A Pathway to Sustainable Photovoltaics Growth

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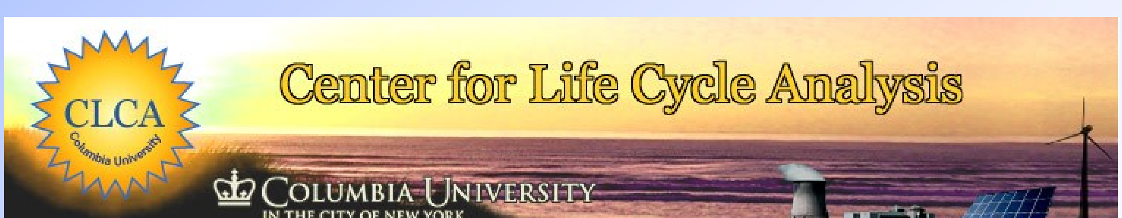
ISES Webinar May 6, 2021



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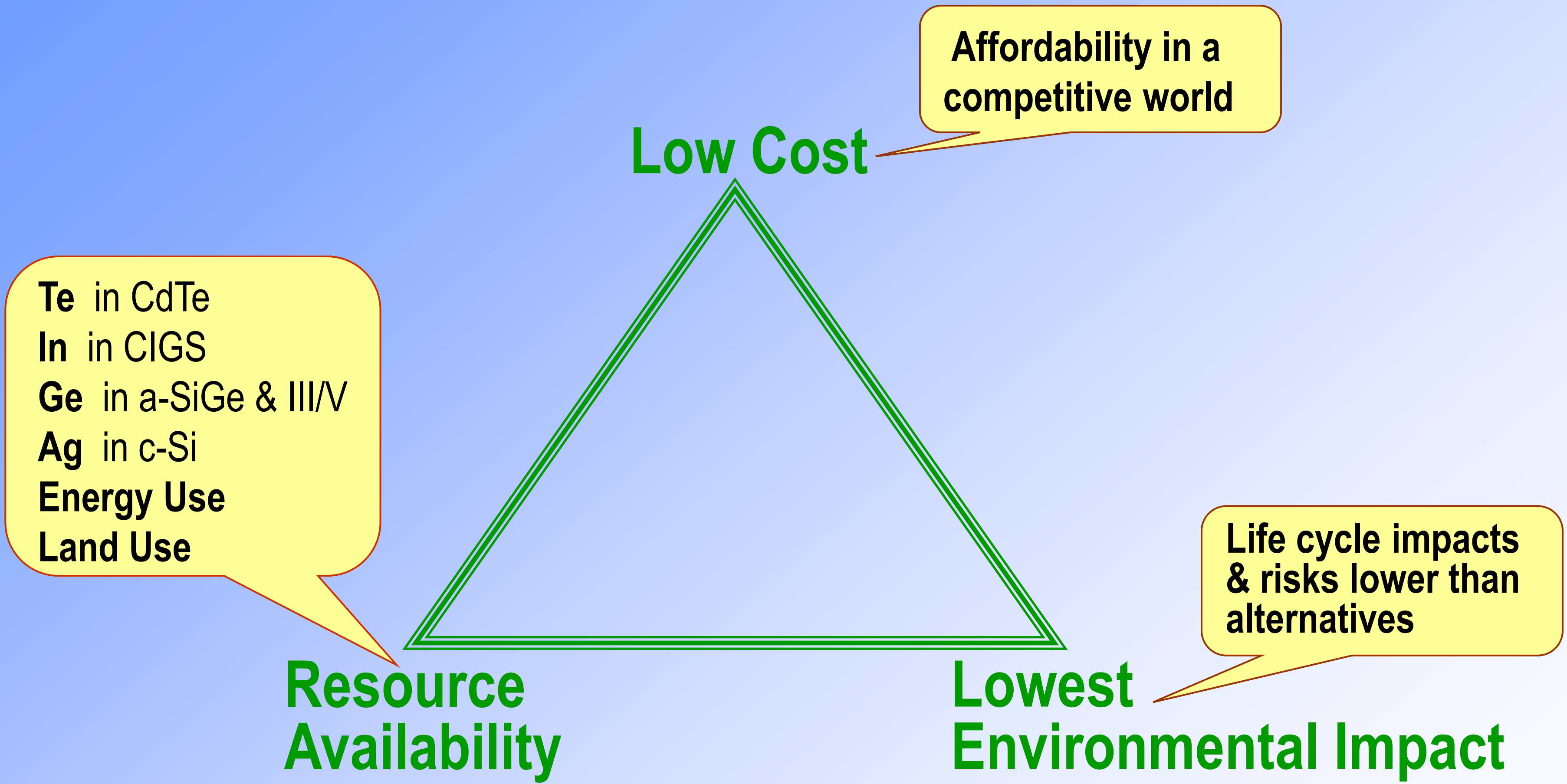
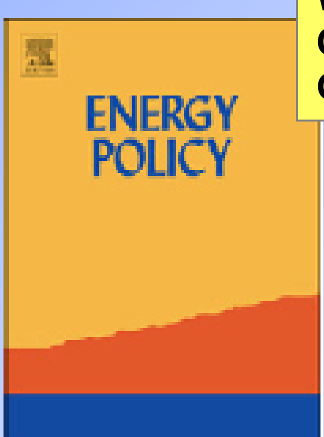
Large Scale PV –Sustainability Criteria



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

A Grand Plan for Solar Energy in the U.S. Feasibility Study

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



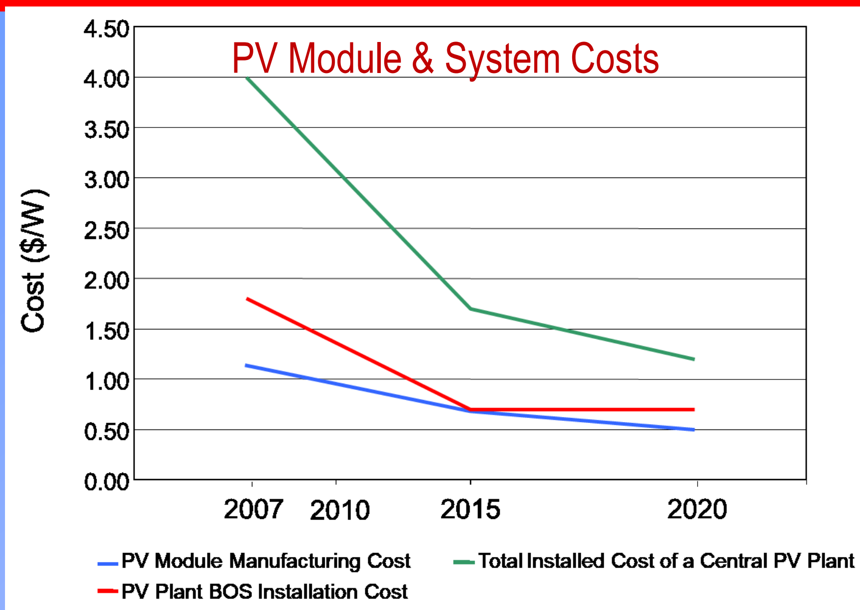
Cumulative Deployment (GW)	2020	2030	2050
PV	46	250	2800
Wind	72	210	698
CSP	28	118	1130
Geoth	17	55	200

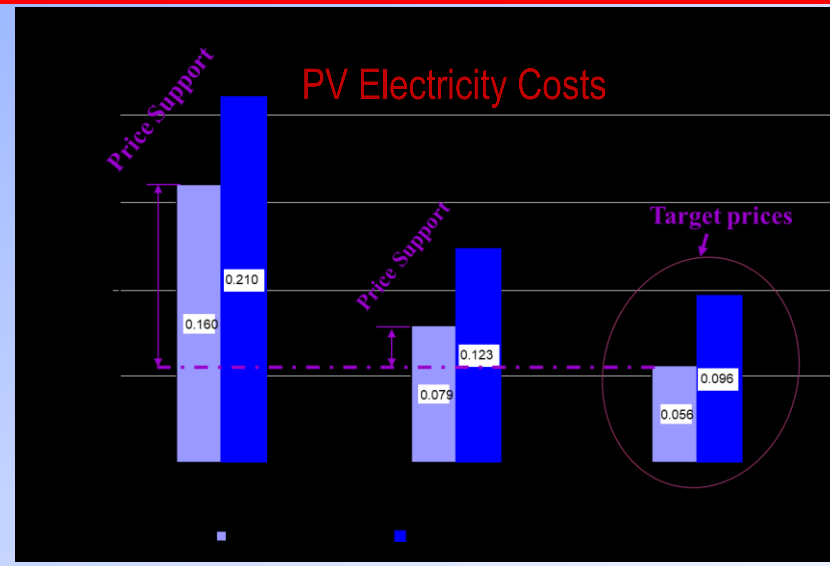
Photovoltaics
Wind
Concentrated Solar Power
Energy Storage
Geothermal, Biomass (cellulosic)
High Voltage DC Transmission
Hybrid plug-in electric cars

