Photovoltaics Sustainability: Past, Present and Future

Vasilis Fthenakis

Center for Life Cycle Analysis
Columbia University

Asian-Pacific Solar Conference
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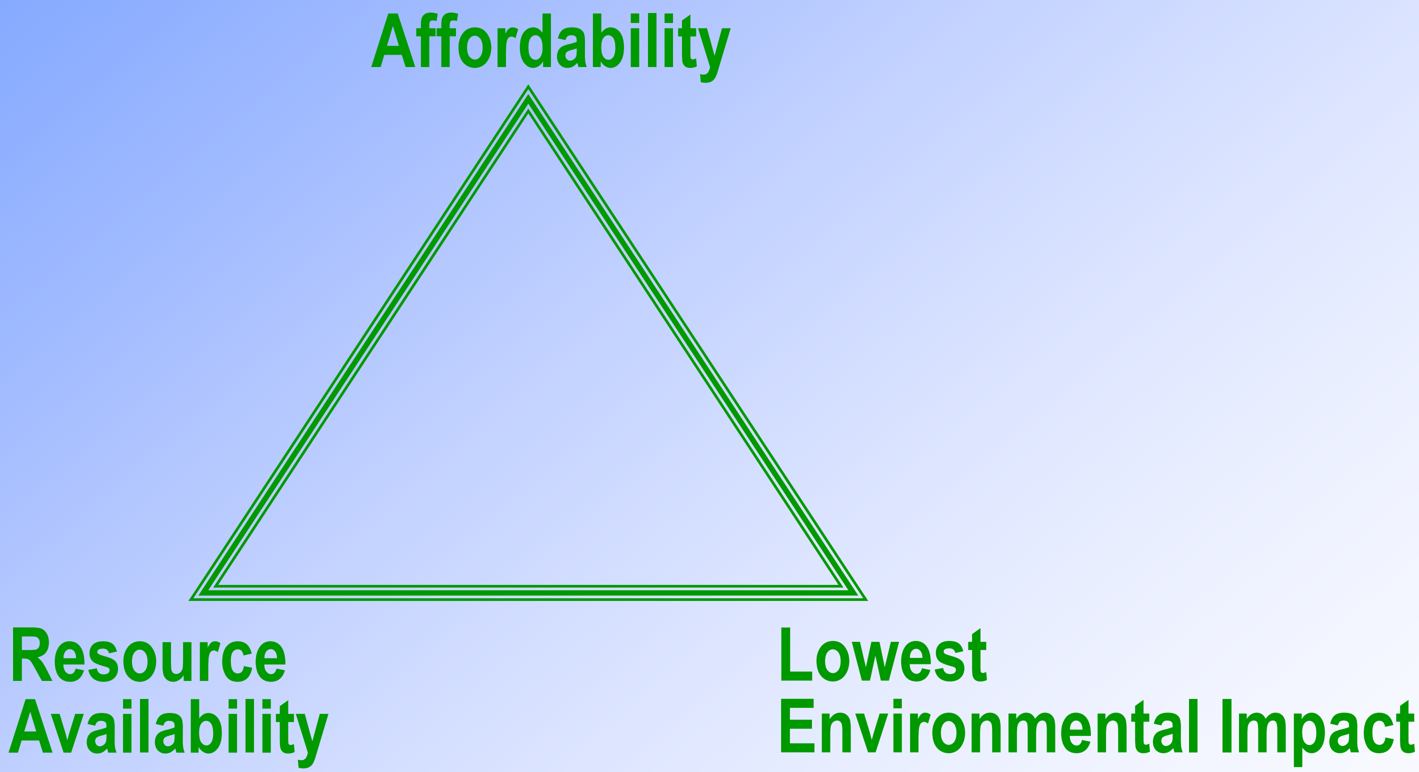
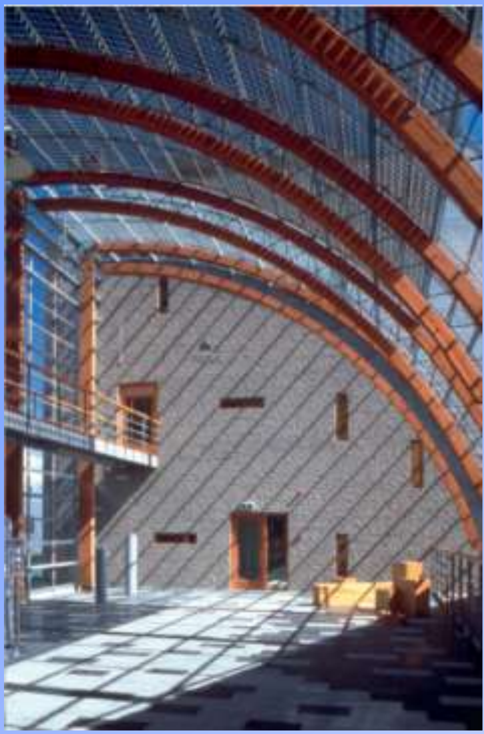
www.clca.columbia.edu
vmf5@columbia.edu

Photovoltaics –Sustainability Criteria



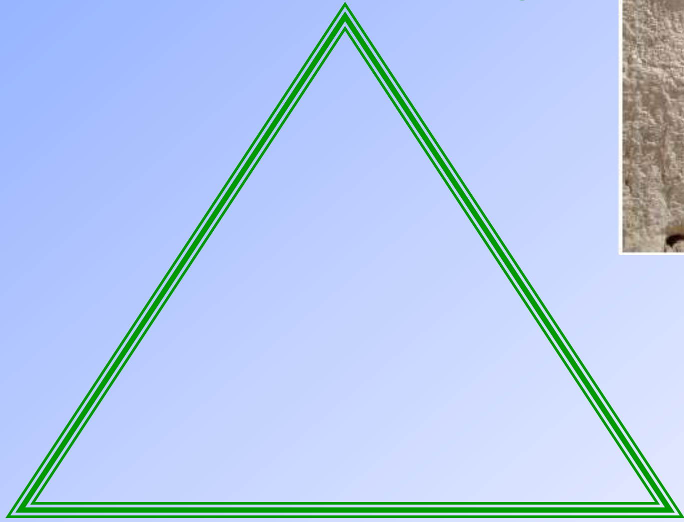
Images from: Fthenakis & Lynn, *Photovoltaic-Systems Integration and Sustainability*, Wiley, 2018

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



-Niche markets

Affordability



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

Resource Availability

Lowest Environmental Impact

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, 201

PV Environmental Health & Safety (PV-EH&S) Assistance Center

Facility Specific EH&S Assistance

- Assistance on R&D and Start-up Facilities
  - Occupational Exposure Prevention
  - Safety Audits/ Incident Analysis

Broad EH&S Issues

- Hazard Analysis of New Technologies, Materials & Processes
- Toxicology of New Materials
- Lead-Free Solder Technology Transfer
- Waste Management/ Recycling
- Information Dissemination
  - PV EH&S Tutorials at IEEE PVSC
  - Four PV EH&S Workshops with Wide Industry Participation
  - 170 Publications on PV EH&S; all technologies

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

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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

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

Can PV compete with electricity from fossil fuels?

Affordability

- Energy Return on Energy Investment
- Te, In, Ga, Ge, Ag in PV
- Li, Co in Batteries

Resource Availability

-EH&S R&D facilities
-EH&S Standards for Industry
-LCA & Recycling
- Large PV Power Plants Environmental Impacts

Lowest Environmental Impact

Fthenakis, The sustainability of thin-film PV, Renewable & Sustainable Energy Reviews, 2009
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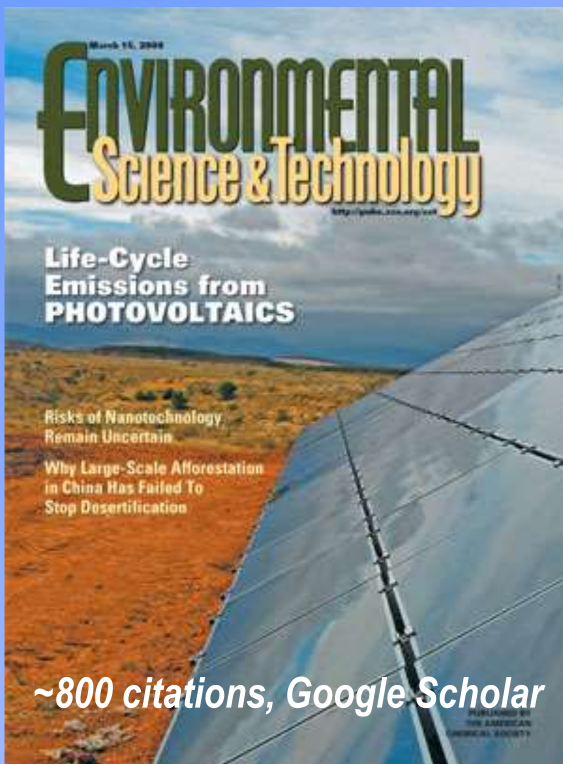
Images from: Fthenakis & Lynn, *Photovoltaic-Systems Integration and Sustainability*, Wiley, 2018

Addressing Issues and Perceptions on PV Environmental Impact -Proactively

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

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

Affordability -A Grand Plan for Solar Energy

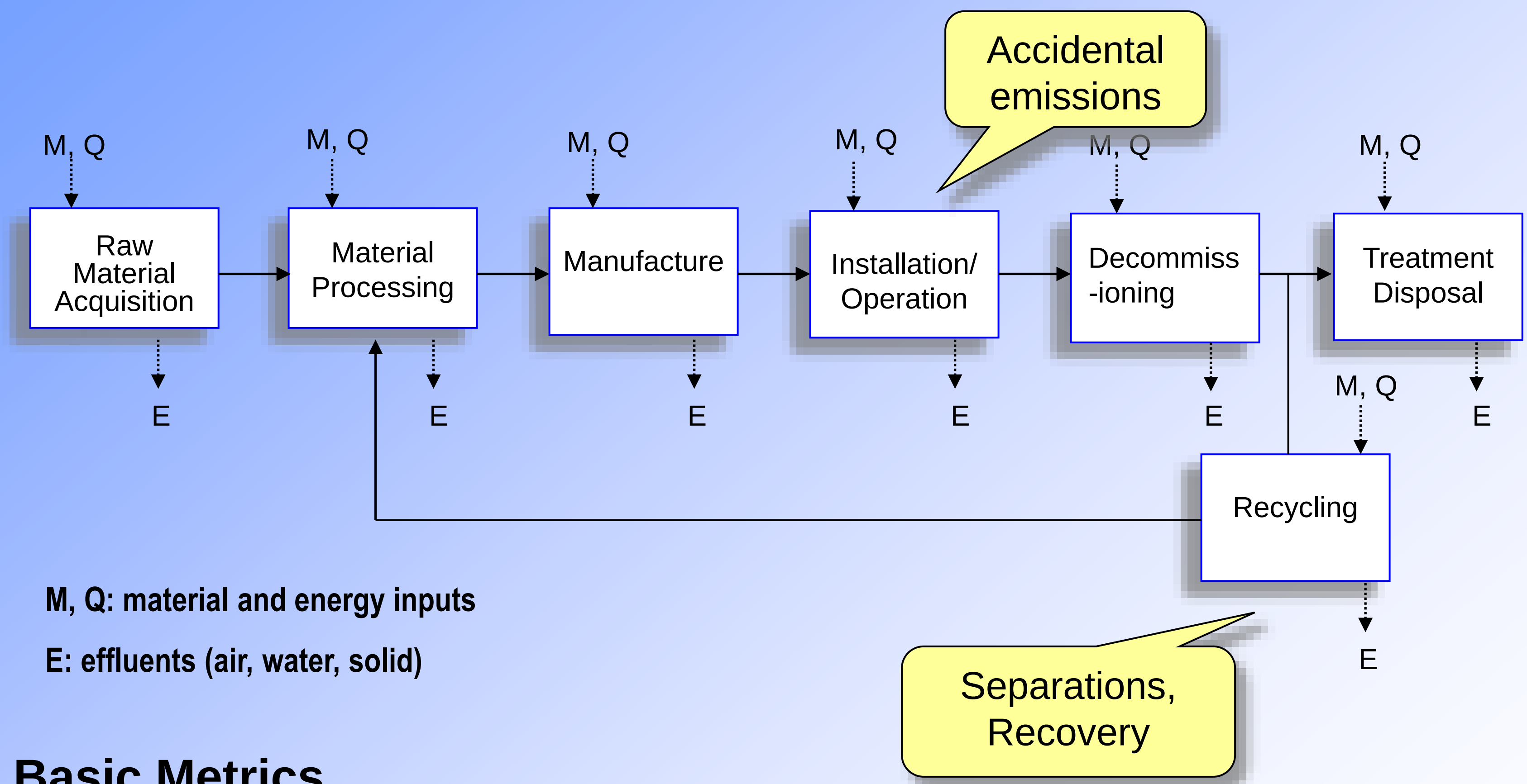
By 2050 renewable energy to supply 69% of electricity, 35% of total energy needs of the U.S.
Zweibel, Mason, Fthenakis, Jan. 2008

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

Environmental Impacts-Life Cycle Analysis

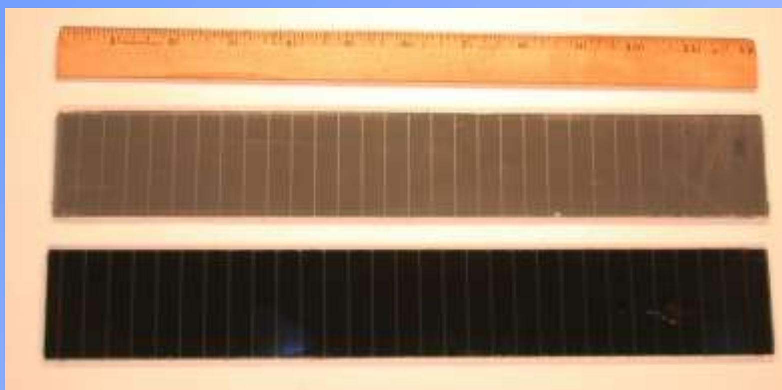
Experimental Research at BNL & Columbia U.



