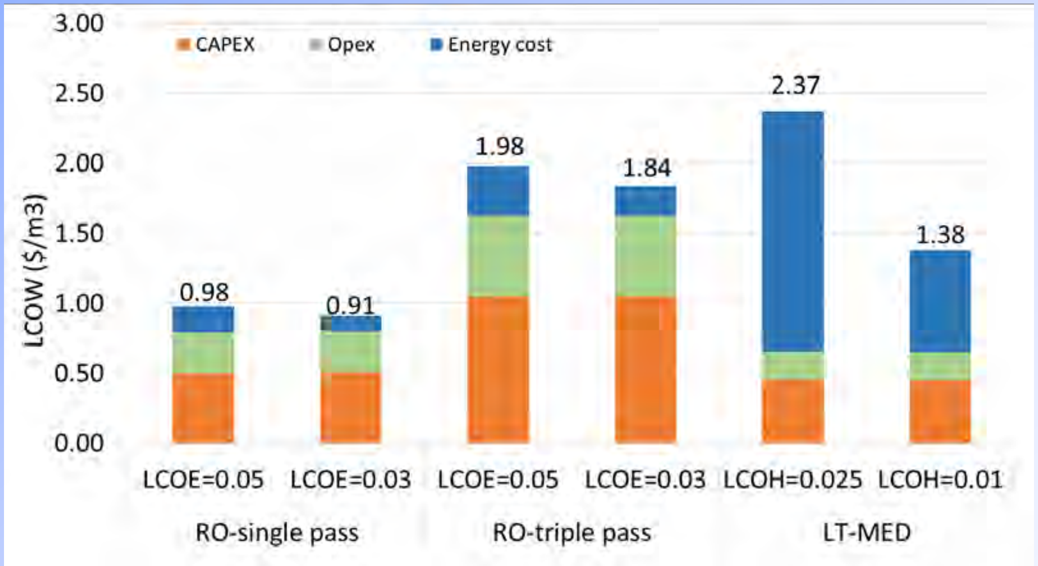
Power Plant Controller (PPC)
- Manages POI Requirements
- Issues P & Q commands to PV inverters & P Command to Electrolyzer
- Executes dispatch schedule & AGC (if required)

Courtesy Mahesh Morjaria, Terabase Energy Inc

Integrated Solar, Desalination & Hydrogen







Ginsberg G., Zhang Z., Atia A., Esposito D., Fthenakis V., Integrating Solar Energy, Desalination and Electrolysis, Solar RRL, , 6(5), 2021

Closing Remarks

- *The PV industry evolves on all sustainability dimensions.*
- *Active dissemination of research results and comprehensive defense against attacks from vested interests is essential to maintain the support of the public and governments.*
- *Recycling end-of-life systems becomes an important aspect of sustainability and needs to be optimized to help rather than hinder the affordability of PV systems.*
- *Low cost solar energy creates new opportunities while addressing humanity's big problems.*
- *The solar variability challenge is addressed with process hybridization, advanced modeling and controls offering flexibility and value earning grid services.*