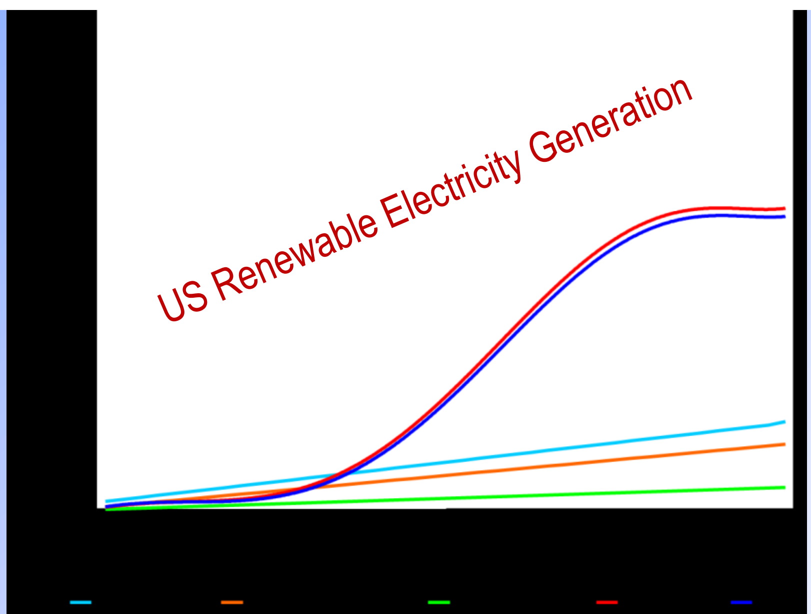
The technical, geographical and economic feasibility for solar energy to supply the energy needs of the U.S.,

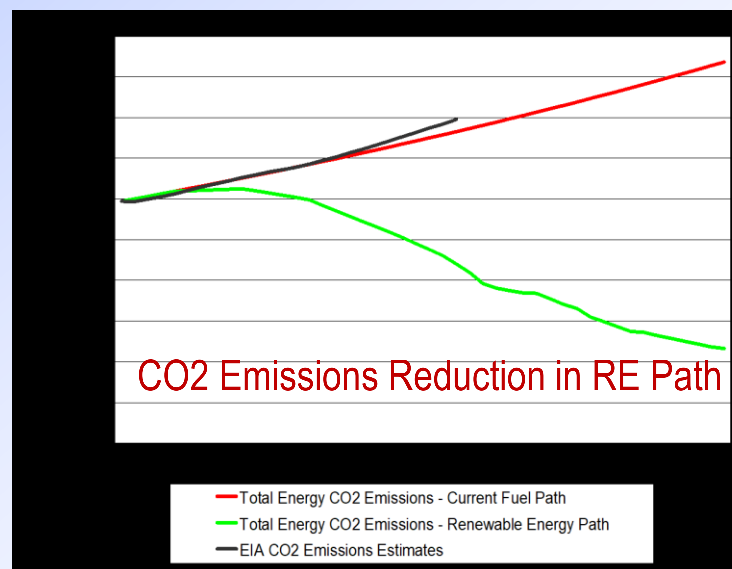
Vasilis Fthenakis, James Mason, Ken Zweibel, Energy Policy 37 (2009)

Grand Solar Plan: Cost & Penetration Projections



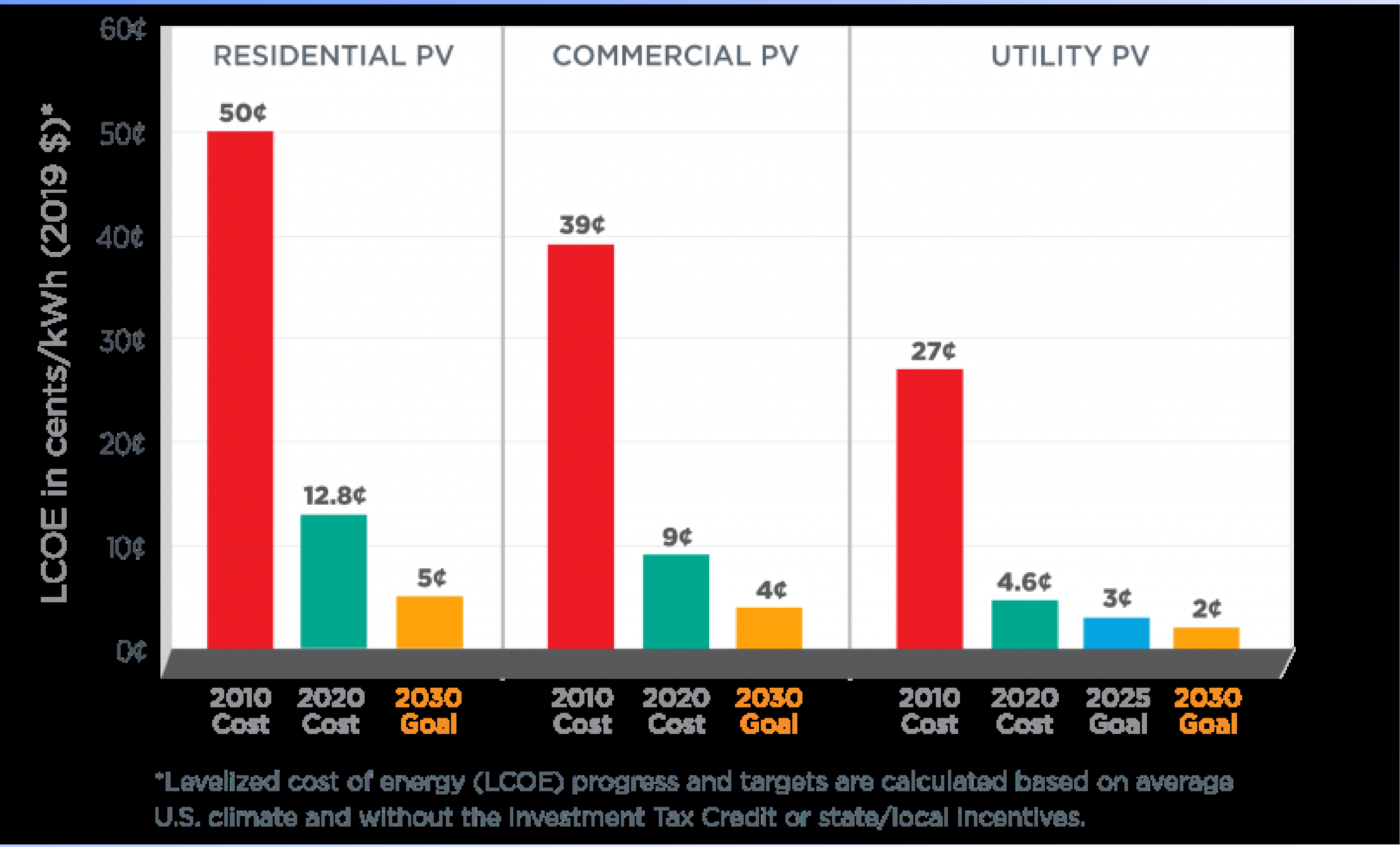






Fthenakis, Mason, Zweibel, The technical, geogpaphical & economic feasibility solar US, Energy Policy, 2019

DOE-EERE SETO PV Costs & Projections)