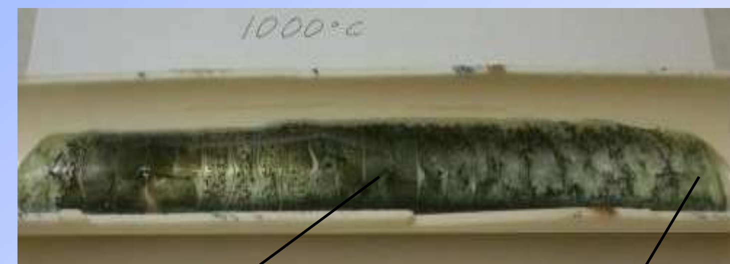
Basic Metrics

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

CdTe PV Fire-Simulation Tests: XRF Analysis

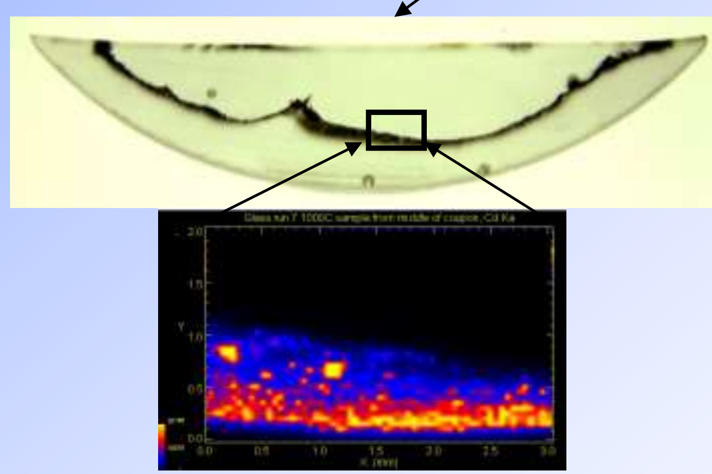


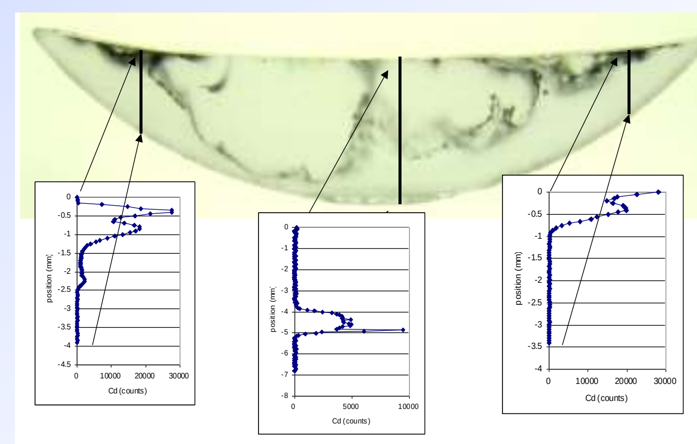
Heat



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

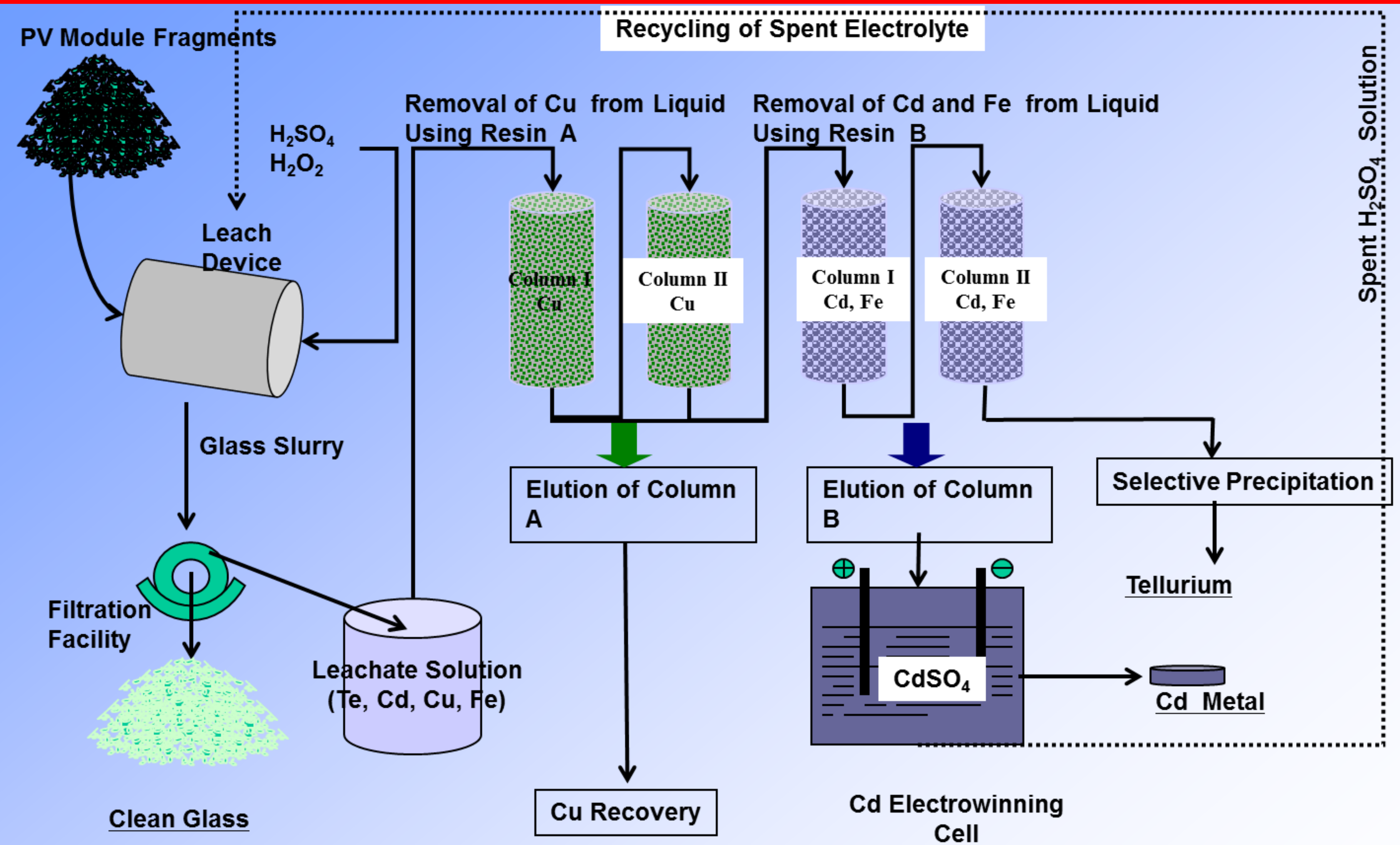
XRF-micro-probing –
Cd Distribution in PV Glass
1000 ˚C, right end of sample





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

Recycling R&D: CdTe PV Modules

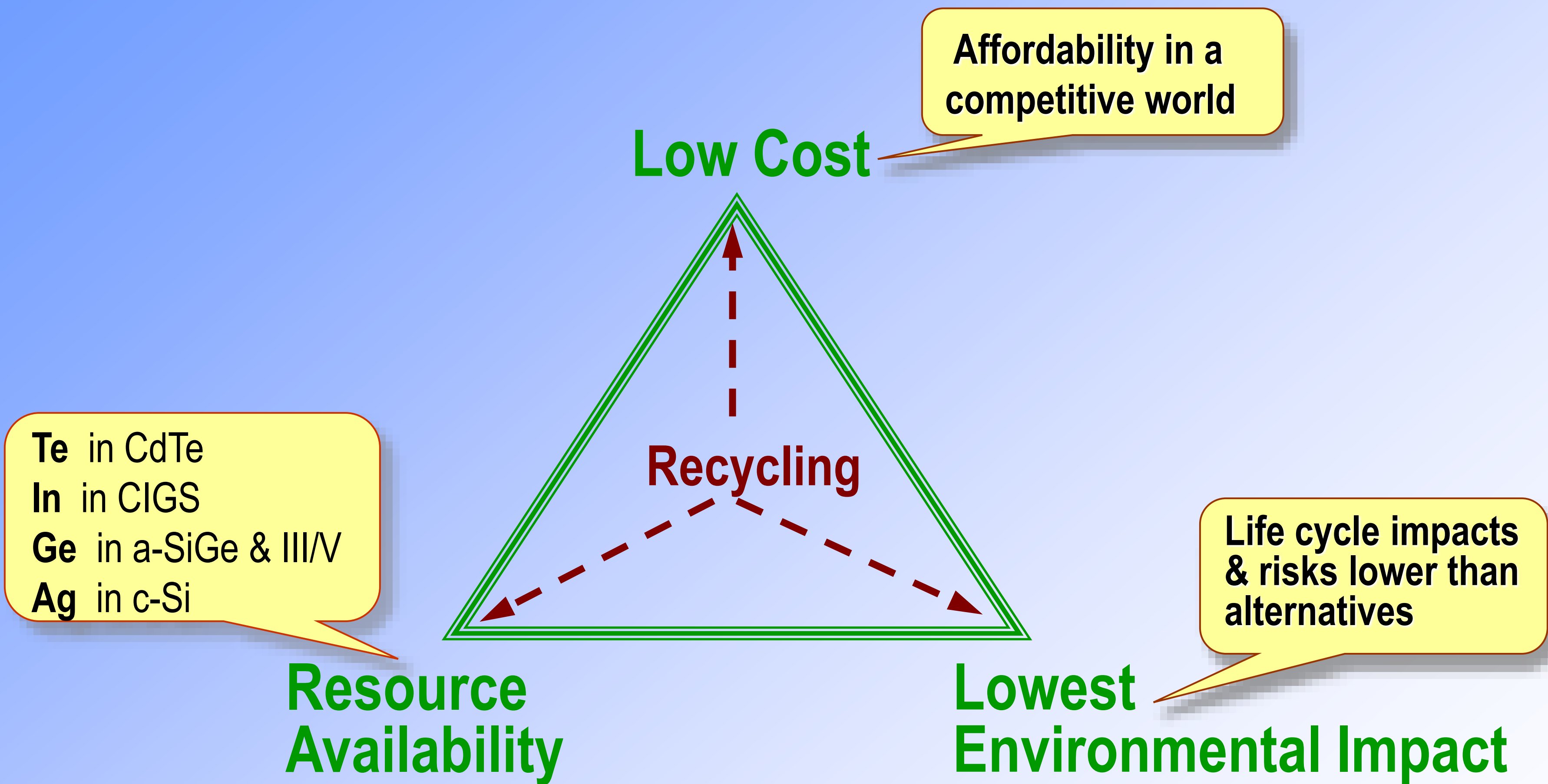


Fthenakis V. and Wang W., Separating Te from Cd Waste Patent No 7,731,920, June 8, 2010

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.

Large Scale PV –The Value of Recycling



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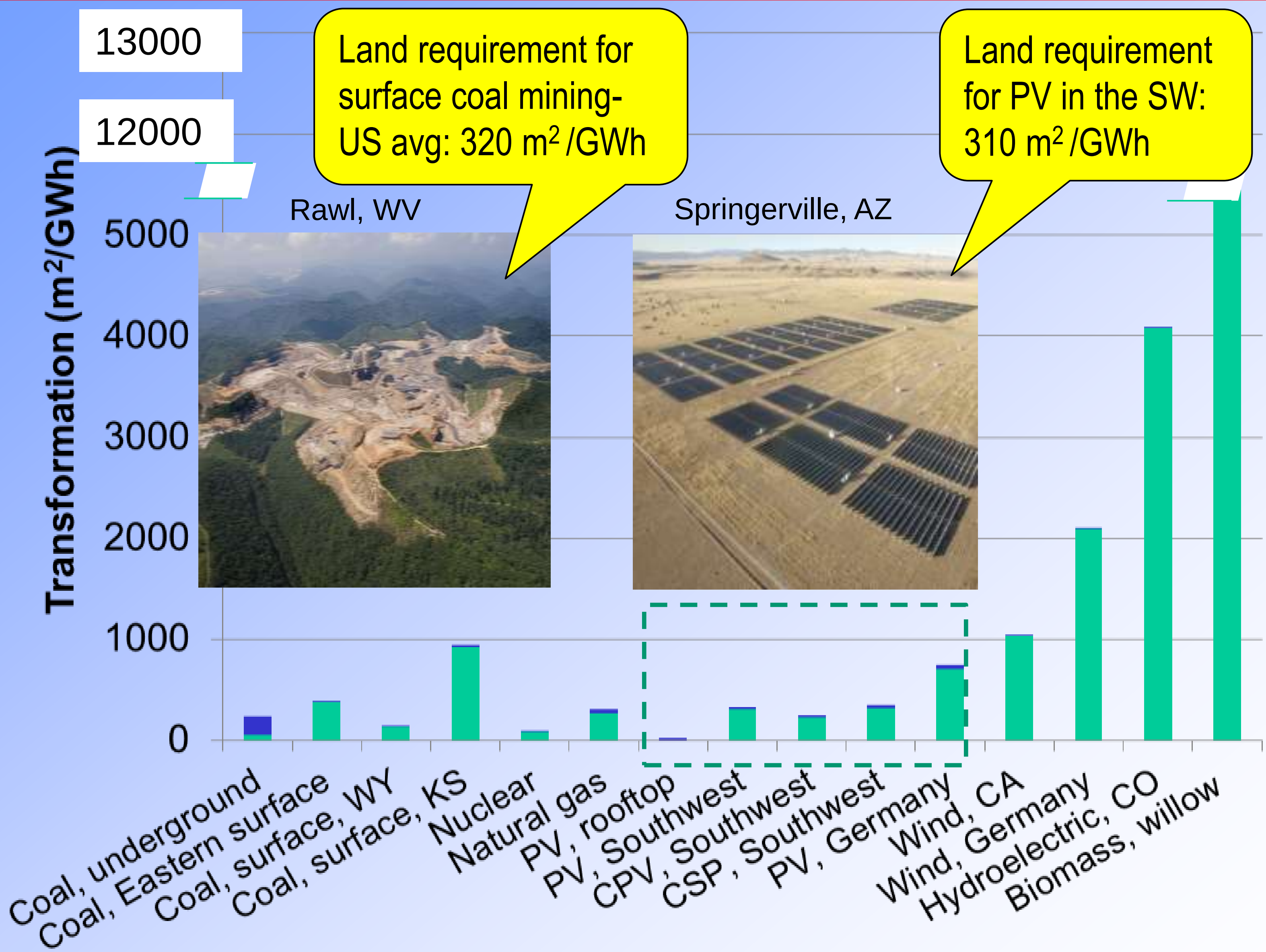
- Fthenakis, Sustainability metrics for extending thin-film PV to terawatt levels. MRS Bulletin, 2012

