Energy-Water-Environmental Challenges: Sustainable Development Solutions in Mining

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Problems awaiting Solutions

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

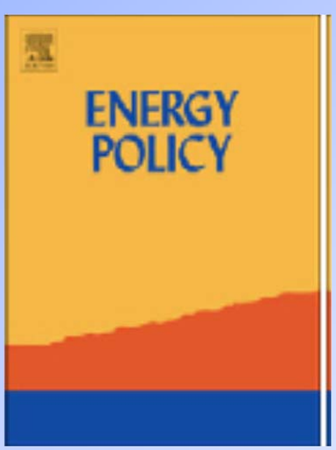
1. Energy
2. Water
3. Food
4. Environment
5. Poverty
6. Terrorism & War
7. Disease
8. Education
9. Democracy
10. Population

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

Photovoltaics
Concentrated Solar Power
Wind

<u>Cumulative Deployment 2030</u>
254 GW PV; 210 GW Wind
118 GW CSP; 55 GW Geothermal



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)

Center for Life Cycle Analysis (CLCA): Energy-Water-Environmental Research

- *Current Research Areas:*

  1. Sustainability Systems Analysis of Energy Life-Cycles

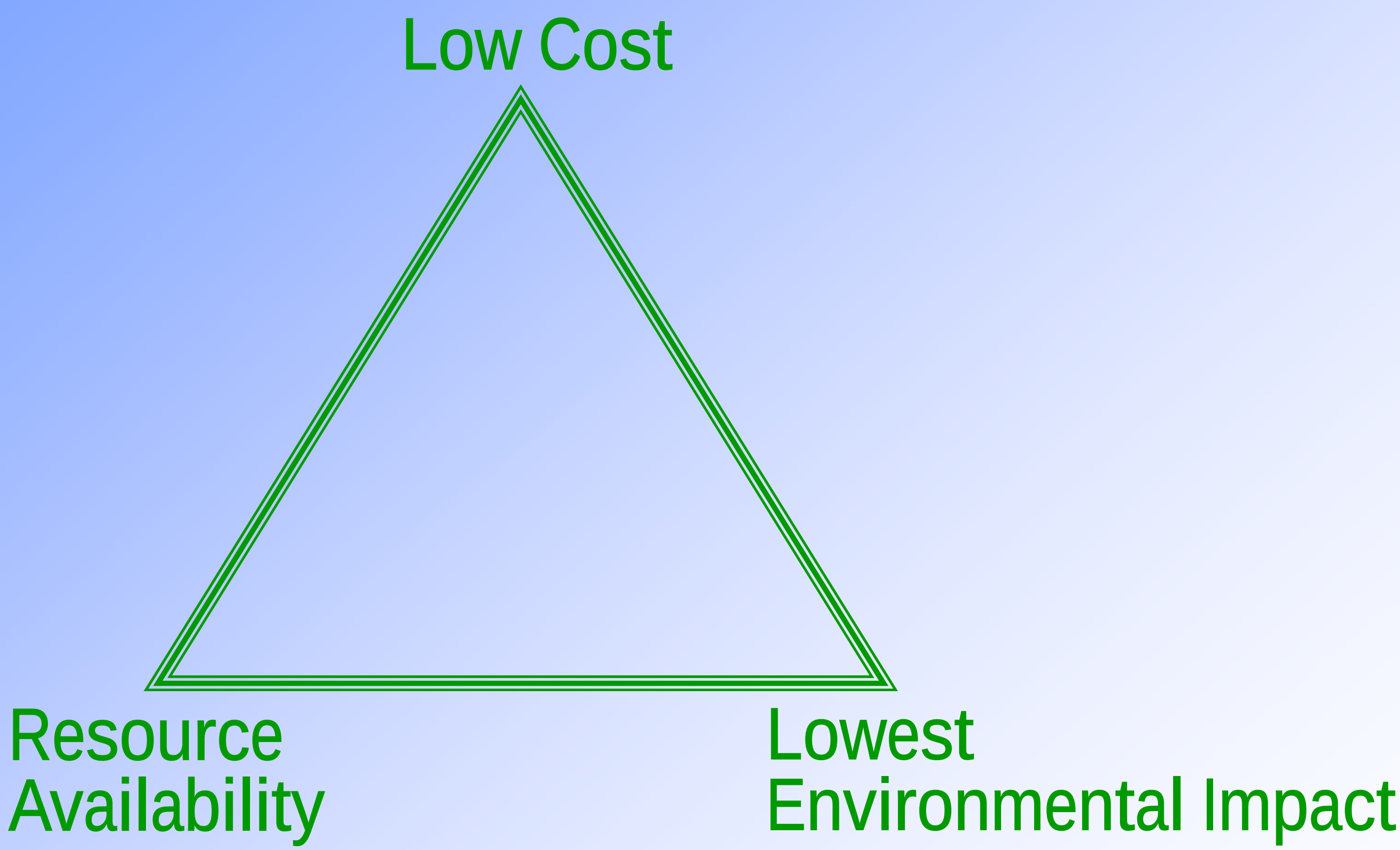
  2. Renewable Energy Systems Integration