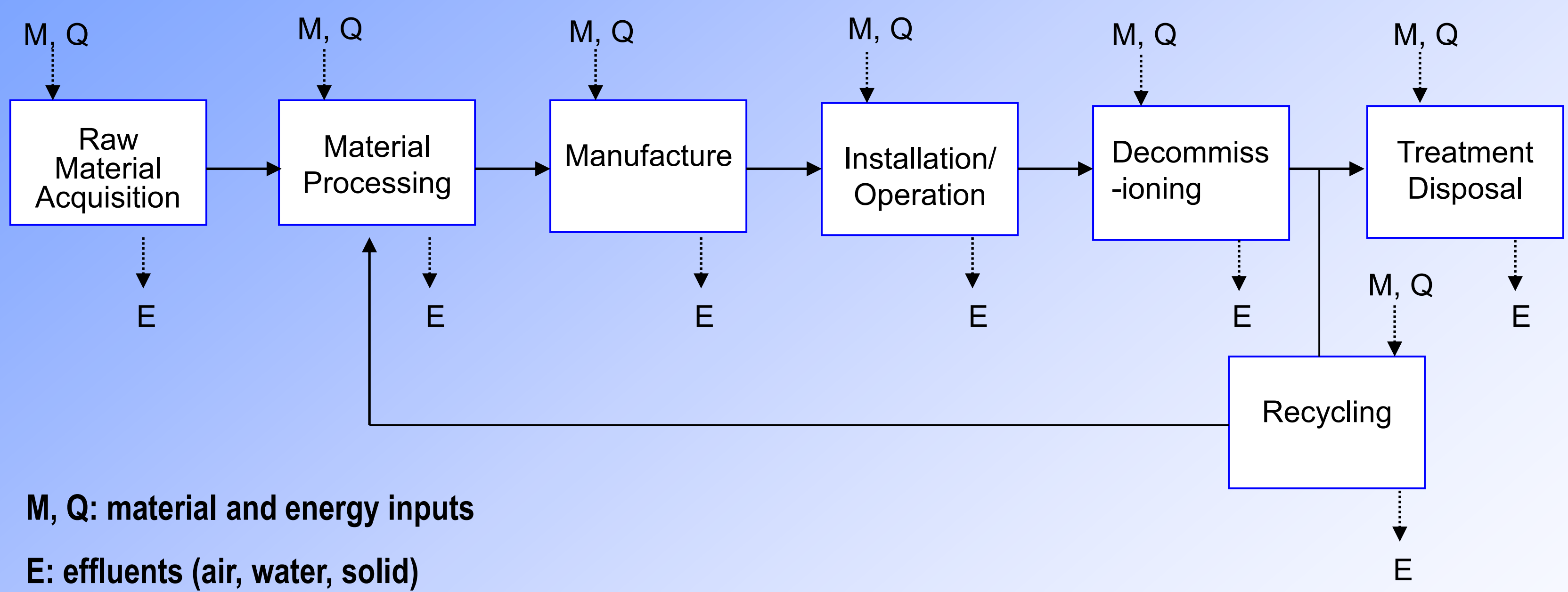
Photovoltaics –Leading the Energy Transition

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

Some Perceptions on Environmental Impact

- PV has significant life-cycle emissions
- PV Energy Return on Energy Investment is too low
- PV deployment uses too much land
- PV power plants create a Heat Island effect

Environmental Impacts-Life Cycle Analysis



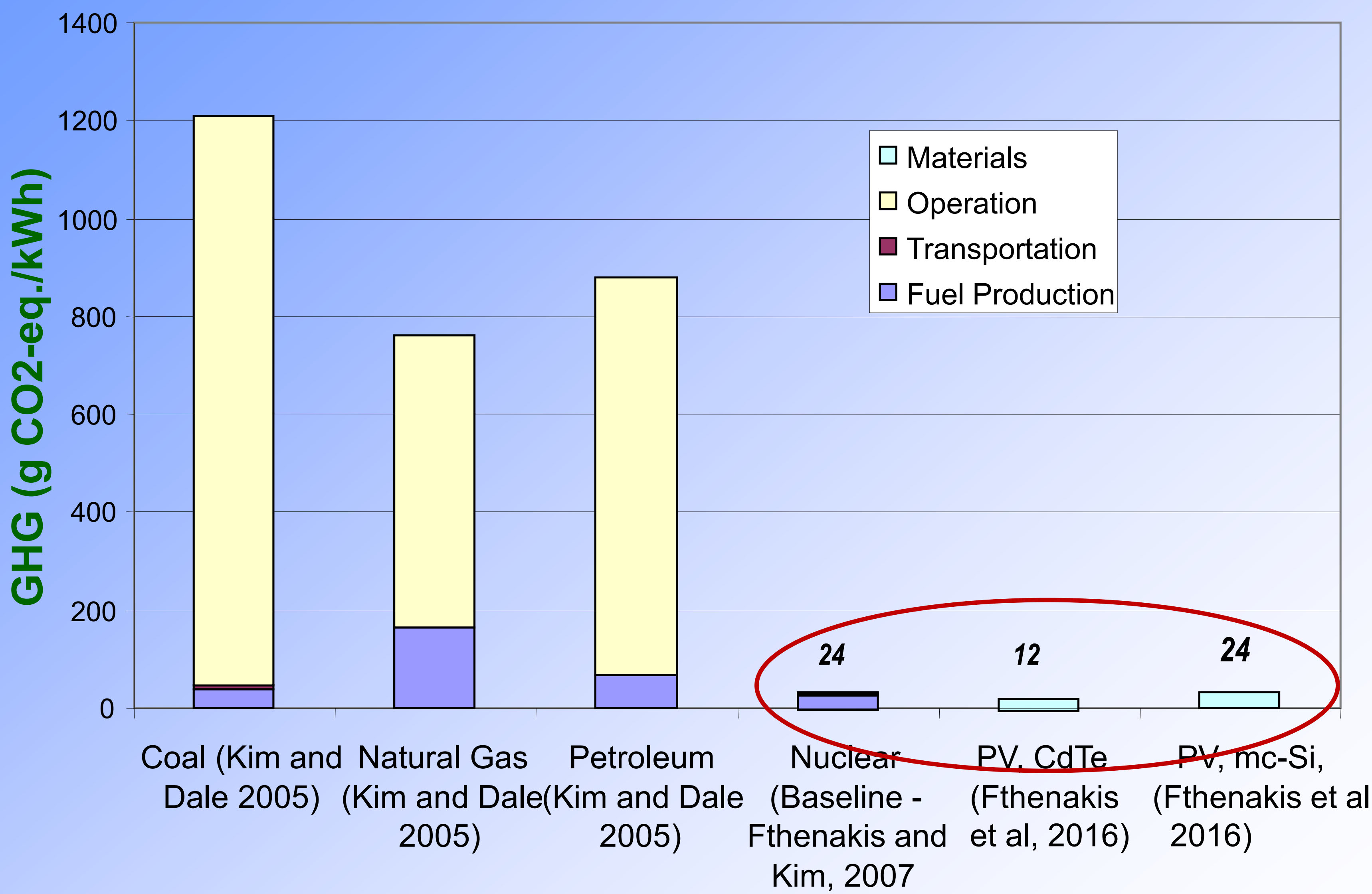
M, Q: material and energy inputs

E: effluents (air, water, solid)