PV Uses less Land than Coal

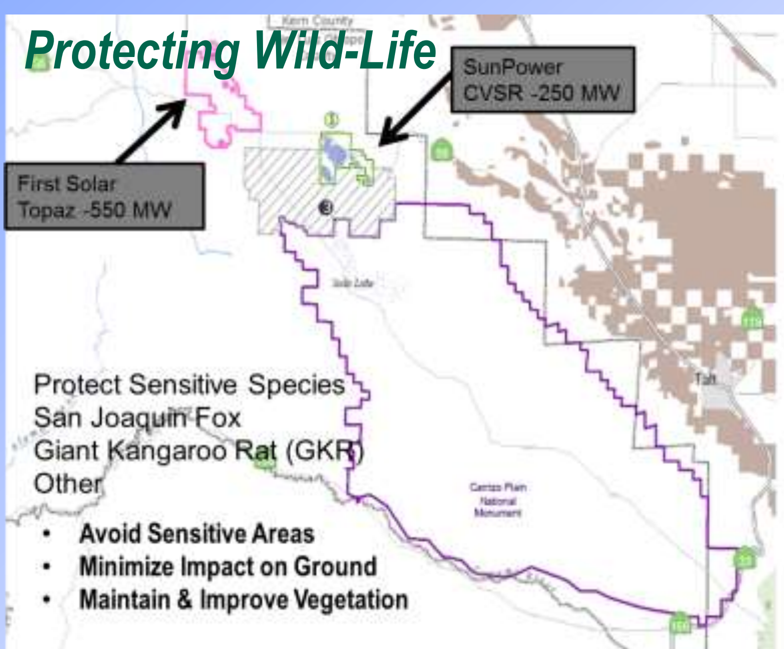


Fthenakis and Kim, Renewable and Sustainable Energy Reviews, 2009;
Burkhardt et al (2011)

Use of Land is Environmentally Friendly

Dual Use of Land

Protecting Wild-Life



- **Avoid Sensitive Areas**
- **Minimize Impact on Ground**
- **Maintain & Improve Vegetation**

Investigating Heat Island Effect

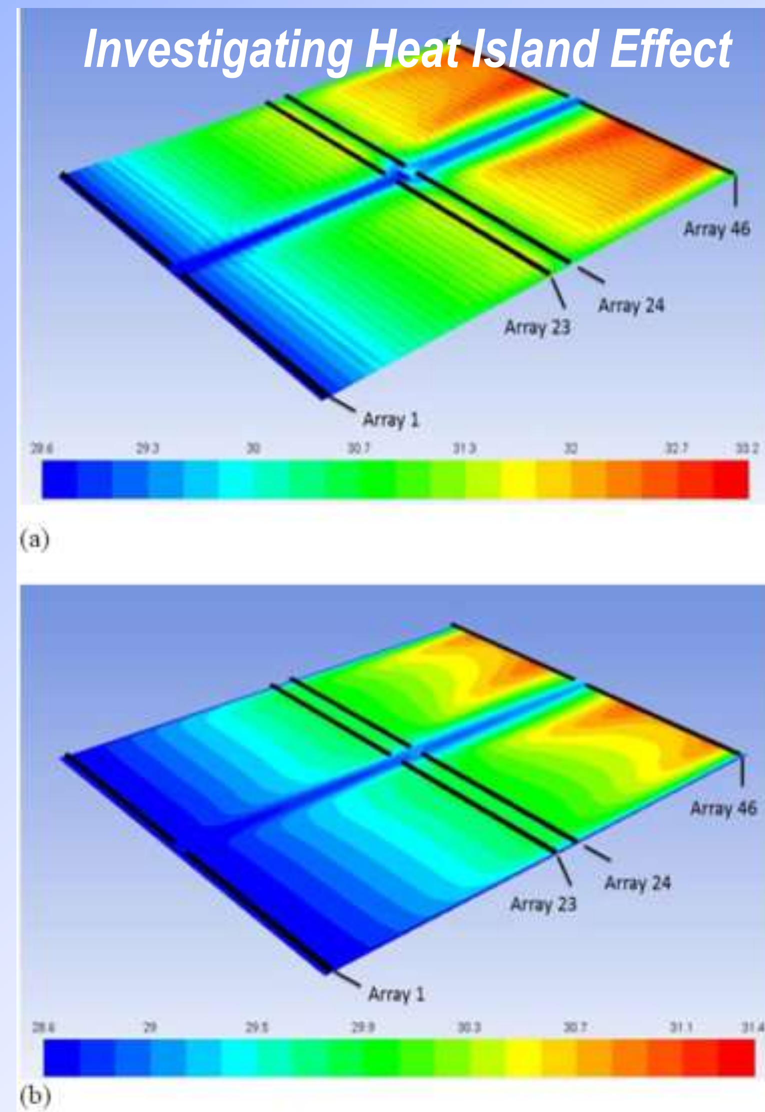


Fig. 11 Air temperatures from 3-D simulations during a sunny day. a) Air temperatures at a height of 1.5 m; b) air temperatures at a height of 2.5 m.

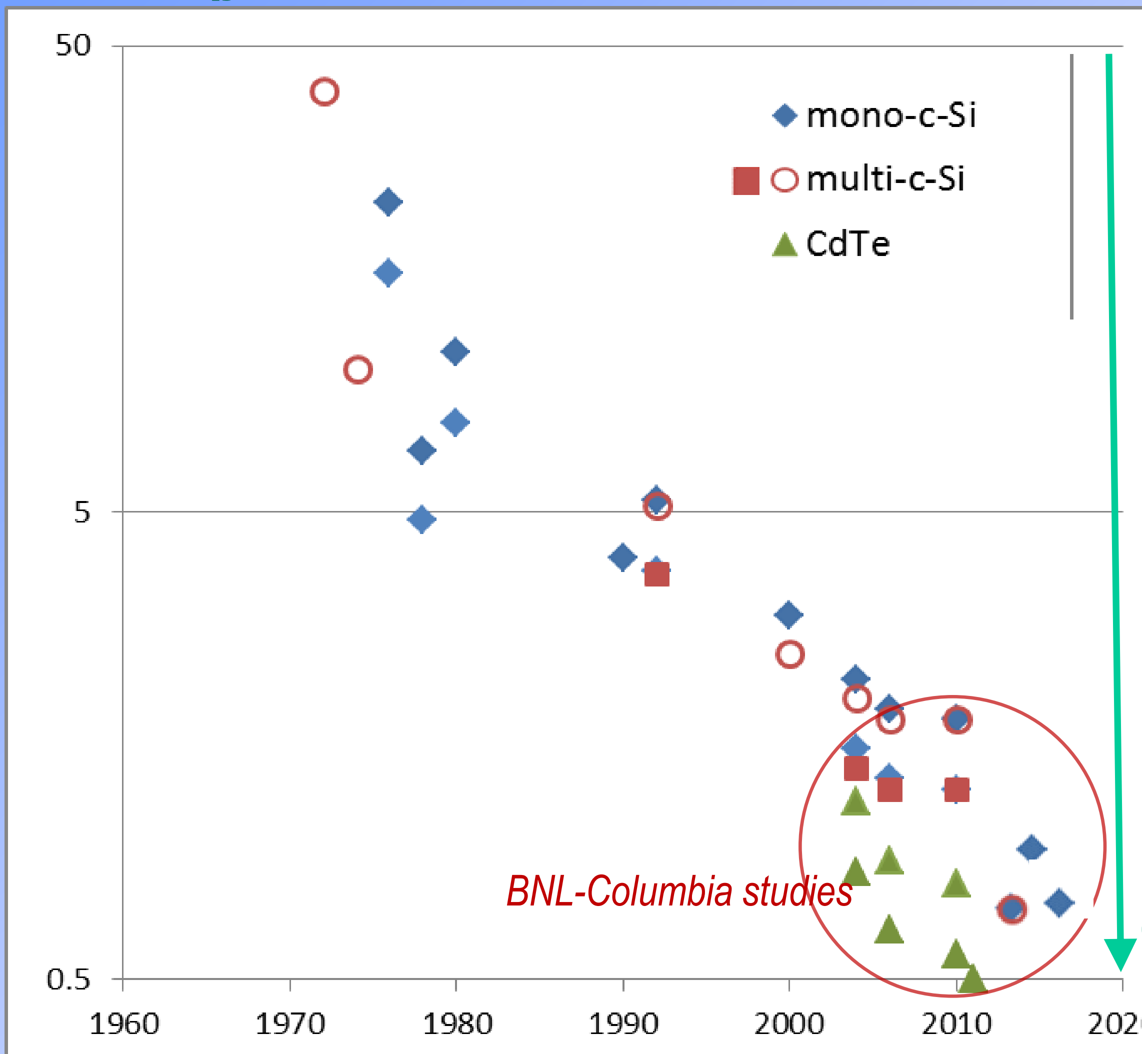
Fthenakis V., Green T., Blunden J. Krueger L., Large Photovoltaic Power Plants: Wildlife Impacts and Benefits, Proceedings 37th IEEE PSC, 2011.

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

Energy Payback Times & Energy Return on Energy Investment Historical Evolution

EPBT (years)