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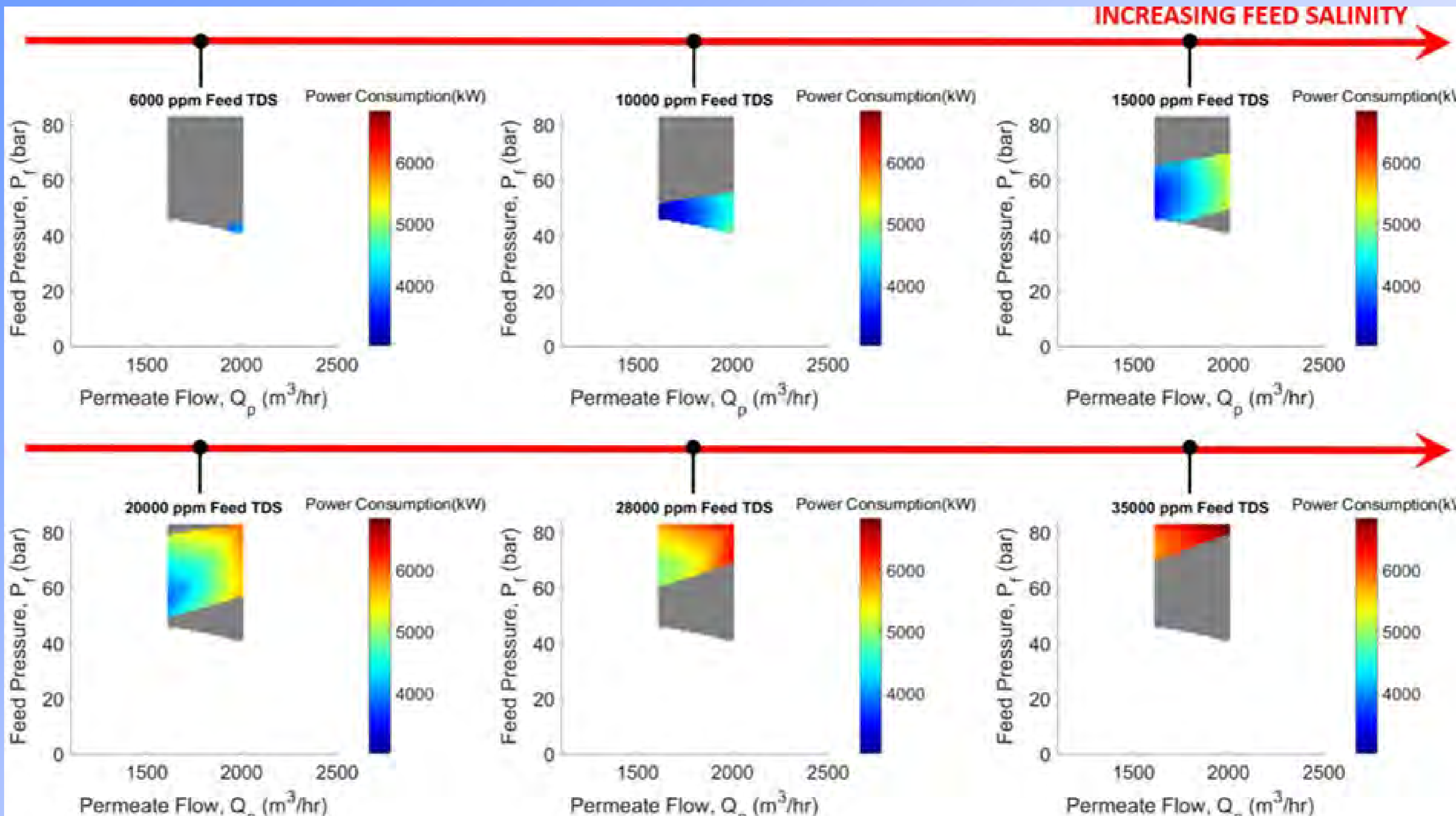
Auxiliary Slides

Active-salinity-control reverse osmosis desalination as a flexible load resource



The operational envelope of the ASCRO system shifts with an increase in feed salinity. Increasing salinity from 6000 to 35000 ppm corresponds to an increase in feed pressure from 40 to 80 bar with corresponding power consumption increasing from ~3500 to 8000 kW, while the freshwater production is maintained in the range of 1500-2000 m^3/hr

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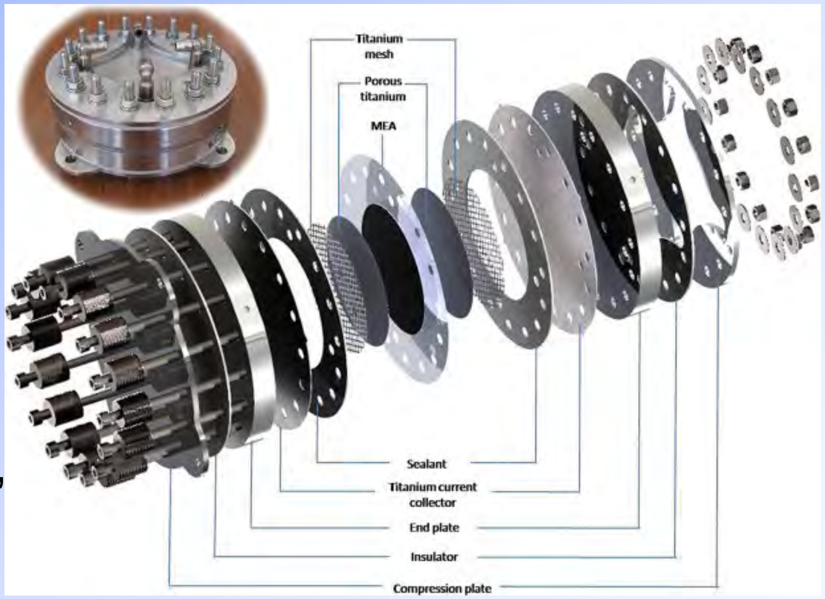