Basic Metrics

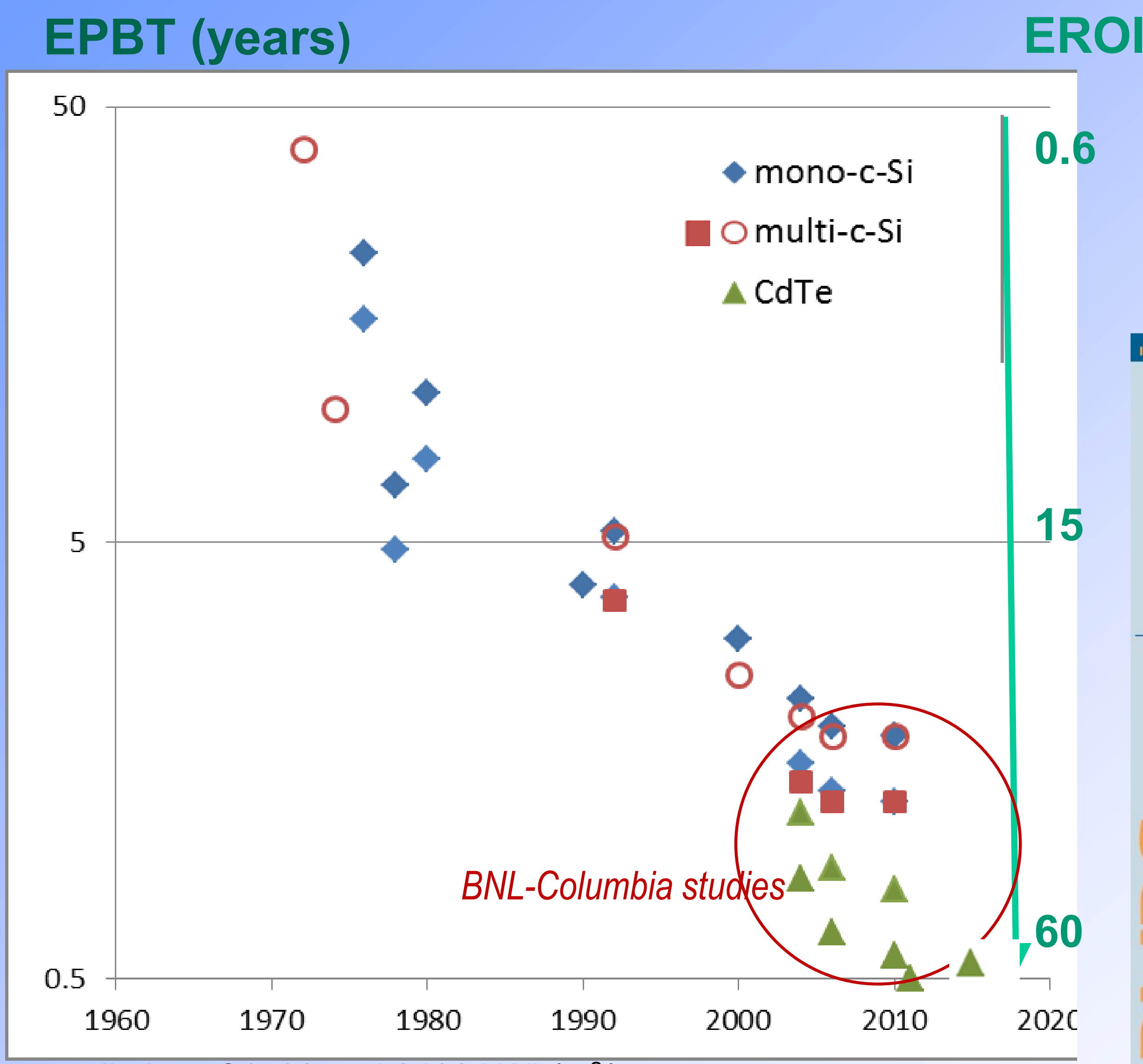
- Greenhouse Gas Emissions
- Toxic Emissions
- Resource Use (materials, water, land)
- Energy Payback Times (EPBT) and Energy Return or Energy Investment (EROI)

GHG Emissions from Life Cycle of Electricity Production: Comparisons

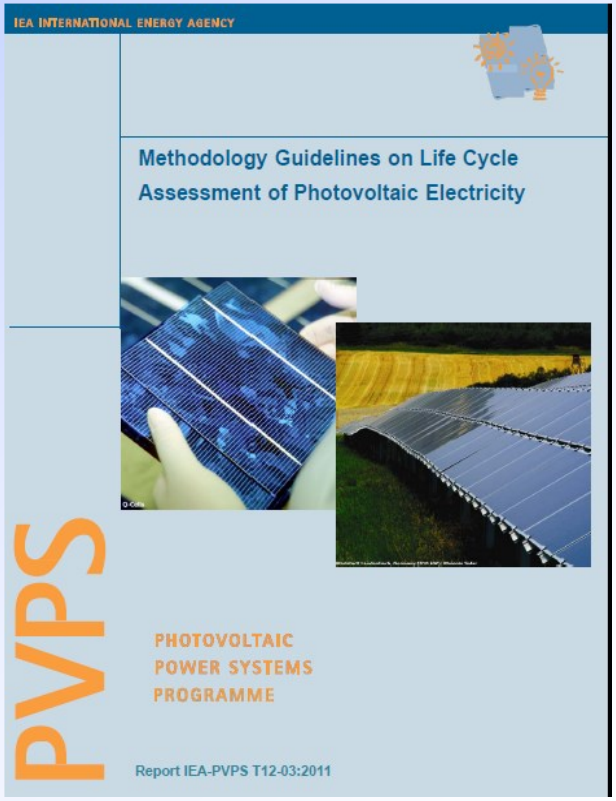


Fthenakis, California Energy Commission, *Nuclear Issues Workshop*, June 2007
Fthenakis & Kim, Life Cycle Emissions…, *Energy Policy, 35, 2549, 2007*
Fthenakis & Kim*, ES&T, 42, 2168, 2008; update 2016*