EROI



0.6

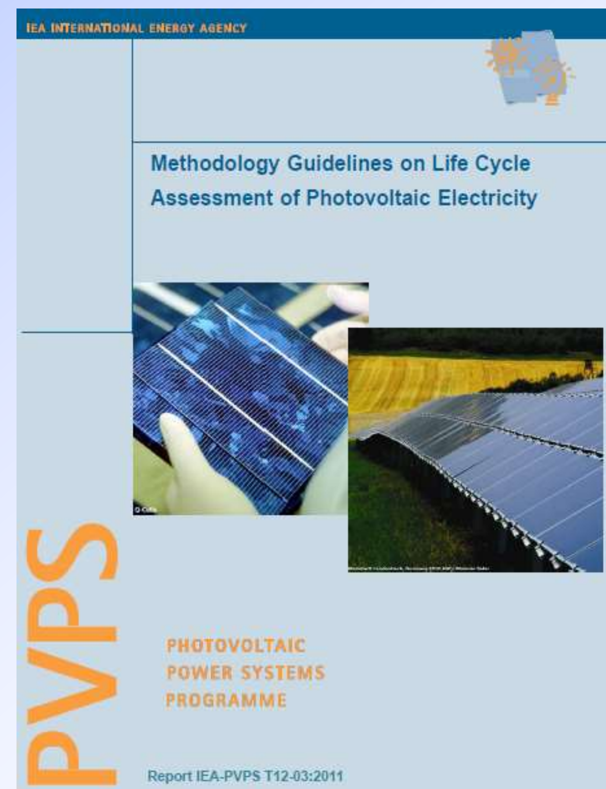
15

60

Irradiation of 1700 and 2400 kWh/m²/yr

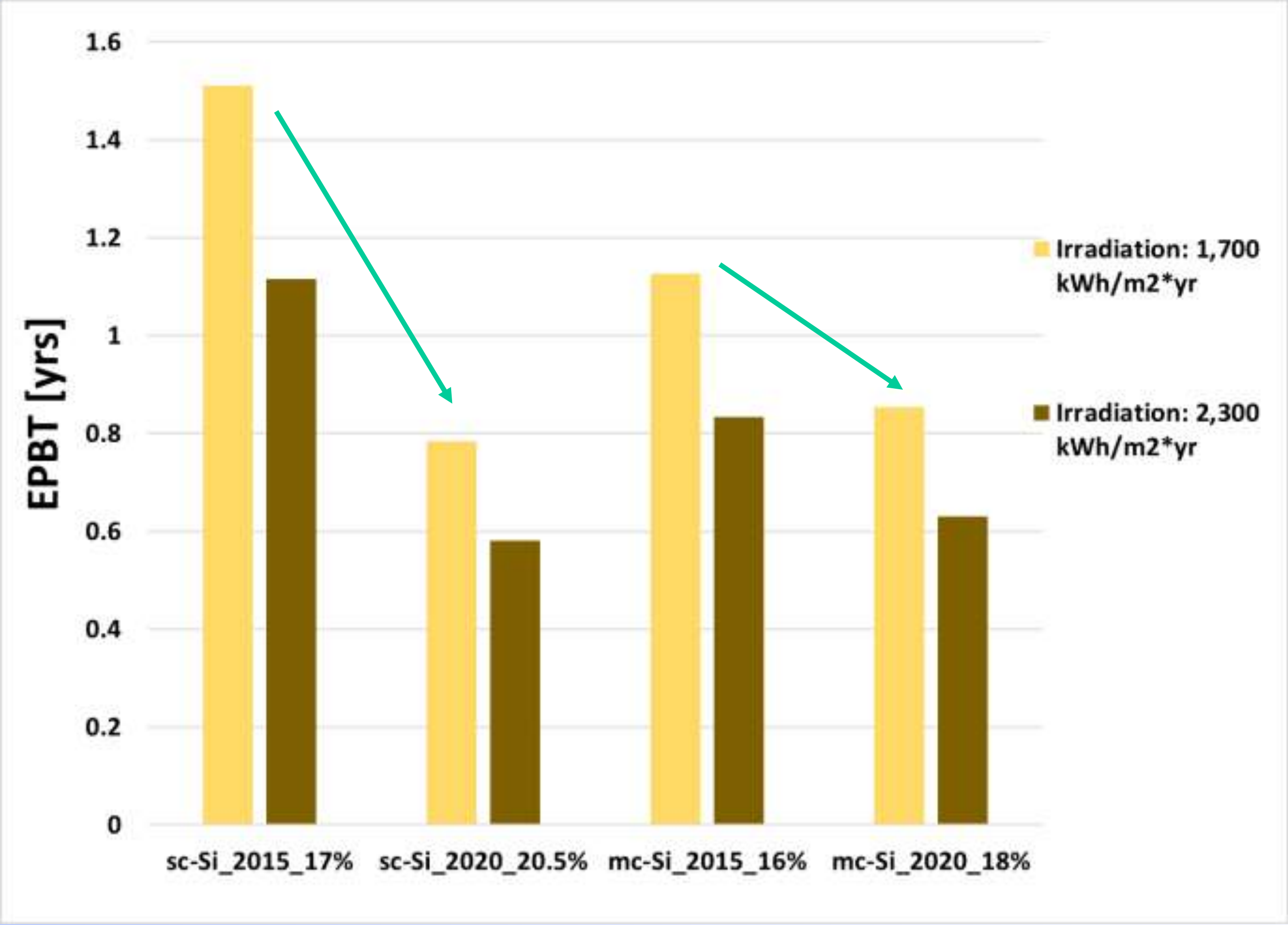
Divergence between studies due to:

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



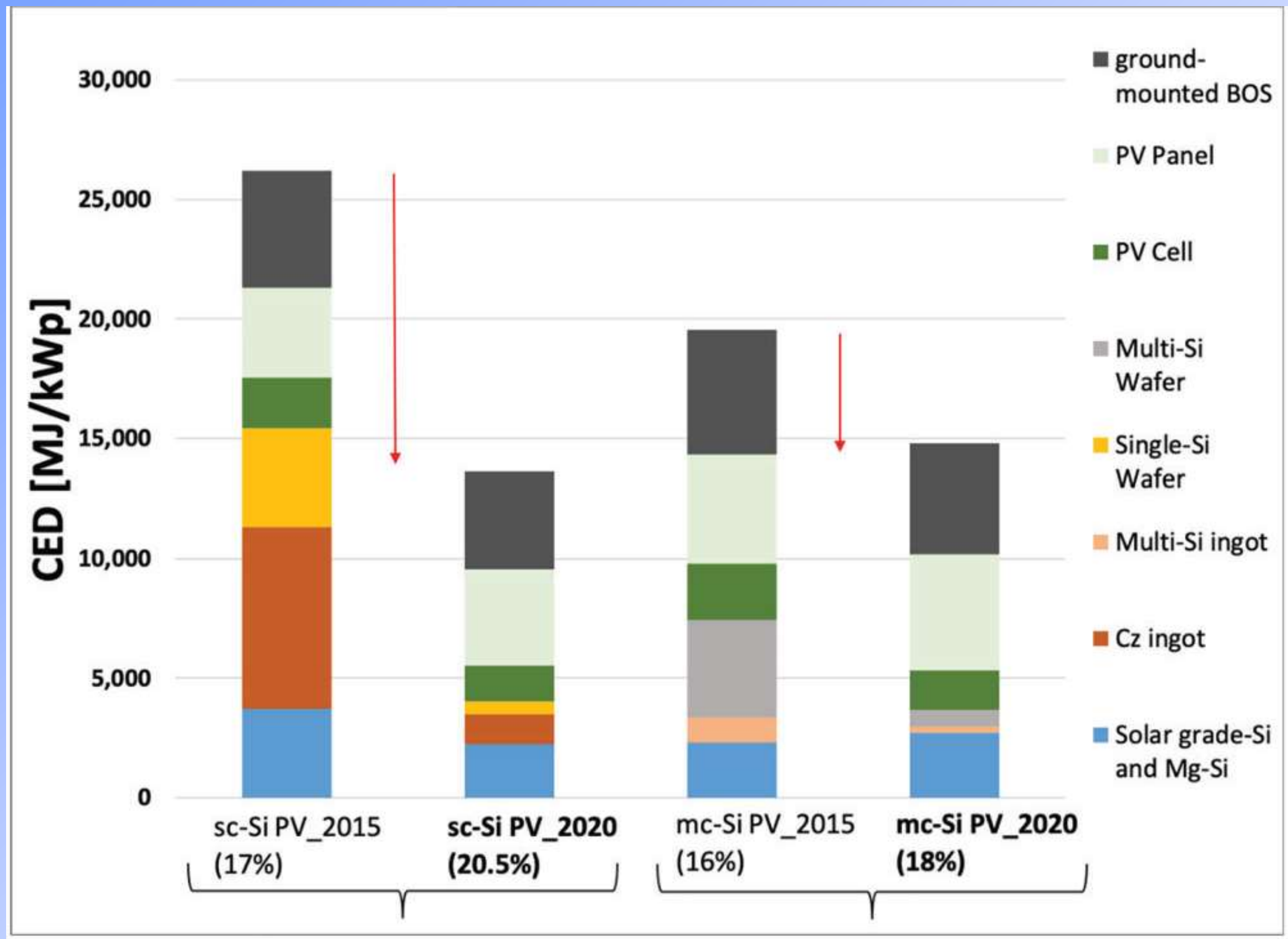
- Fthenakis V., PV Energy ROI Tracks Efficiency Gains, ASES Solar Today, 2012
- Fthenakis V., PV Total Cost of Electricity from Sunlight, Proceedings of IEEE, 2015

The Evolution Continues with Established Technologies



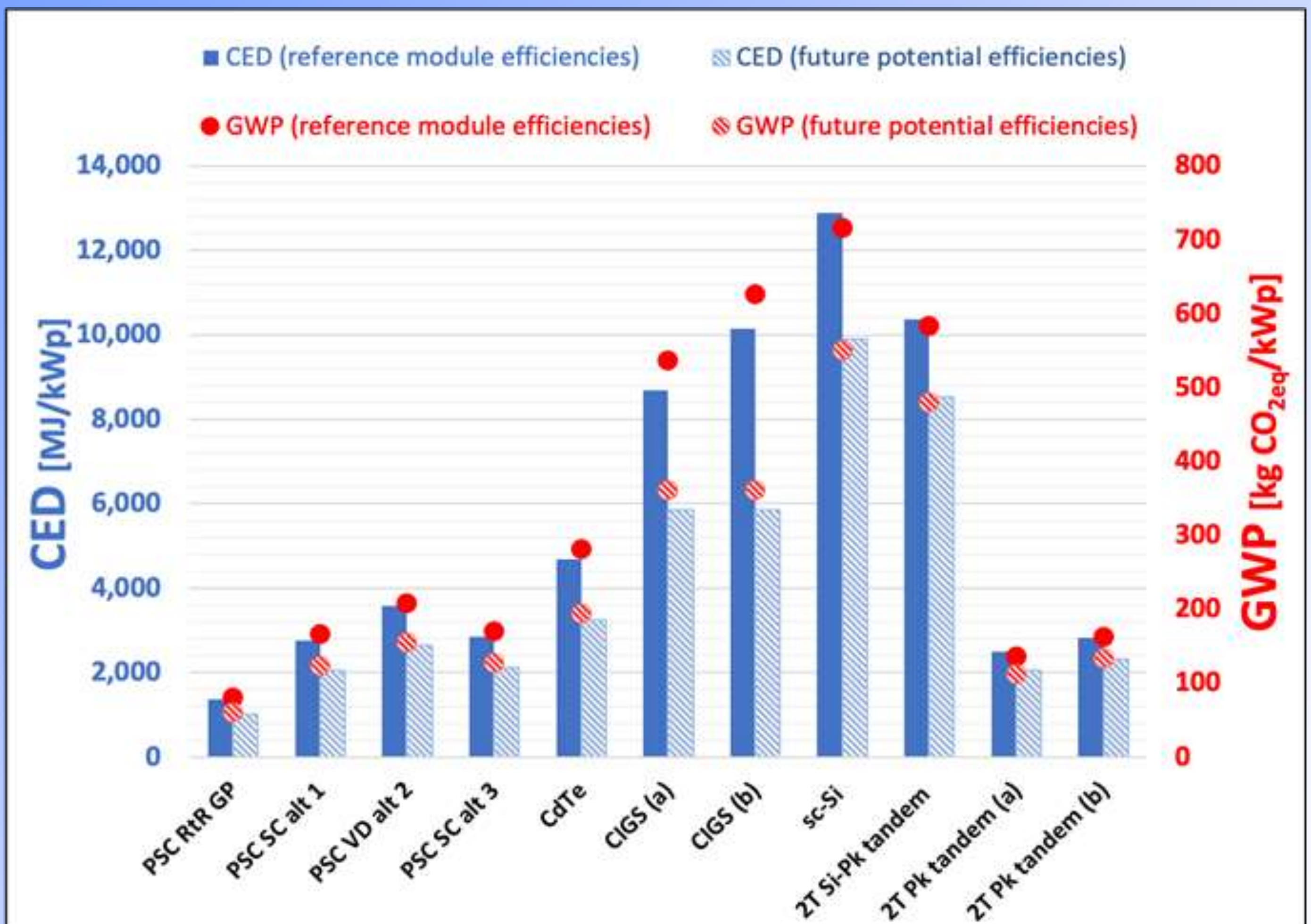
Fthenakis, V. and Leccisi, E., 2021. Updated sustainability status of crystalline silicon-based photovoltaic systems: Life-cycle energy and environmental impact reduction trends. *Progress in Photovoltaics: Research and Applications*, *29*(10), pp.1068-1077.

Improvements in Conventional c-Si PV



and PV continues to improve with emerging perovskite technologies

Cumulative Energy Demand (CED) comparisons of single-junction and tandem Perovskite with commercial PV panels



Lecissi, Fthenakis, Progress in Photovoltaics, 2021

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

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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)

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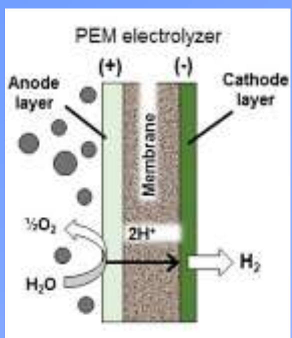
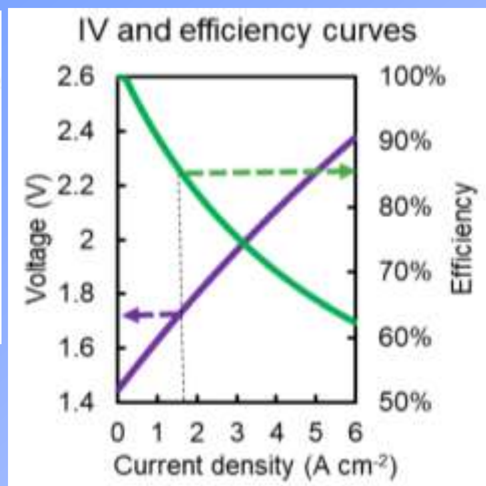
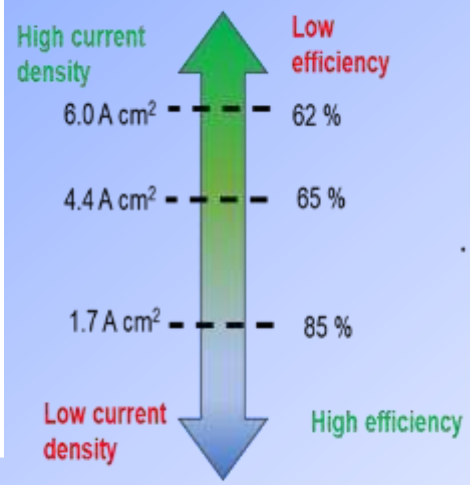
Columbia University in the City of New York

Water Electrolysis with Variable Energy

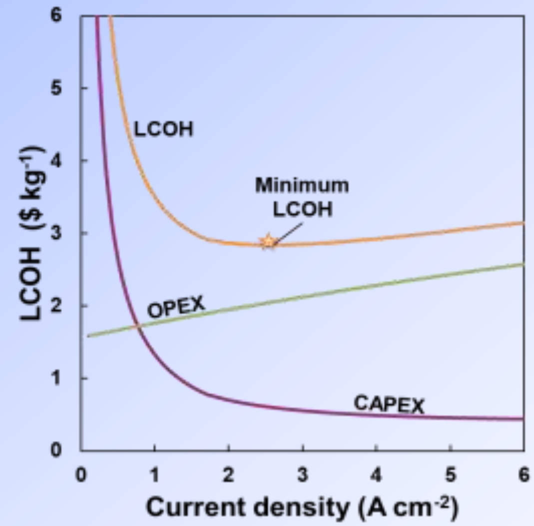
Efficiency vs. Current Density in PEM electrolyzers