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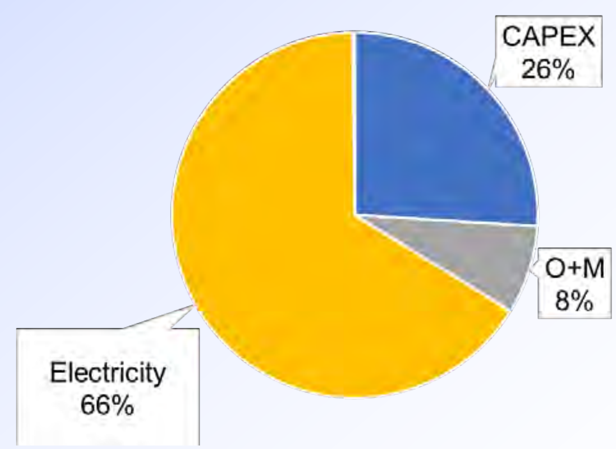
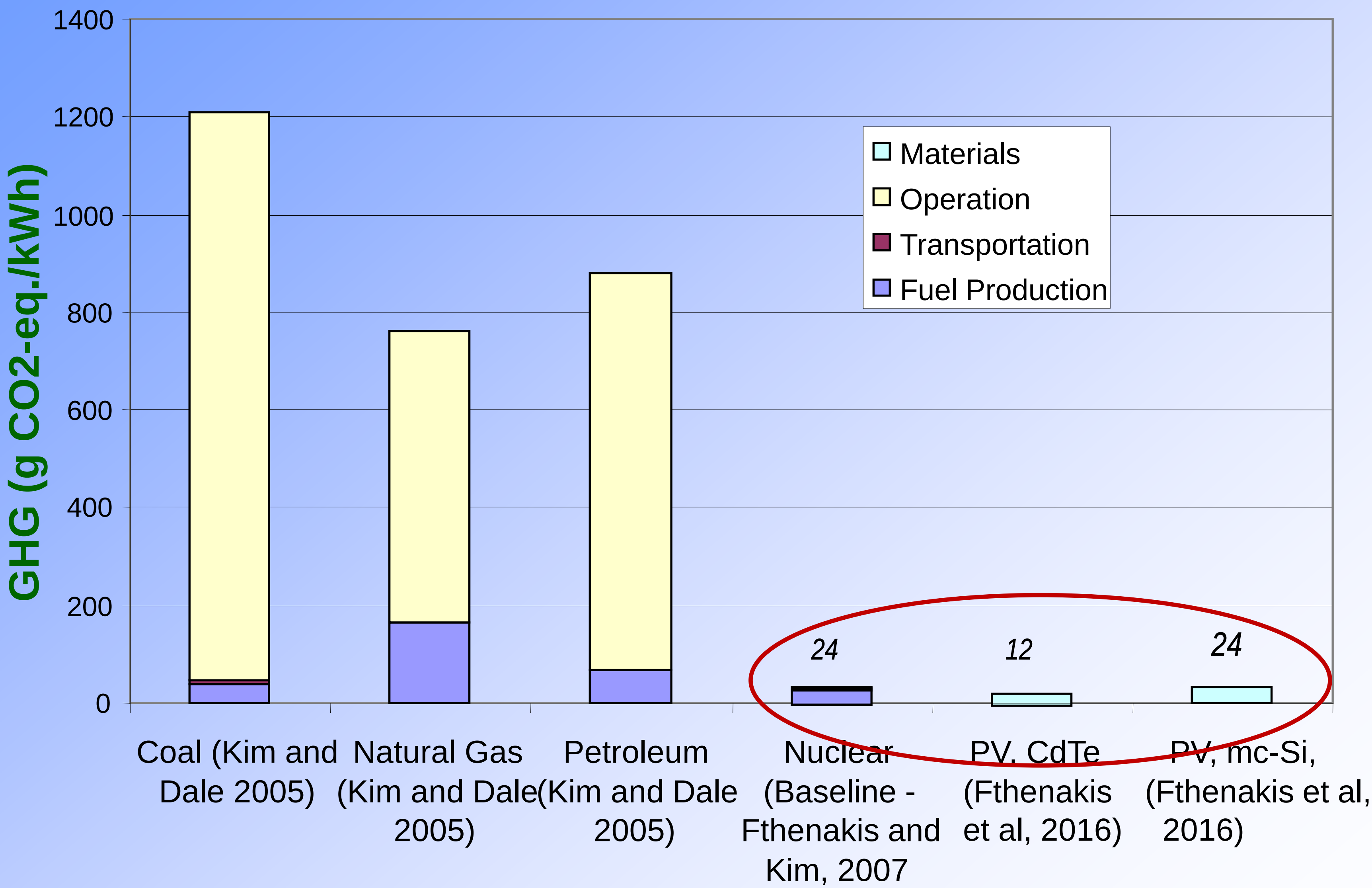


PEM System CAPEX: ~$700 – 1,000/kW

Center for Life Cycle Analysis
Columbia University in the City of New York

GHG Emissions from Life Cycle of Electricity Production: Comparisons



Fthenakis, California Energy Commission, *Nuclear Issues Workshop*, June 2007
Fthenakis & Kim, Life Cycle Emissions…, *Energy Policy, 35, 2549, 2007*
Fthenakis & Kim*, ES&T, 42, 2168, 2008; update 2016*