Energy Payback Times & Energy Return on Energy Investment Historical Evolution

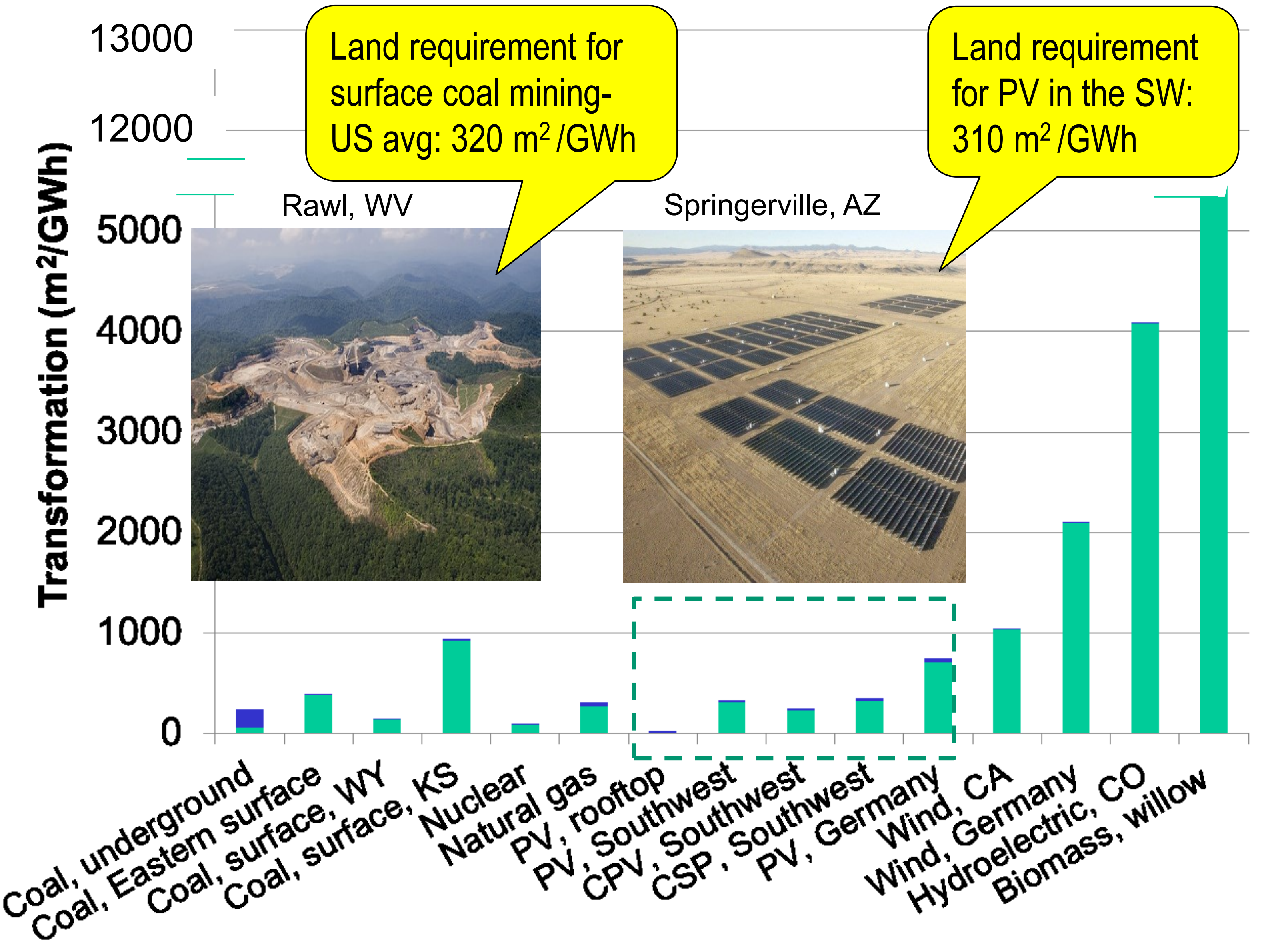


Irradiation of 1700 and 2400 kWh/m²/yr



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

PV Uses less Land than Coal



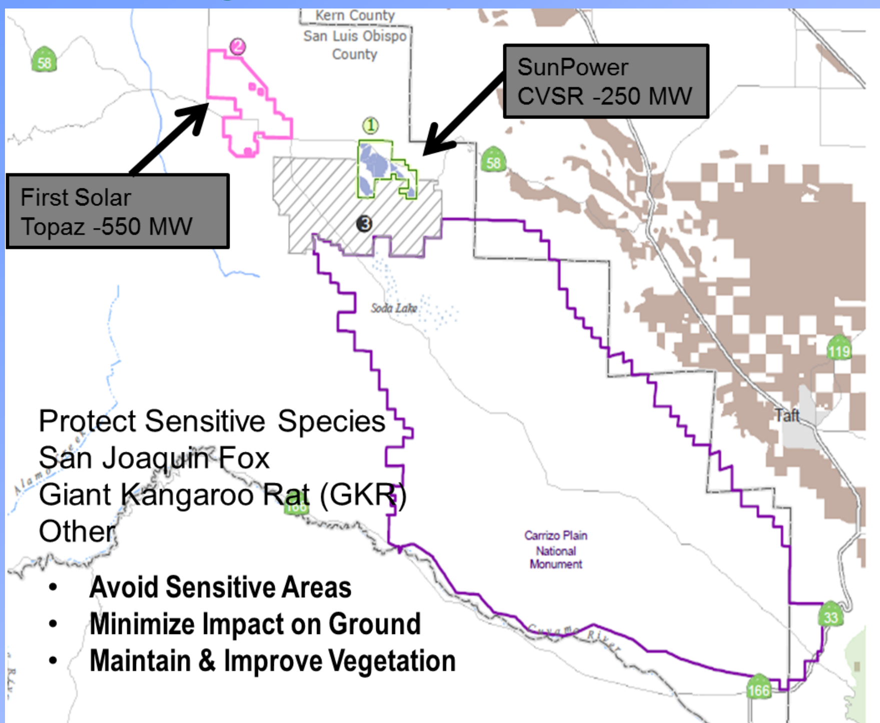
Fthenakis and Kim, Renewable and Sustainable Energy Reviews, 2009; Burkhardt et al (2011)

…and does not disturb the Land

...dual Use of Land

Use of Land is Environmentally Friendly

Protecting Wild-Life



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

Investigating Heat Island Effect

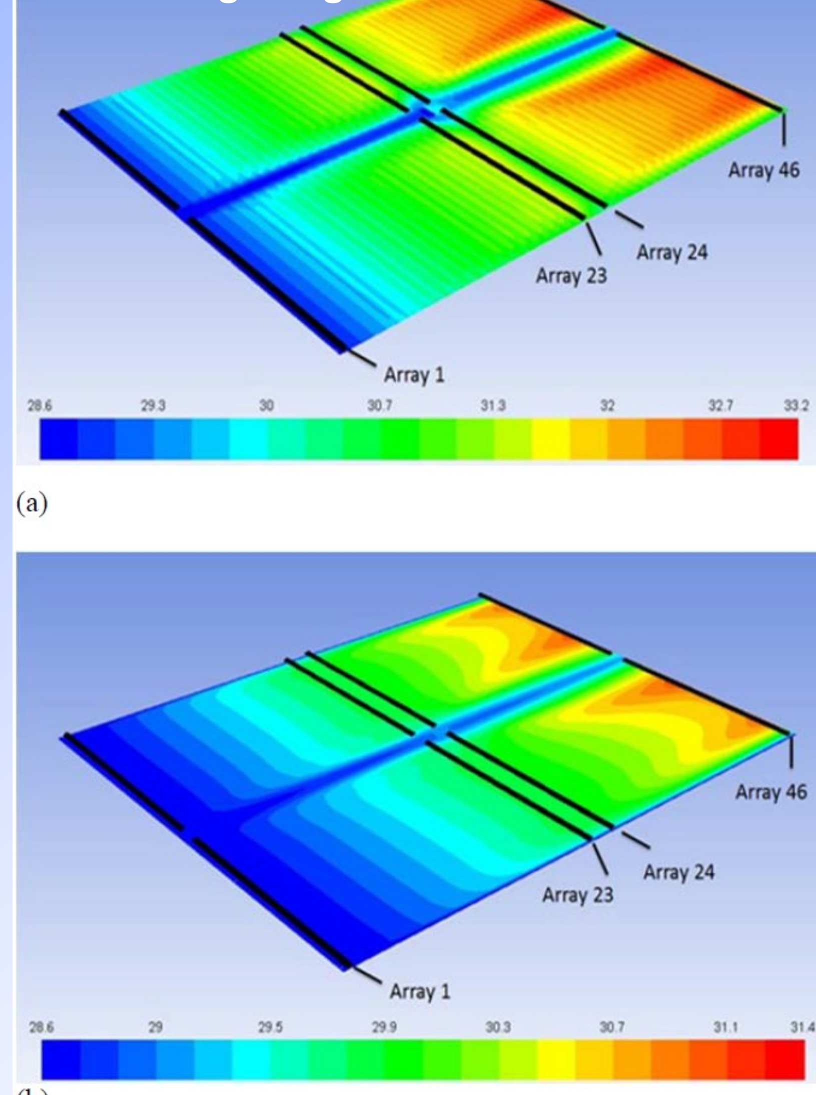
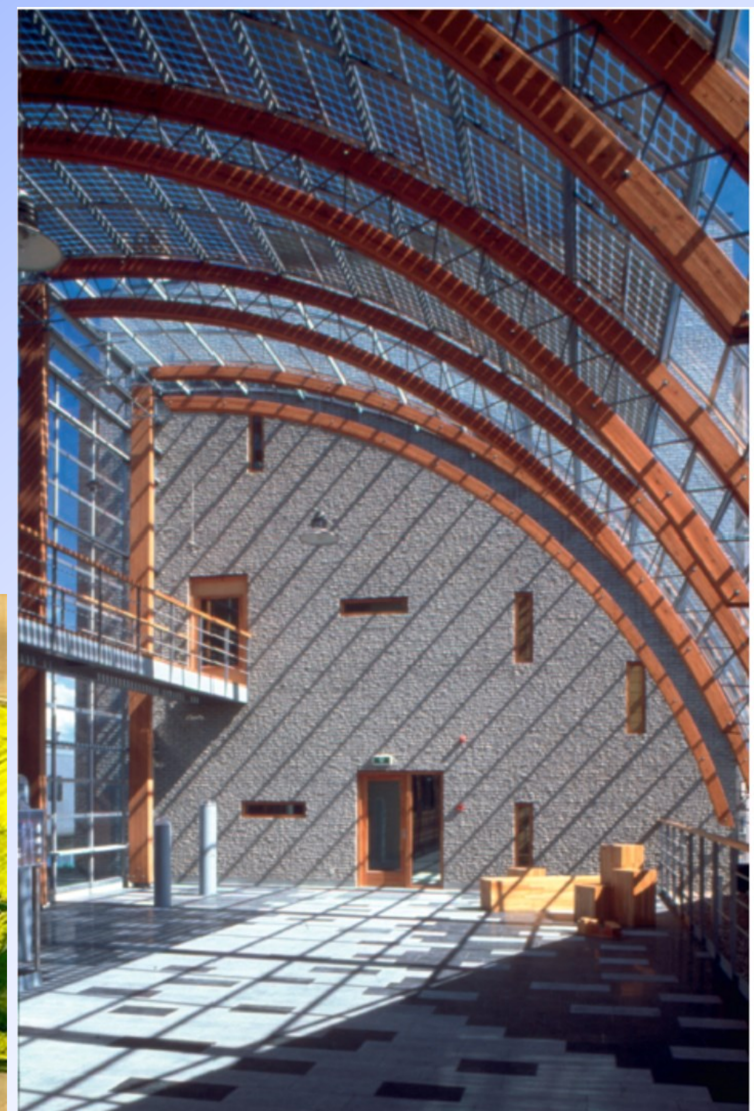


Fig. 11 Air temperatures from 3-D simulations during a sunny day. a) Air temperatures at a height of 1.5 m; b) air temperatures at a height of 2.5 m.