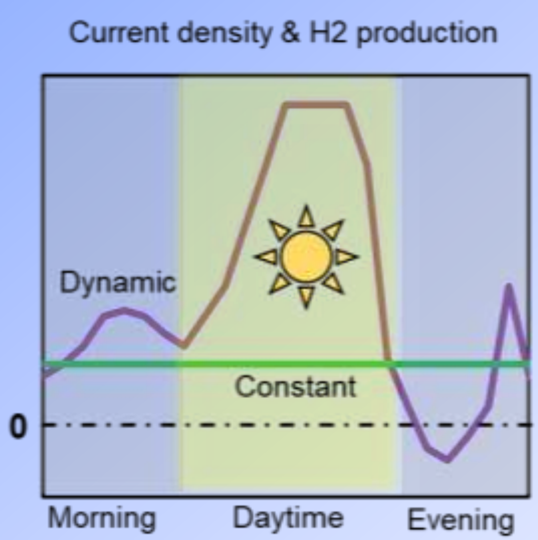


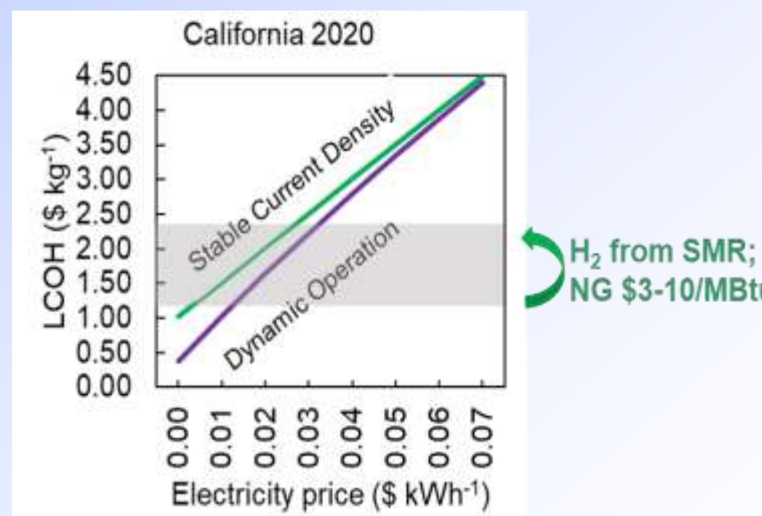




Levelized Cost of H2 (LCOH)

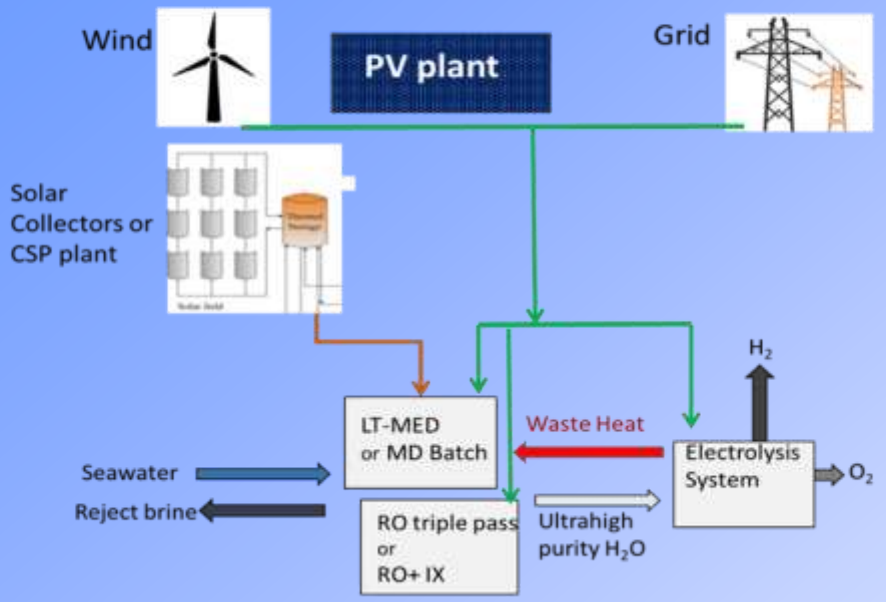


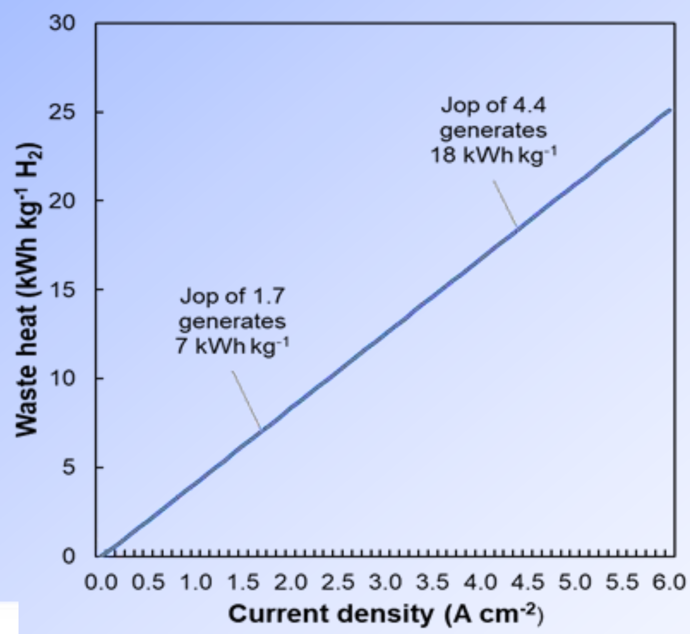


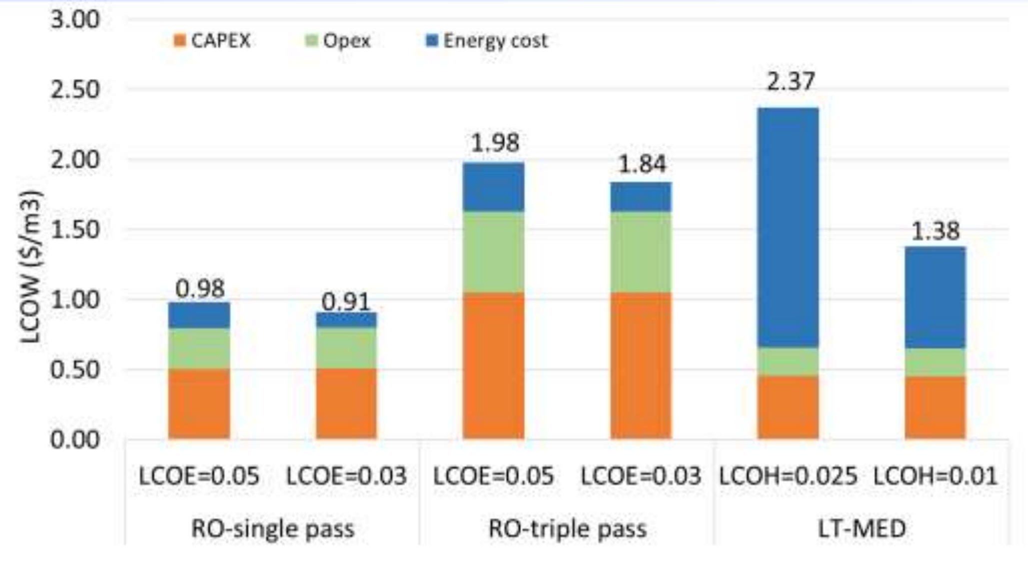


Ginsberg G.,Venkatraman M., Esposito D., Fthenakis V, Minimizing the Cost of Green Hydrogen Production through Dynamic Polymer Electrolyte Membrane Electrolyzer Operation, Cell Reports Physical Science, 3(6), 100935, 2022
Ginsberg M., Esposito D., Fthenakis V, Designing Off-Grid Green Hydrogen Plants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

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 and I am very lucky and happy to be part of this evolution.*
- *EH&S vigilance and proactive approach must continue.*
- *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.*

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email: **vmf5@columbia.edu**

Collaborators Gratefully Acknowledged

- **PV EH&S**

  Charlie Gay, Larry Kazmerski, Paul Moskowitz, Brent Nelson, Doug Rose, William Shafarman

- **PV Recycling**

  Chris Bohland, Jun-Ki Choi, Jan Clyncke, Chris Eberspatcher, Keichi Komoto, Parikhit Sinha, Andreas Wade, Wenming Wang

- **Life Cycle Analysis**

  Erik Alsema, Enrica Leccisi, Marco Raugei, Arnulf Jäger-Waldau, Chul Kim

- **Large Solar Environmental Impact Studies**

  Julie Blunden, Lisa Krueger, Ricky Sinha

- **Renewable Energy & Storage Modeling**

  Rob van Haaren, Mahesh Morjaria, Thomas Nikolakakis, Marc Perez, Ken Zweibel

- **Solar Desalination**

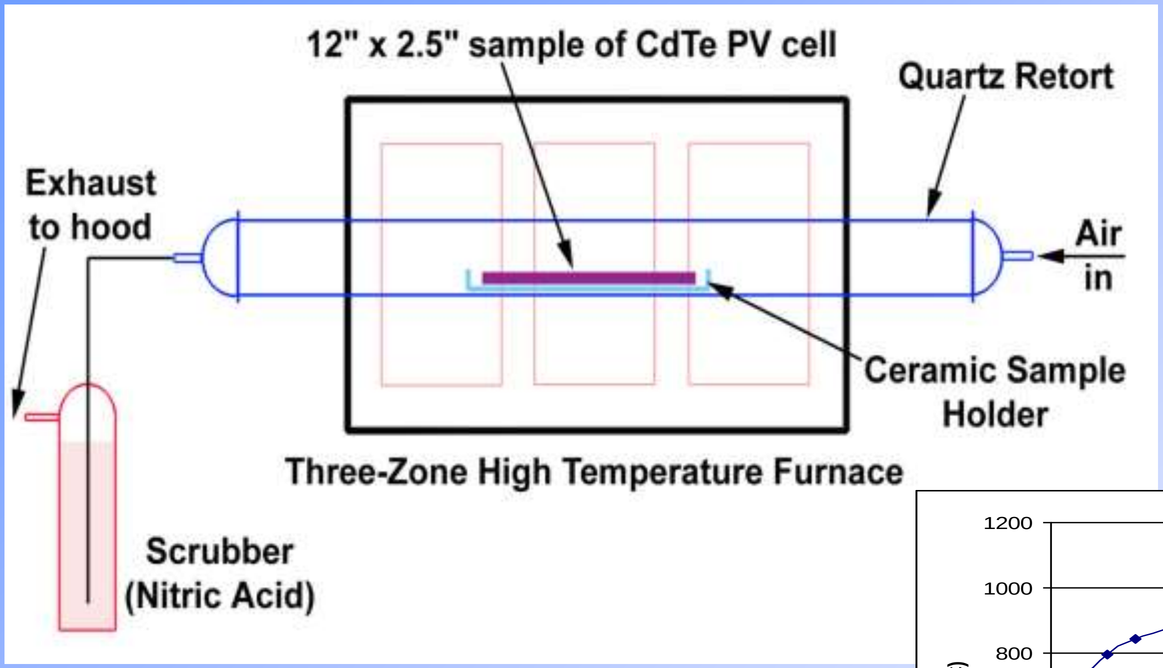
  Adam Atia, Zhuoran Zhang, Diego Alarcon-Padilla, Guillermo Zaragoza, George Papadakis