- *Applications:*

  Industry: Photovoltaics, Energy Storage, Water Desalination, Mining

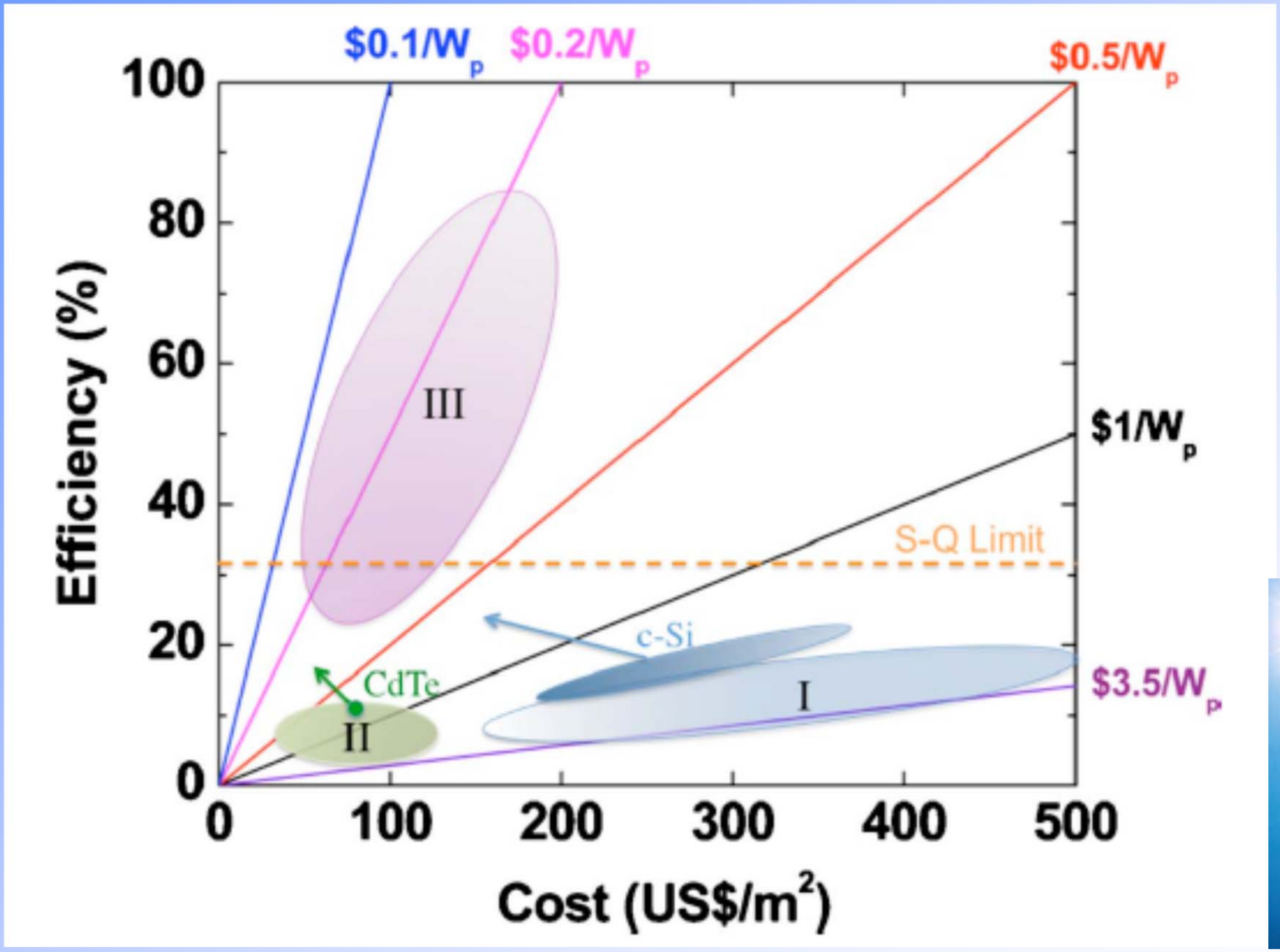
  Country: Europe, United States, Chile, Arabian Gulf Countries

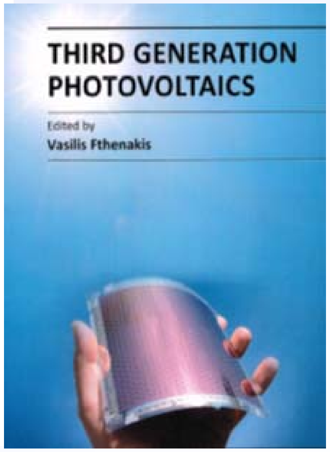
Area 1: Sustainability Systems Analysis of RE Life-Cycles
Large Scale PV –Sustainability Criteria



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.