…combines Usefulness and Beauty



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

… changes Lives in the Developing World

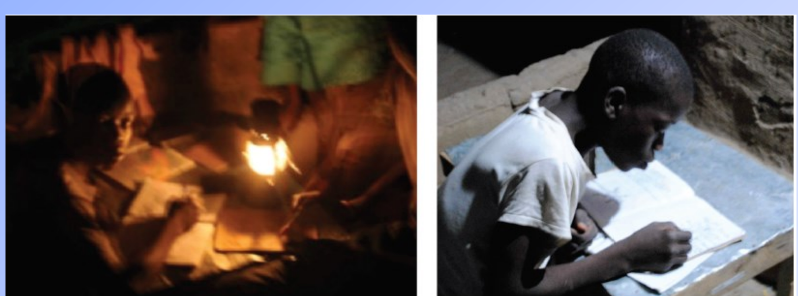
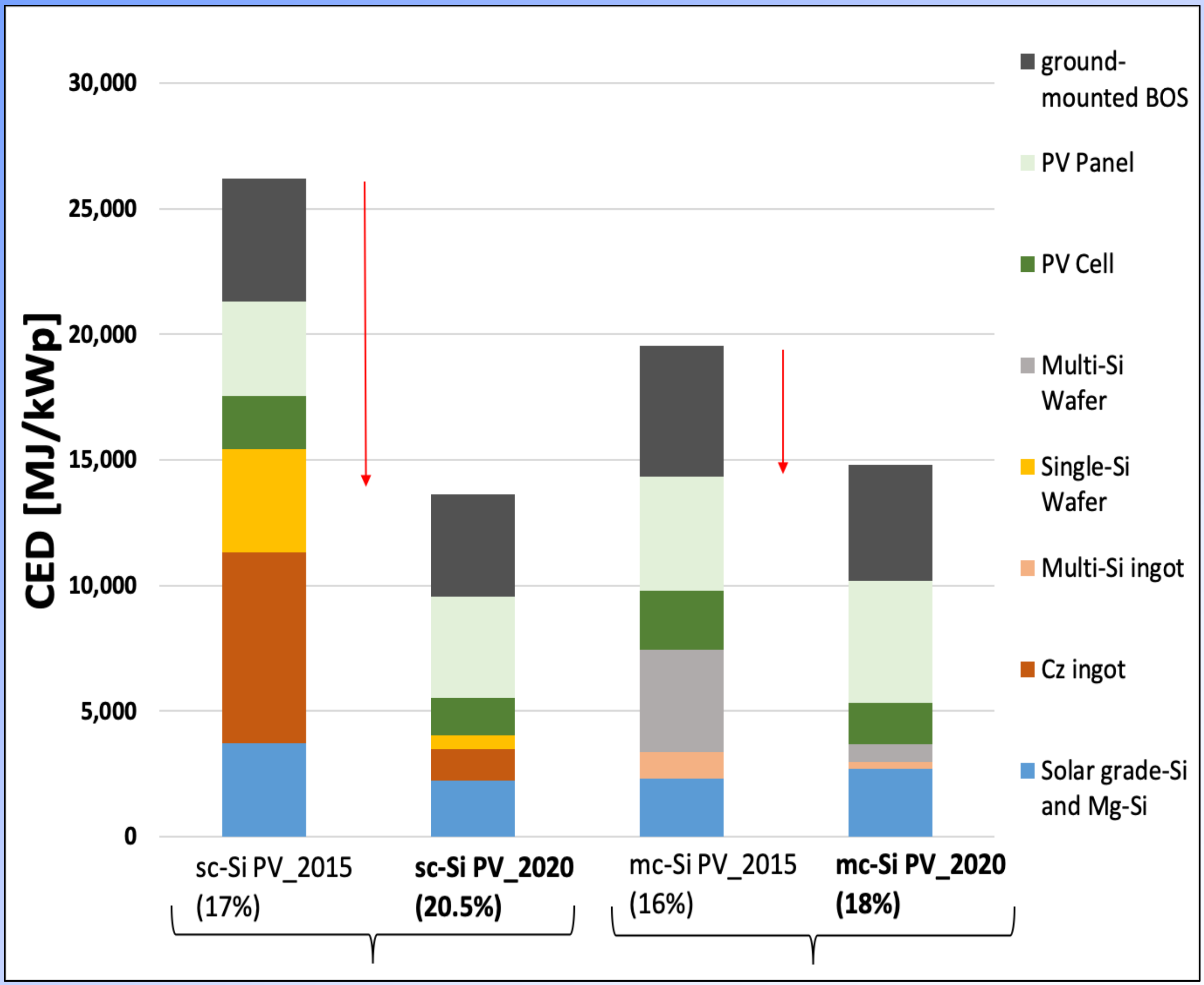


Figure 7.10 PV modules and low-energy lights replaced kerosene lighting. Sharedsolar user Uganda, 2012 (*Source:* Courtesy of V. Modi, Columbia University).

Figure 7.12 Sharedsolar mini-grid installation during construction phase. Mali, 2011 (*Source:* Courtesy of V. Modi, Columbia University).

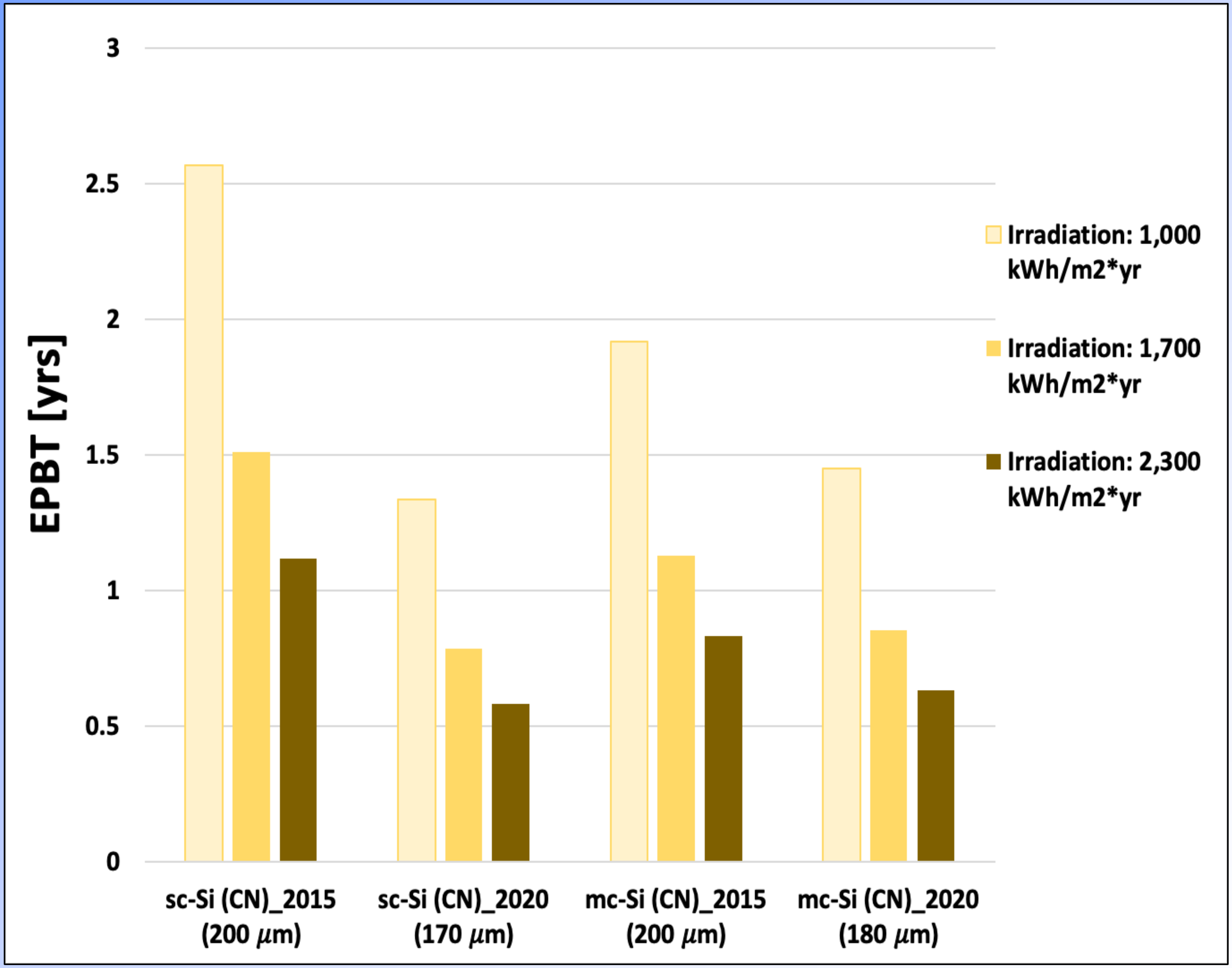
Images from: Fthenakis & Lynn, *Photovoltaic-Systems Integration and Sustainability*, Wiley, 2018