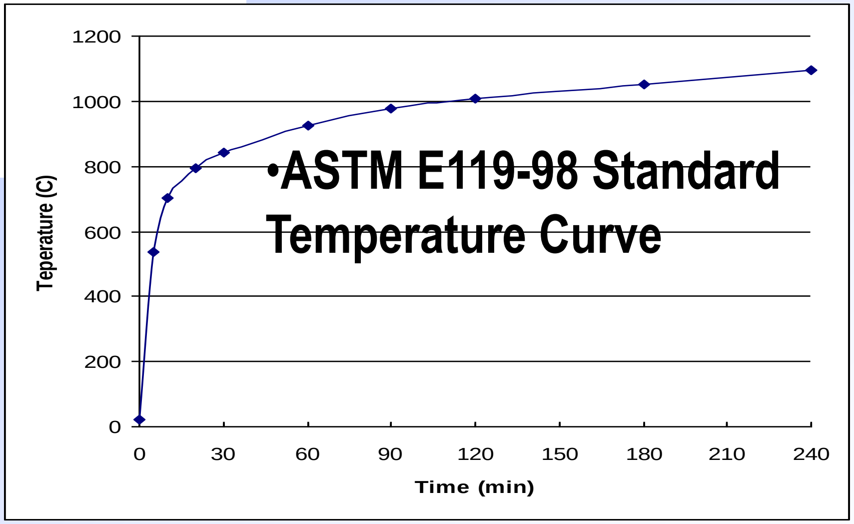
- **Solar Hydrogen**

  Michael Ginsberg, Daniel Esposito

Auxiliary Slides

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 Molten Glass

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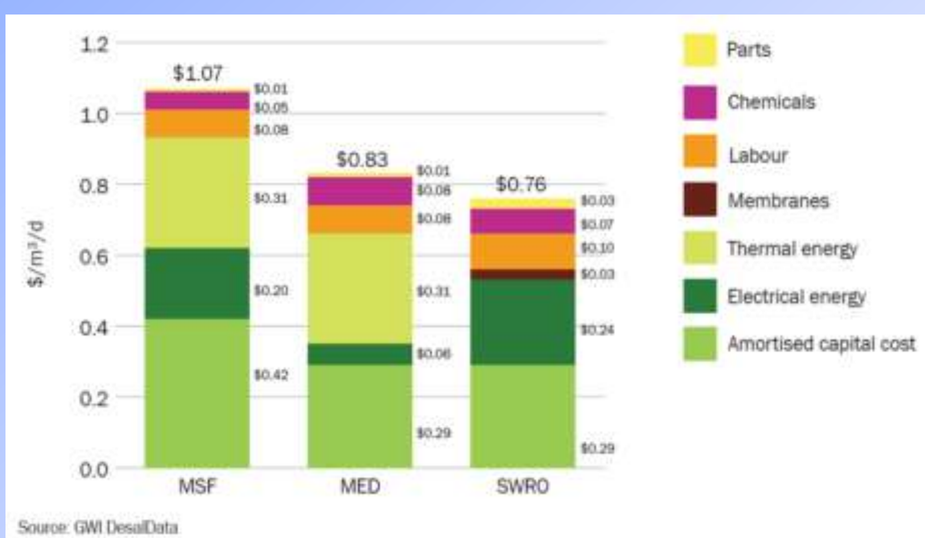
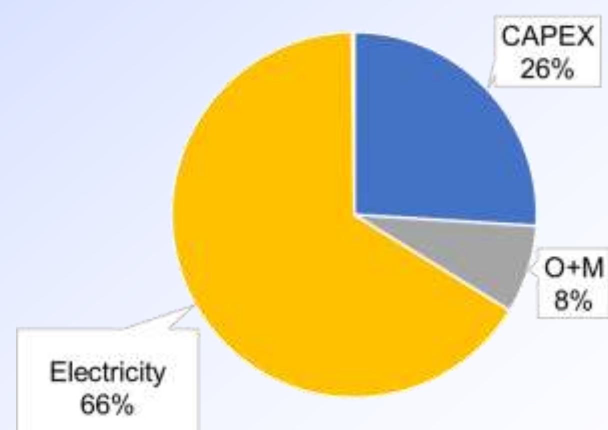
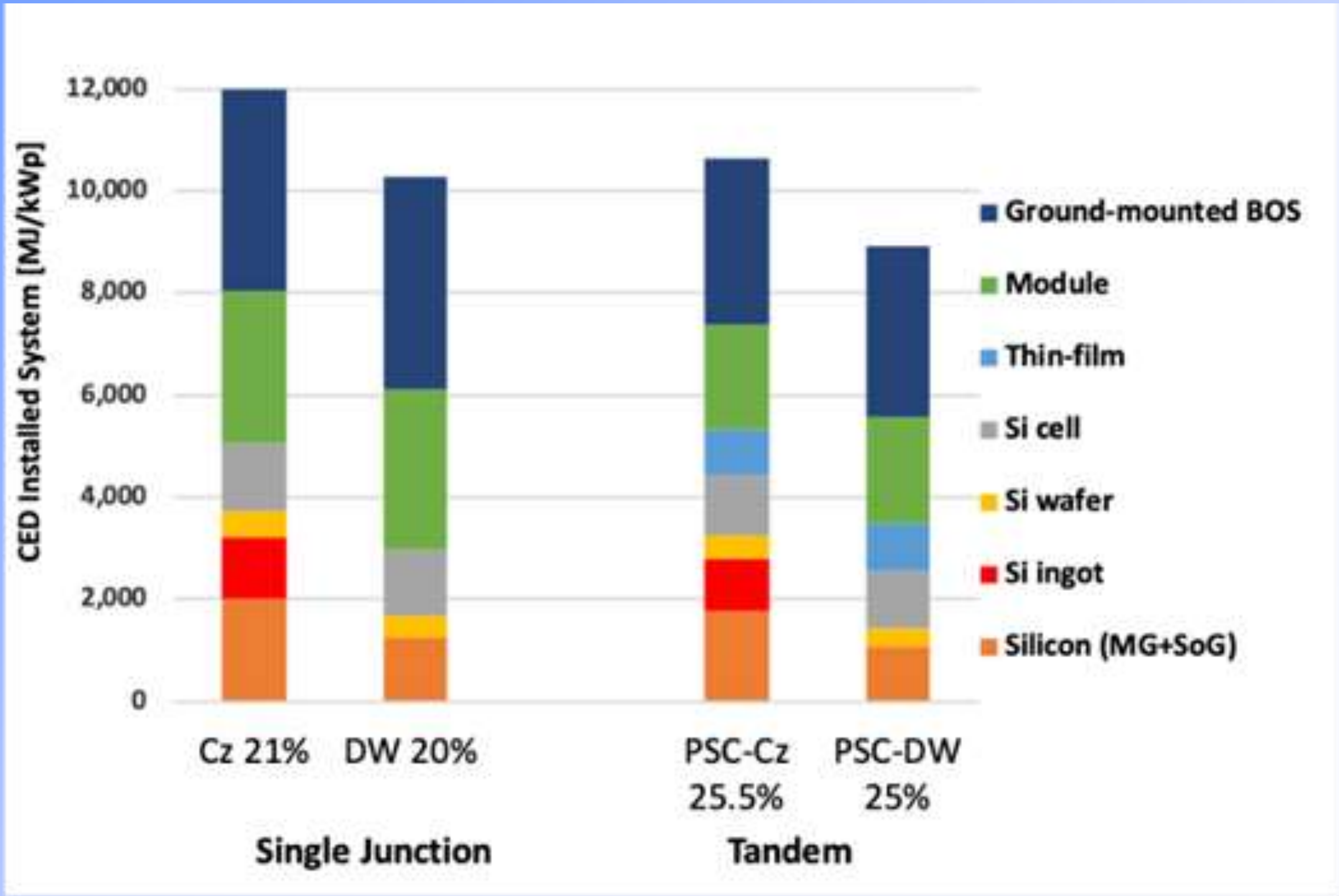




PEM System CAPEX: ~$700 – 1,000/kW

Further improvements possible with kerfless wafers



Illumination	Czochralski	Direct Wafer
AM1.5 1 sun	22.5% (688mV, 39.8mA/cm^2, 82.3% FF)	21.4% (667mV, 39.5 mA/cm^2, 81.3%)
80% transmission above 780nm (~1.6eV)	7.21% (660mV, 13.1mA/cm^2, 83.3%FF)	6.76% (638mV, 12.9mA/cm^2, 82.3%)

Material Candidates for Longer Lives

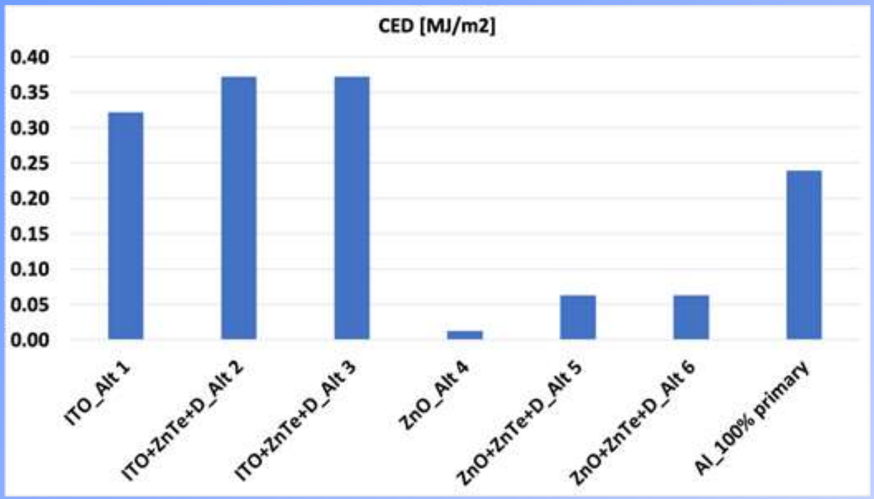
Alternative back contact materials for CdTe solar cells

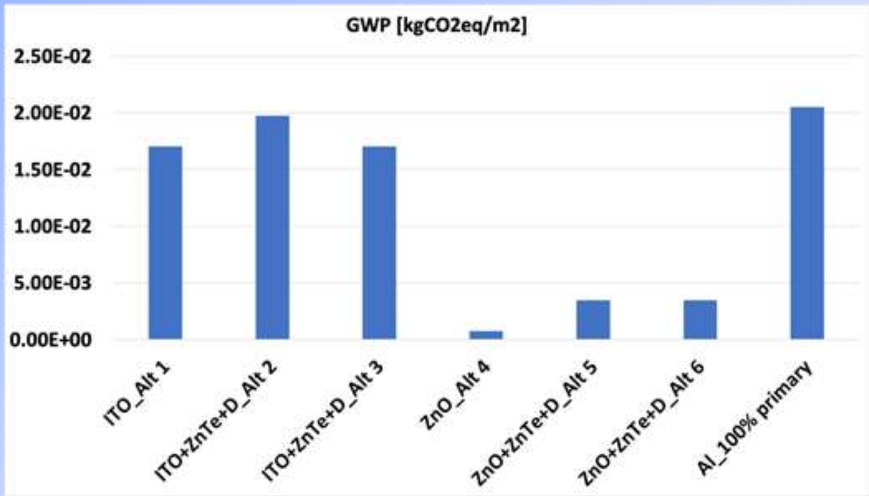
a. In_2O_5Sn (ITO), In_2O_3, ZnO, CdO
b. ITO or ZnO plus ZnTe and doping element (D)

Alternative PV module edge sealant materials

a. Polyisobutylene (PIB) with dessicant filler
b. Silicone + Polyisobutylene
c. AclarTM [poly-chloro-tri-fluoro-ethylene (PCTFE)]

Comparisons of Back-Contact Options

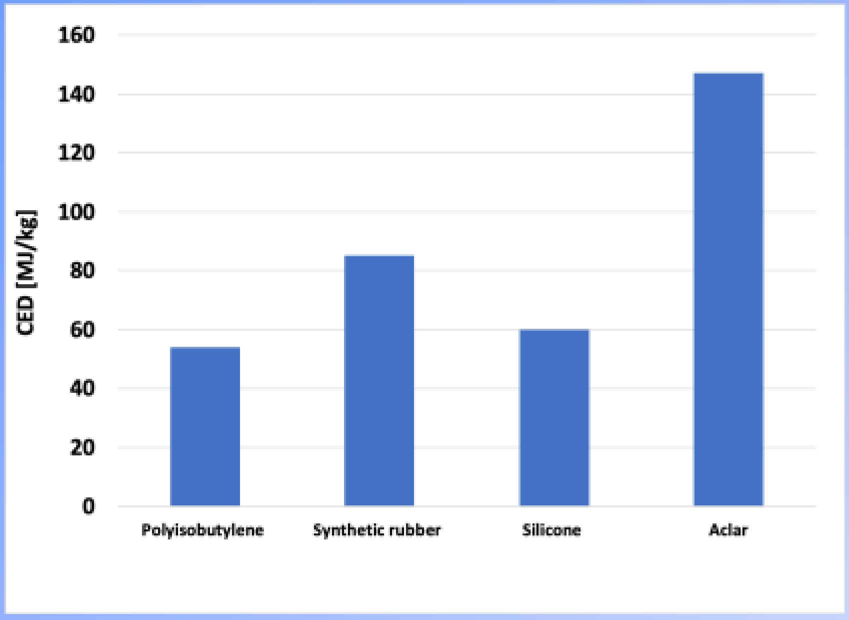


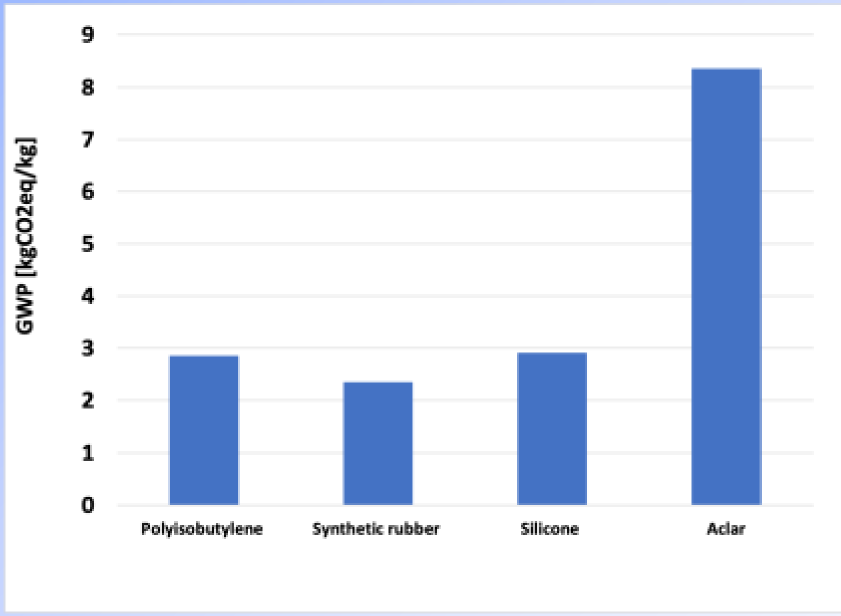


Impact Indicator	Units	Al	ITO+ZnTe+D	% difference
Cumulative Energy Demand (CED)	MJ/m2	2.39E-01	3.72E-01	56
Global Warming Potential (GWP)	kgCO2eq/m2	2.05E-02	1.97E-02	-4
Acidification Potential (AP)	kgSO2eq/m2	1.14E-04	1.23E-04	7
Human toxicity potential (HTP) cancer	CTU/m2	1.43E-09	4.62E-09	223
Human toxicity potential (HTP) non cancer	CTU/m2	3.58E-09	1.97E-08	450
Eco-toxicity potential (ETP)	CTU/m2	5.73E+00	1.29E+01	125
Ozone depletion potential (ODP)	CFC-11 eq/m2	6.57E-10	1.60E-09	143
Abiotic resource depletion potential (ADP)	kg Sb eq/m2	4.20E-08	7.83E-06	18,559
Eutrophication potential (EP)	kg PO4-eq/m2	3.04E-05	8.12E-05	167
Photochemical Oxidation	kg C2H4 eq/m:	7.02E-06	1.21E-05	72

Estimated by using Simapro 9.2; Cut-off System Modeling

Comparisons of Edge-Sealant Options





Impact Indicator	Units	Synthetic rubber	Aclar	% difference
Cumulative energy demand (CED)	MJ/kg	8.51E+01	1.47E+02	73
Global warming potential (GWP)	kgCO2eq/kg	2.35E+00	8.36E+00	255
Acidification potential (AP)	kgSO2eq/kg	1.10E-02	6.31E-02	474
Human toxicity potential (HTP) cancer	CTU/kg	6.29E-08	2.46E-07	290
Human toxicity potential (HTP) non cancer	CTU/kg	2.15E-07	1.80E-06	734
Eco-toxicity potential (ETP)	CTU/kg	4.99E+02	2.73E+03	447
Ozone depletion potential (ODP)	CFC-11 eq/kg	5.09E-07	3.65E-06	618
Abiotic resource depletion potential (ADP)	kg Sb eq/kg	5.03E-05	2.34E-04	366
Eutrophication potential (EP)	kg PO4-eq/kg	3.67E-03	1.66E-02	352
Photochemical oxidation potential (POP)	kg C2H4 eq/kg	6.39E-04	2.64E-03	313

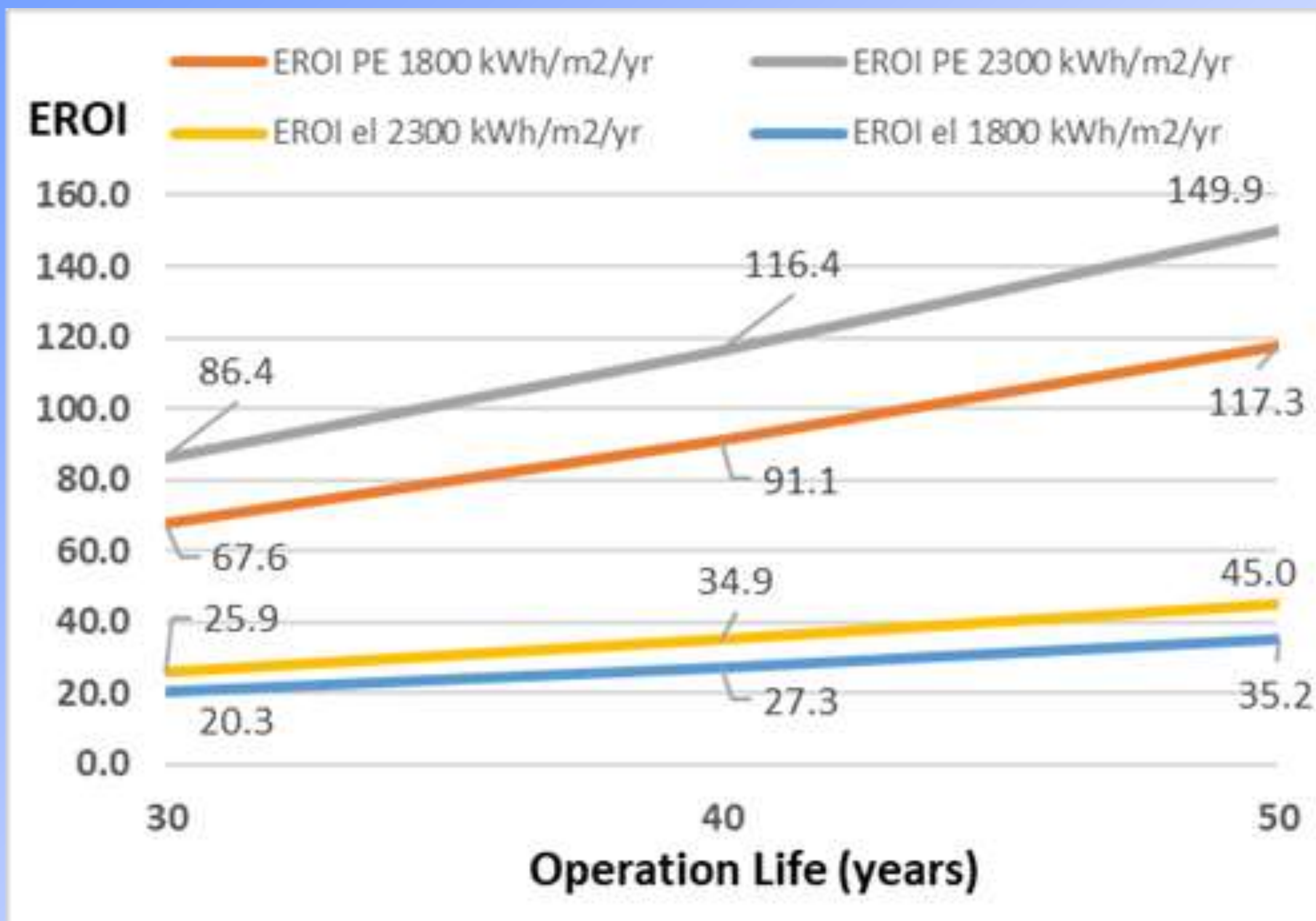
System LCA Results

Assumptions:
Degradation Rate is reduced from 0.3%/yr to 0.2%/yr and then 0.1%/yr
Operational Life is increased from 30 yrs to 40 and then 50 yrs

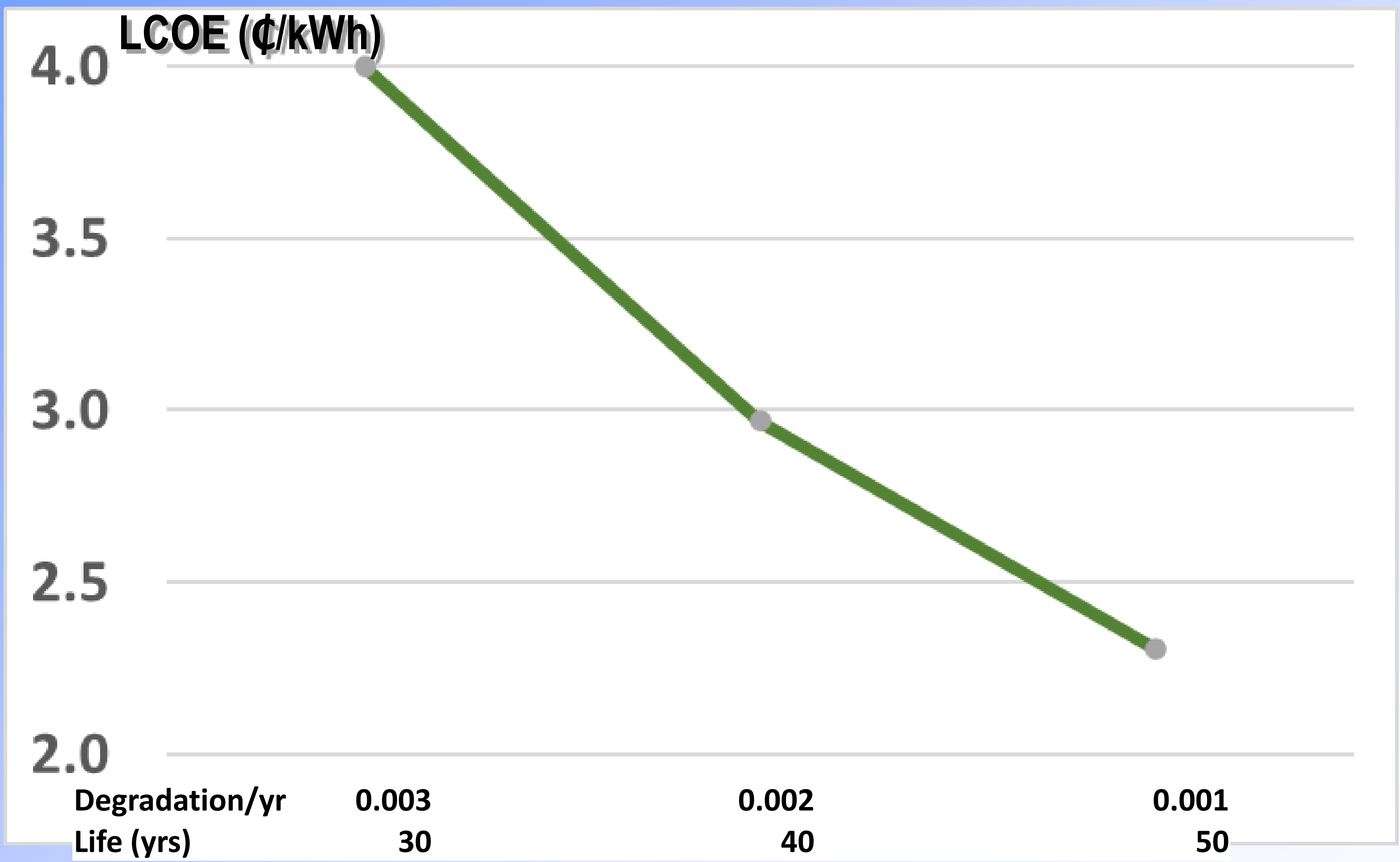
	---Operation Life (years) under 1800 kWh/m2/yr--			
Environmental Impact Indicator	Units **/kWh**	**30**	**40**	**50**
Global Warming Potential (GWP)	gCO_{2eq}	10.3	7.7	5.9
Human toxicity potential (HTP)	CTU	3.8E-09	2.8E-09	2.2E-09
Eco-toxicity potential (ETP)	CTU	11.7	8.7	6.7
Ozone depletion potential (ODP)	g CFC-11 eq	8.5E-07	6.3E-07	4.9E-07
Abiotic resource depletion potential (ADP)	g Sb eq	2.0E-03	1.5E-03	1.1E-03
Eutrophication potential (EP)	g PO4--- eq	2.0E-02	1.5E-02	1.1E-02

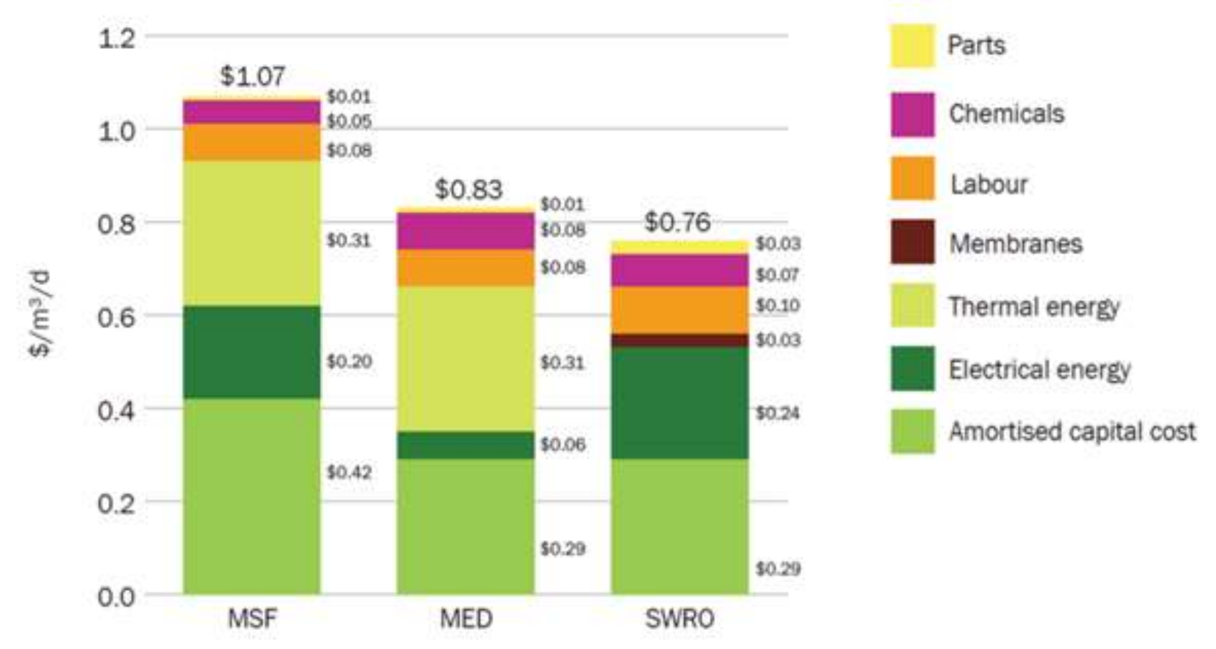
	---Operation Life (years) under 2300 kWh/m2/yr--			
Environmental Impact Indicator	Units/kWh	**30**	**40**	**50**
Global Warming Potential (GWP)	gCO_{2eq}	8.1	6.0	4.6
Human toxicity potential (HTP)	CTU	3.0E-09	2.2E-09	1.7E-09
Eco-toxicity potential (ETP)	CTU	9.2	6.8	5.3
Ozone depletion potential (ODP)	g CFC-11 eq	6.7E-07	5.0E-07	3.8E-07
Abiotic resource depletion potential (ADP)	g Sb eq	1.6E-03	1.2E-03	9.0E-04
Eutrophication potential (EP)	g PO4--- eq	1.5E-02	1.1E-02	8.9E-03