… PV continues to improve



Fthenakis Lecissi, Progress in Photovoltaics, in press

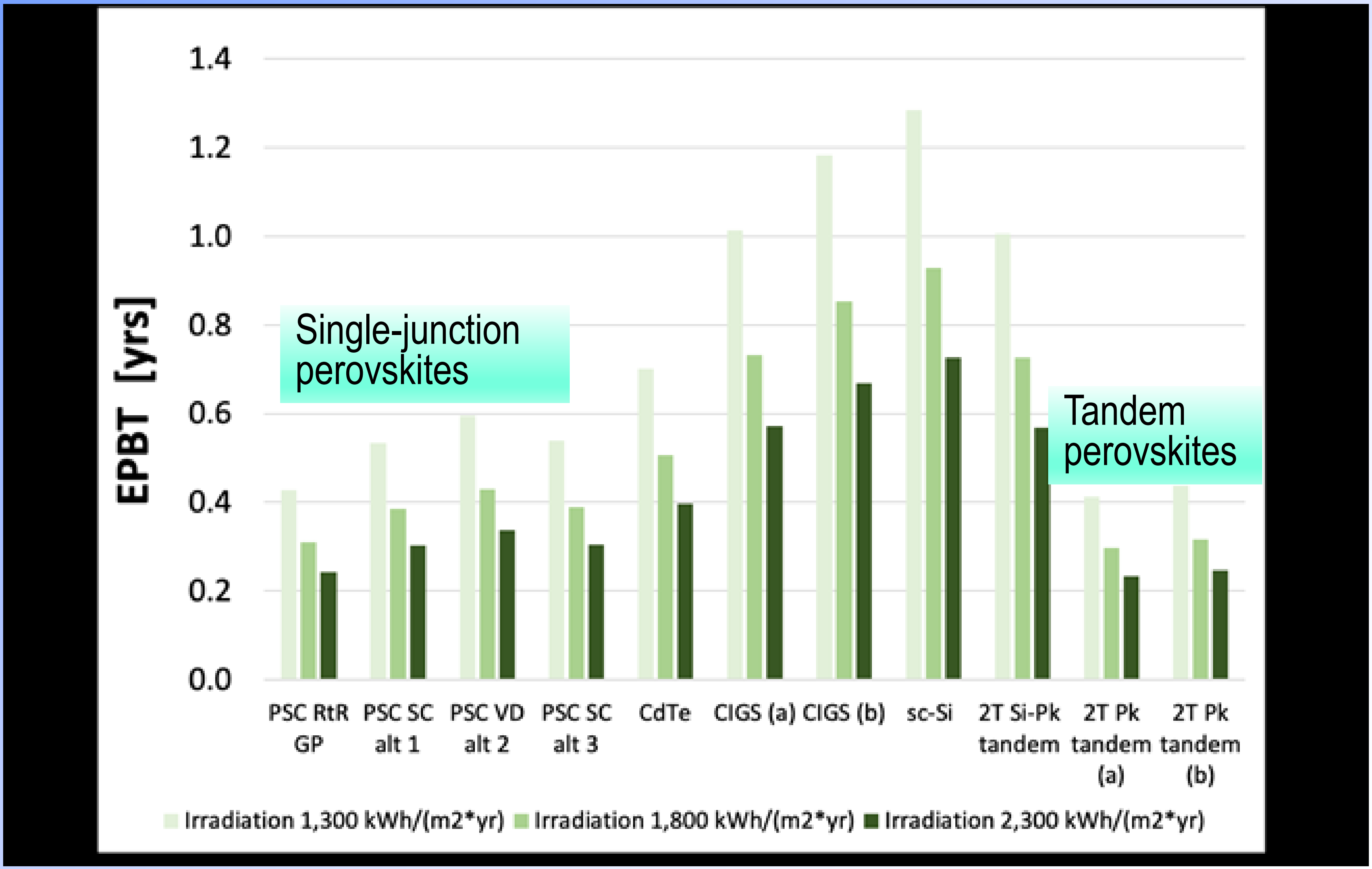
… PV continues to improve



Fthenakis Lecissi, Progress in Photovoltaics, in press

… PV continues to improve

Energy Payback Times (ERPT) comparisons of Single-junction and Tandem Perovskite with commercial PV panels



Lecissi, Fthenakis Progress in Photovoltaics, 2021

Points for Discussion

- Solar energy can sustainably grow to multi-TW levels and supply a large fraction of our energy needs if we continue and accelerate the current deployment.
- Solar energy is an enabler for resolving the water and environmental challenges of humanity.
- Distributed solar enhances grid resiliency.
- Need for full cost accounting of energy including external environmental and health costs & benefits.

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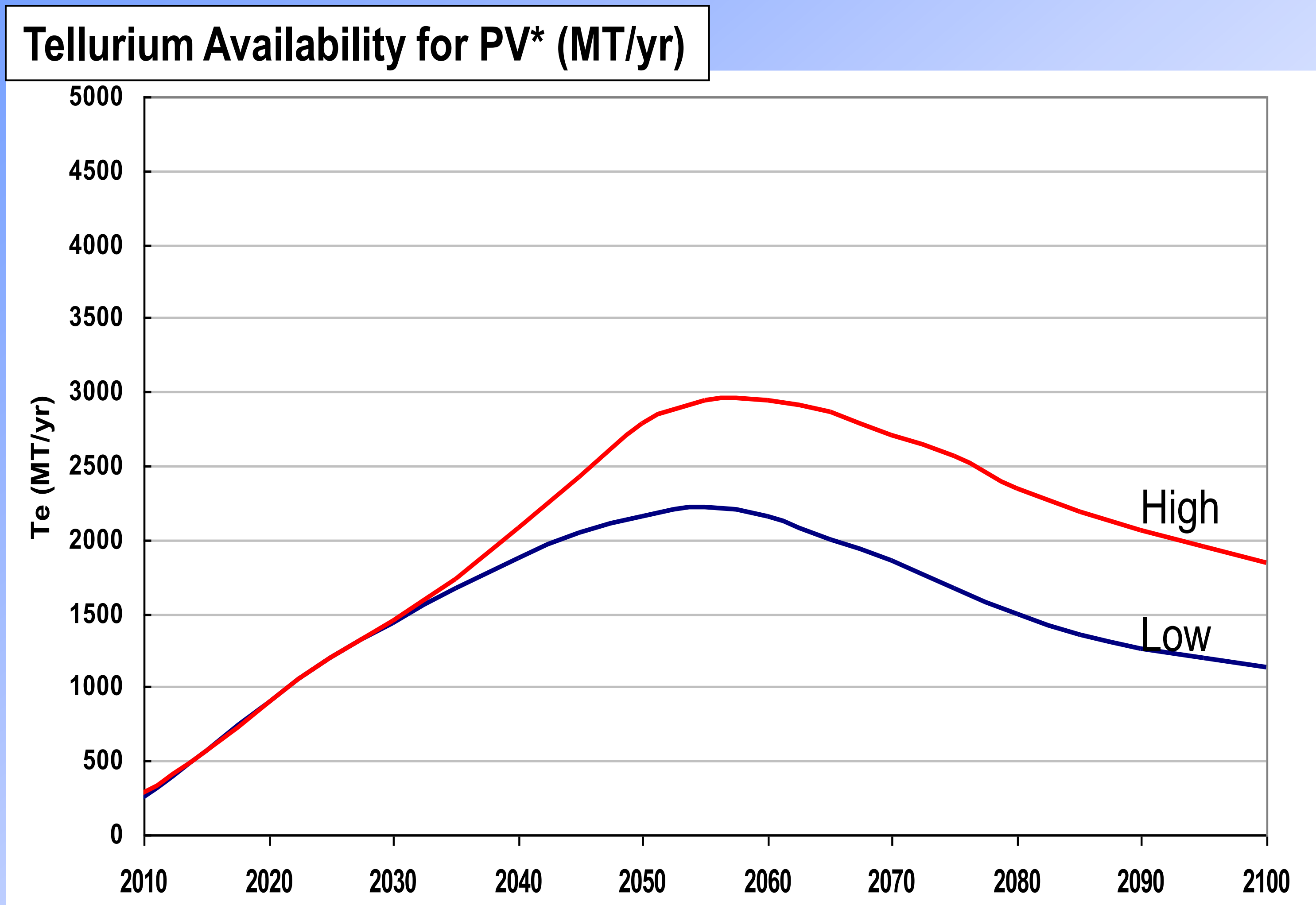
Auxiliary slides

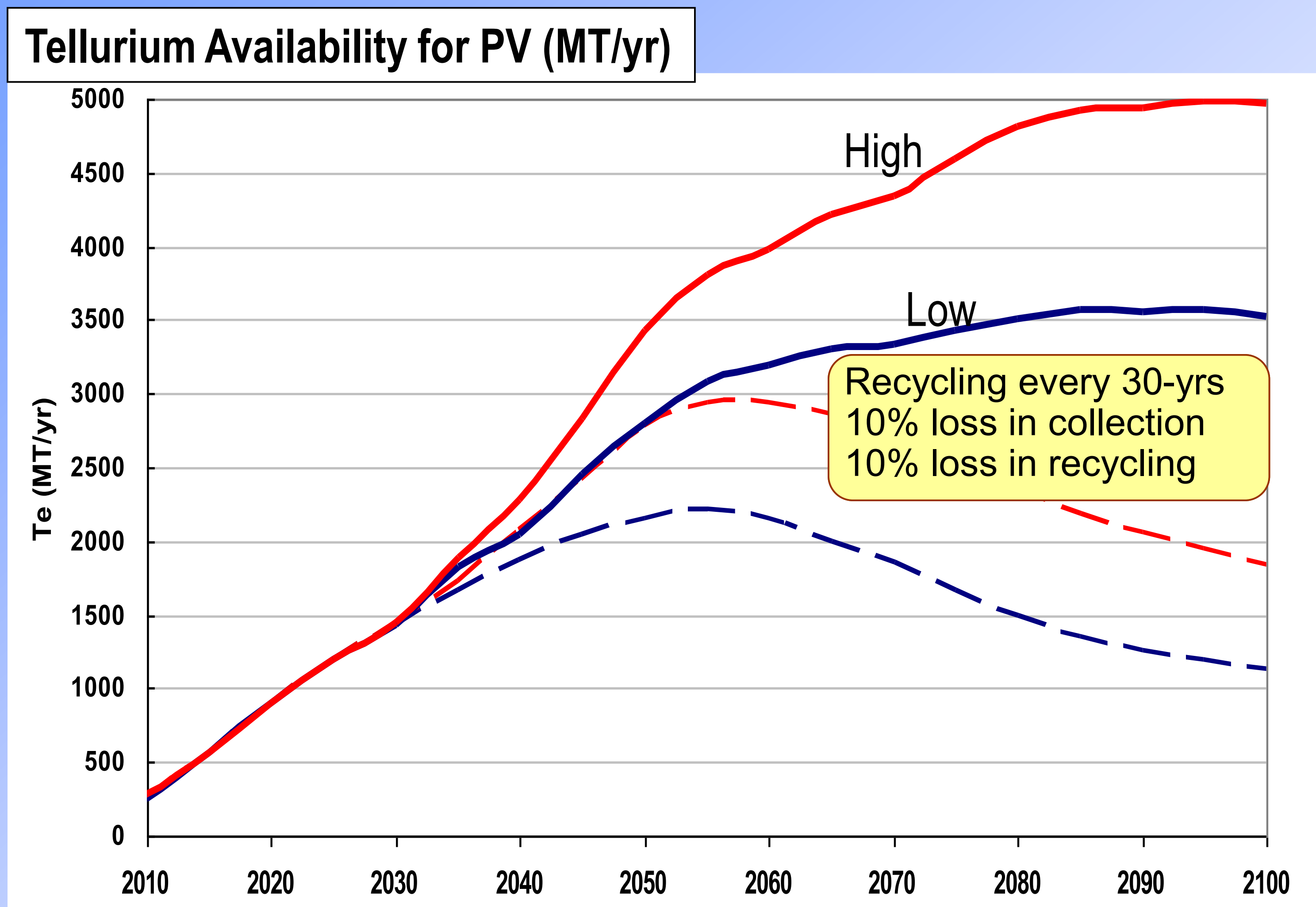
Is PV growth is constrained by materials availability? Case study: Tellurium for PV* from Copper Smelters



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

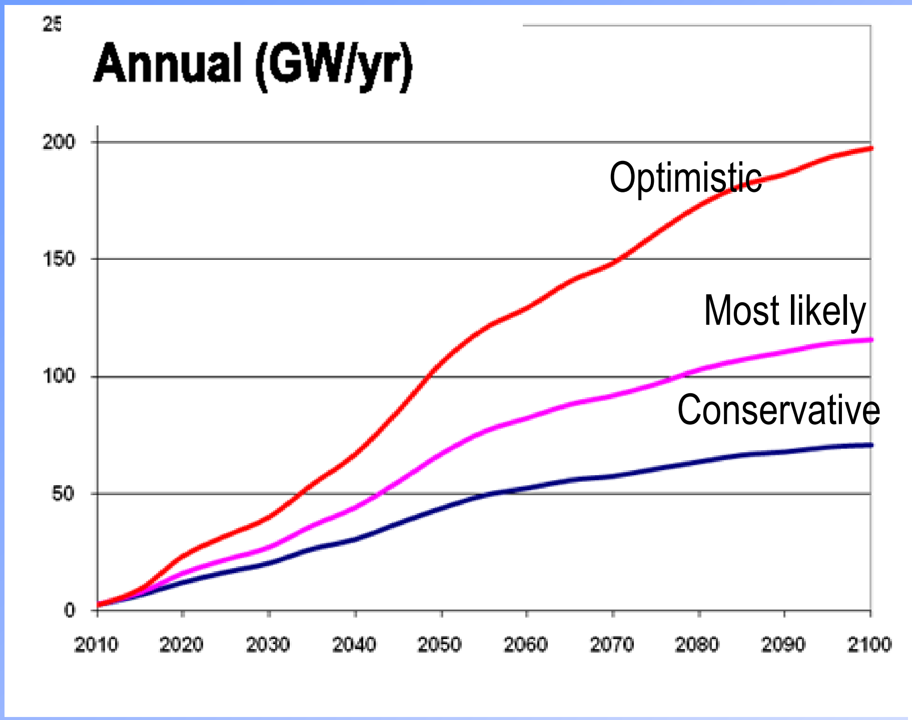
* 322 MT/yr Te demand for other uses has been subtracted
All the future growth in Te production is allocated to PV

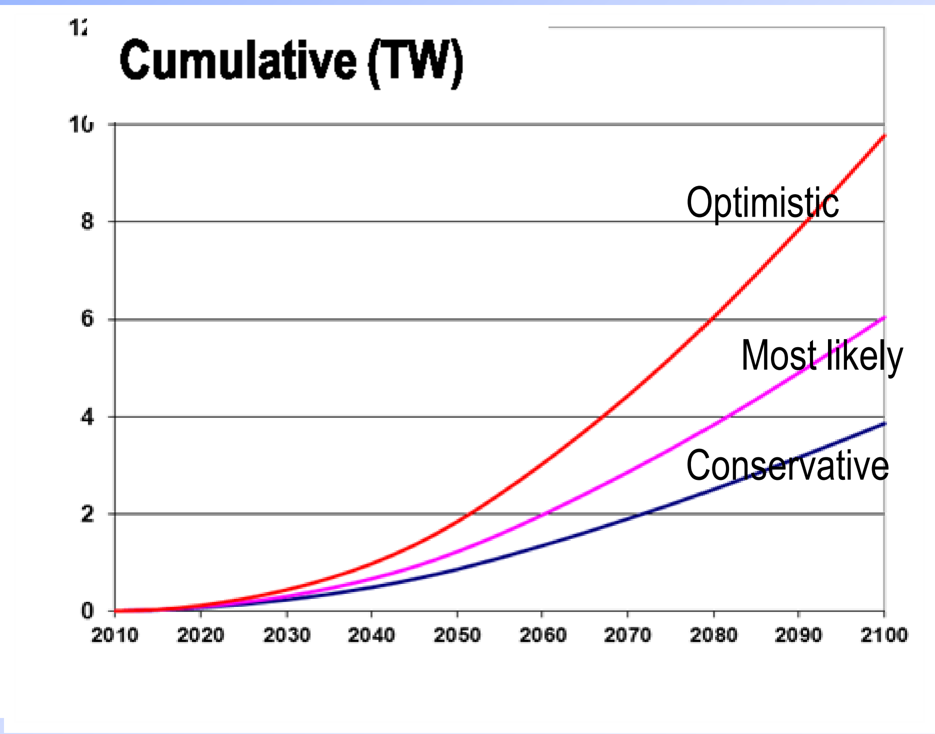
Te Availability for PV: Primary + Recycled



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

CdTe PV Production Constraints





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Special Issue; MRS Bulletin, 37, 425, 2012