EROI as a function of Insolation and Life Expectancy



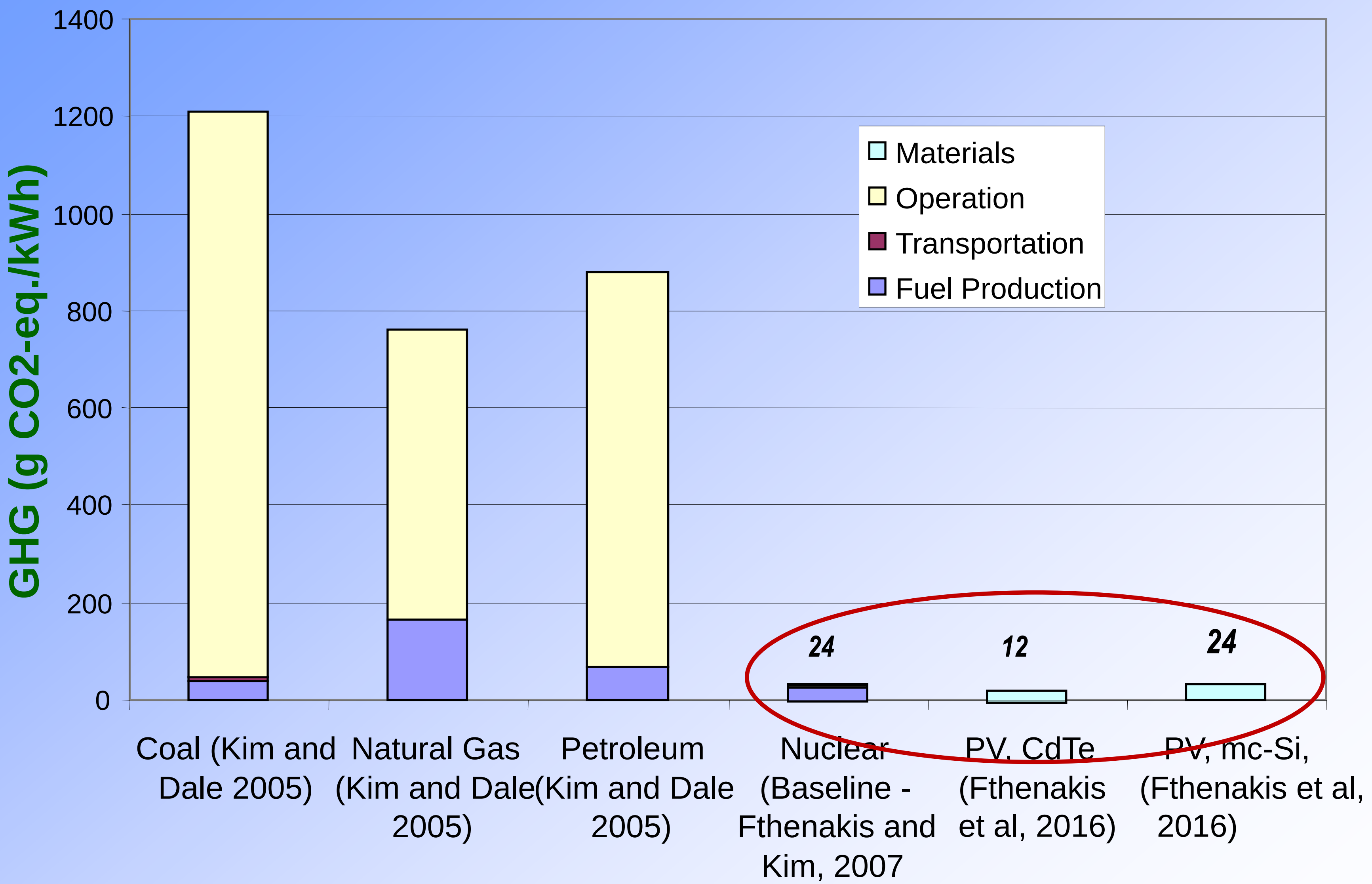
LCOE as a function of Degradation and Life Expectancy





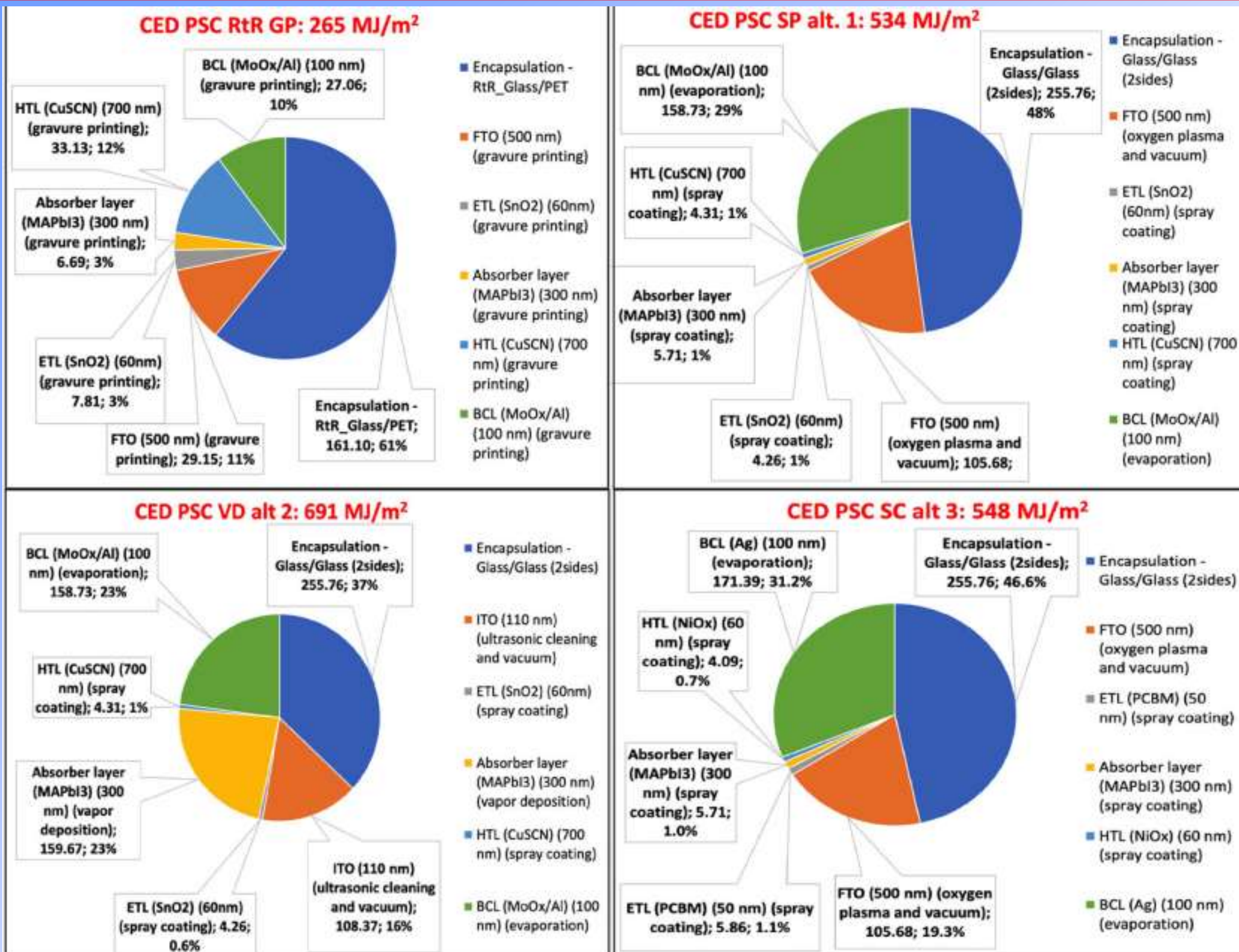
Source: GWI DesalData

GHG Emissions from Life Cycle of Electricity Production: Comparisons

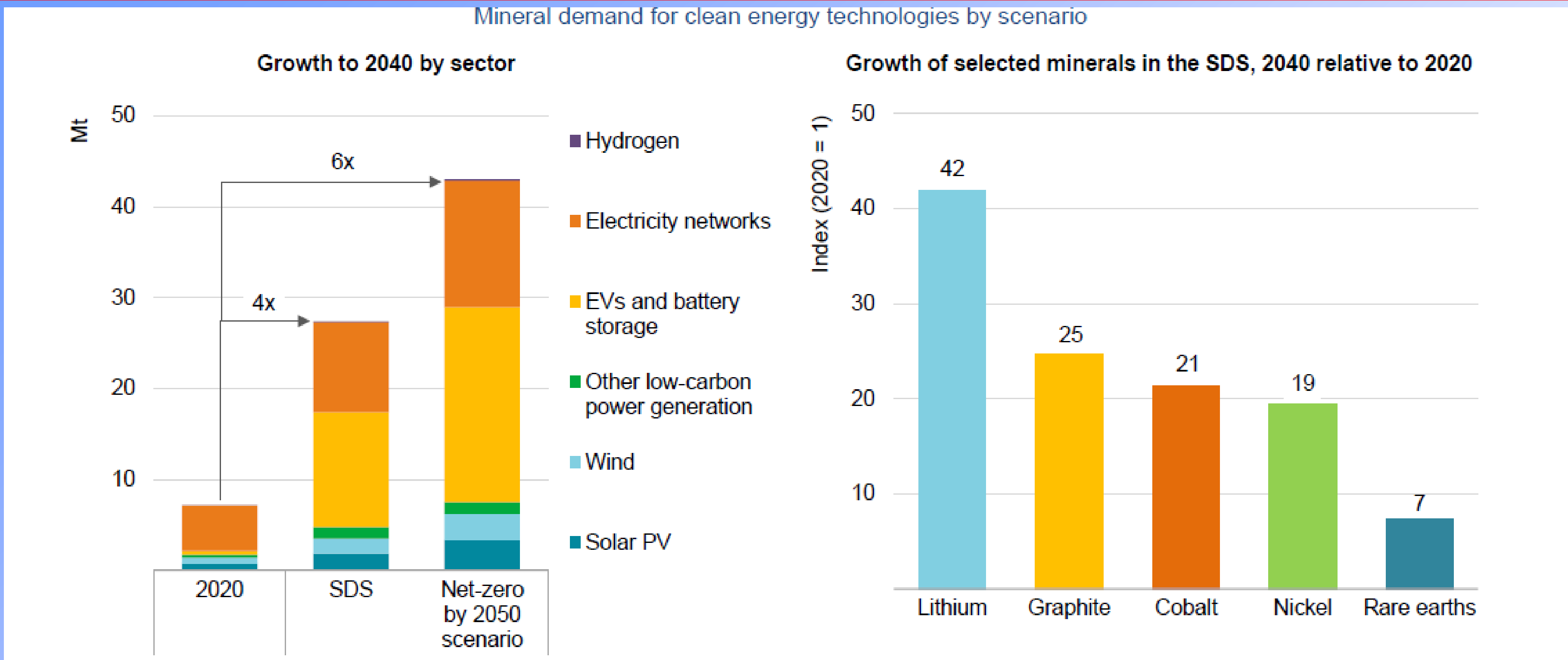


Fthenakis, California Energy Commission, *Nuclear Issues Workshop*, June 2007
Fthenakis & Kim, Life Cycle Emissions…, *Energy Policy, 35, 2549, 2007*
Fthenakis & Kim*, ES&T, 42, 2168, 2008; update 2016*

Single-junction and Tandem Perovskite PV Cumulative Energy Demand (CED)



IEA Critical Minerals Demand Projections



Recommendations to meet Demand

1. Adequate investment to diversified sources of supply
2. Technology innovation along value chain
3. Scale-up Recycling
4. Resilience in supply chain
5. Maintain environmental, social & governance standards
6. International collaboration

Source: The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions, IEA, 2021

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]

[1] The REAL Green New Deal Project, Albany, OR 97321, USA; wrees@mail.ubc.ca
[2] Faculty of Applied Science, School of Community and Regional Planning, University of British Columbia, Vancouver, BC V6T 1Z2, Canada
* Correspondence: megan.seibert@realgnd.org

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]

1 Center for Life Cycle Analysis, School of Engineering and Applied Science, Columbia University, New York, NY 10027, USA

2 Brookhaven National Laboratory, Interdisciplinary Sciences Department, Building 815, Upton, NY 11973, USA

3 School of Engineering, Computing and Mathematics, Faculty of Technology, Design and Environment, Oxford Brookes University, Wheatley Campus, Oxford OX3 0BP, UK

4 Ricardo plc, 30 Eastbourne Terrace, London W2 6LA, UK

5 School of Energy Systems, LUT University, 53850 Lappeenranta, Finland

6 Civil and Environmental Engineering Department, University of Surrey, Guildford GU2 7XH, UK

7 Environmental Engineering & Earth Sciences, Clemson University, Clemson, SC 29634, USA

8 European Commission, Joint Research Centre, 21014 Ispra, Italy

9 Institut Photovoltaïque d'Île de France (IPVF), CNRS UMR 9006, 18 Boulevard Thomas Gobert, 91120 Palaiseau, France

10 Environmental Studies Department, St. Lawrence University, Canton, NY 13617, USA

11 Clean Power Research, 1541 3rd Street, Napa, CA 94559, USA

12 First Solar, 350 W Washington St., Tempe, AZ 85281, USA

13 Angus Rockett, Department of Metallurgical and Materials Engineering, 305b Hill Hall, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, USA

14 INL-International Iberian Nanotechnology Laboratory, Av. Mestre José Veiga s/n, 4715-330 Braga, Portugal

15 HelioSourceTech, 8987 E. Tanque Verde, Suite 309, PMB216, Tucson, AZ 85749, USA

16 Sunpower Founder, Retired, 24700 Voorhees Drive, Los Altos Hills, CA 94022, USA

17 AMROCK Group, Sydney, NSW 2052, Australia

18 School of Photovoltaic & Renewable Energy Engineering, University of New South Wales, Sydney, NSW 2052, Australia

19 State Key Laboratory of PVST, Trina Solar, Xinbei District, Changzhou 213031, China

— Hide full affiliation list

Joint Effort brings results

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 utmo
for the energy-conversion-systems community, to its scientific merit, to the methods of
appropriateness of the citations, conclusions, ethics, and academic style. Our record in this
a source of great pride for us.

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

For a series of reasons, the original Seibert and Rees manuscript (S&R in the following) slipped through our 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