Three Generations of Solar Cells: Module Costs



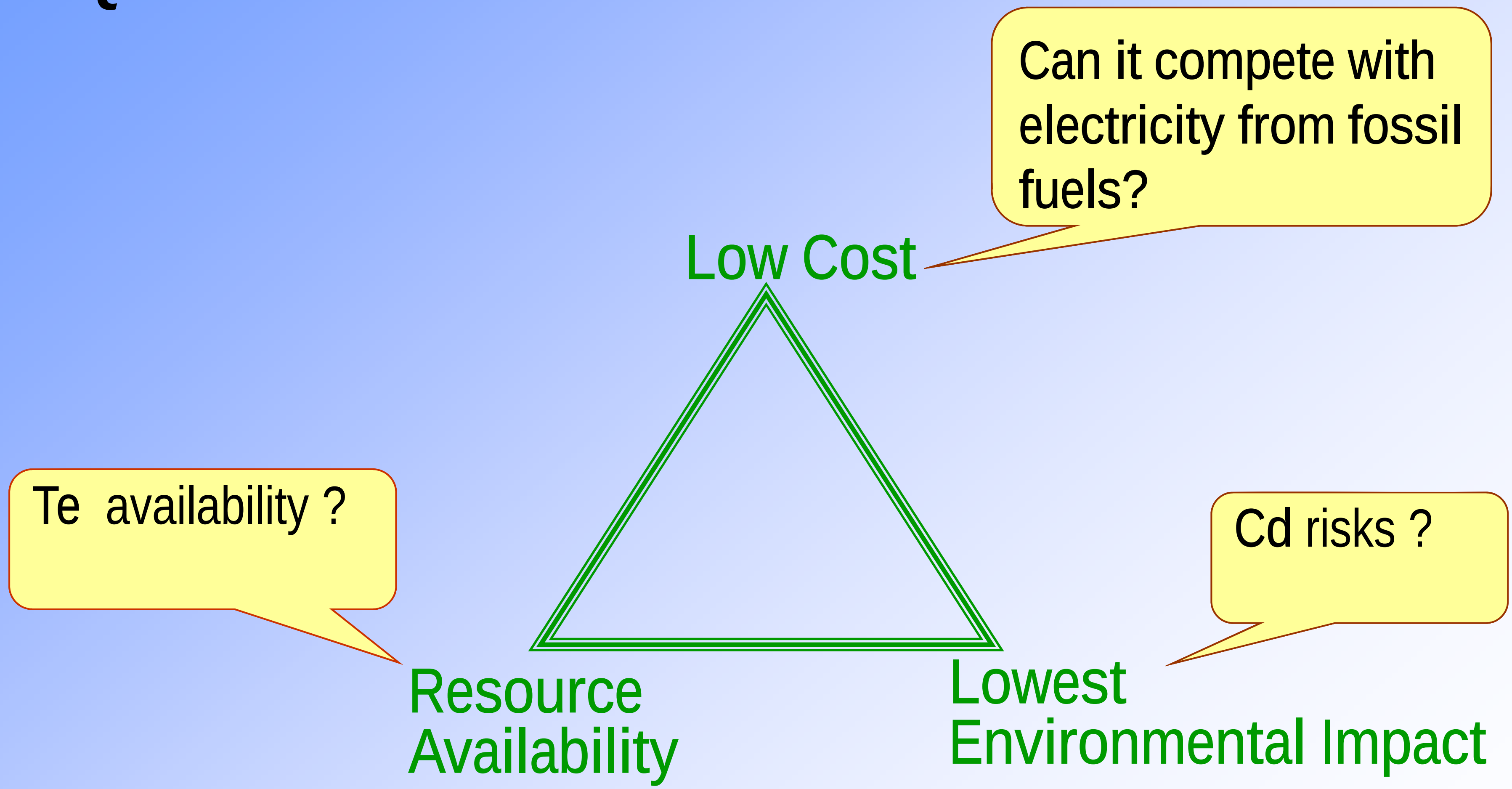


Wolden C, Kurtin J., Baxter J., Repins I., Shaheen S., Torvik J., Rockett A., Fthenakis V., Aydil E., Photovoltaic Manufacturing: Present Status and Future Prospects, <u>J. Vac. Sci. Technolo. A</u> 29(3), 030801-16, 2011

Fthenakis V. (editor), <u>Third Generation Photovoltaics</u>, InTech Publishing, 2012

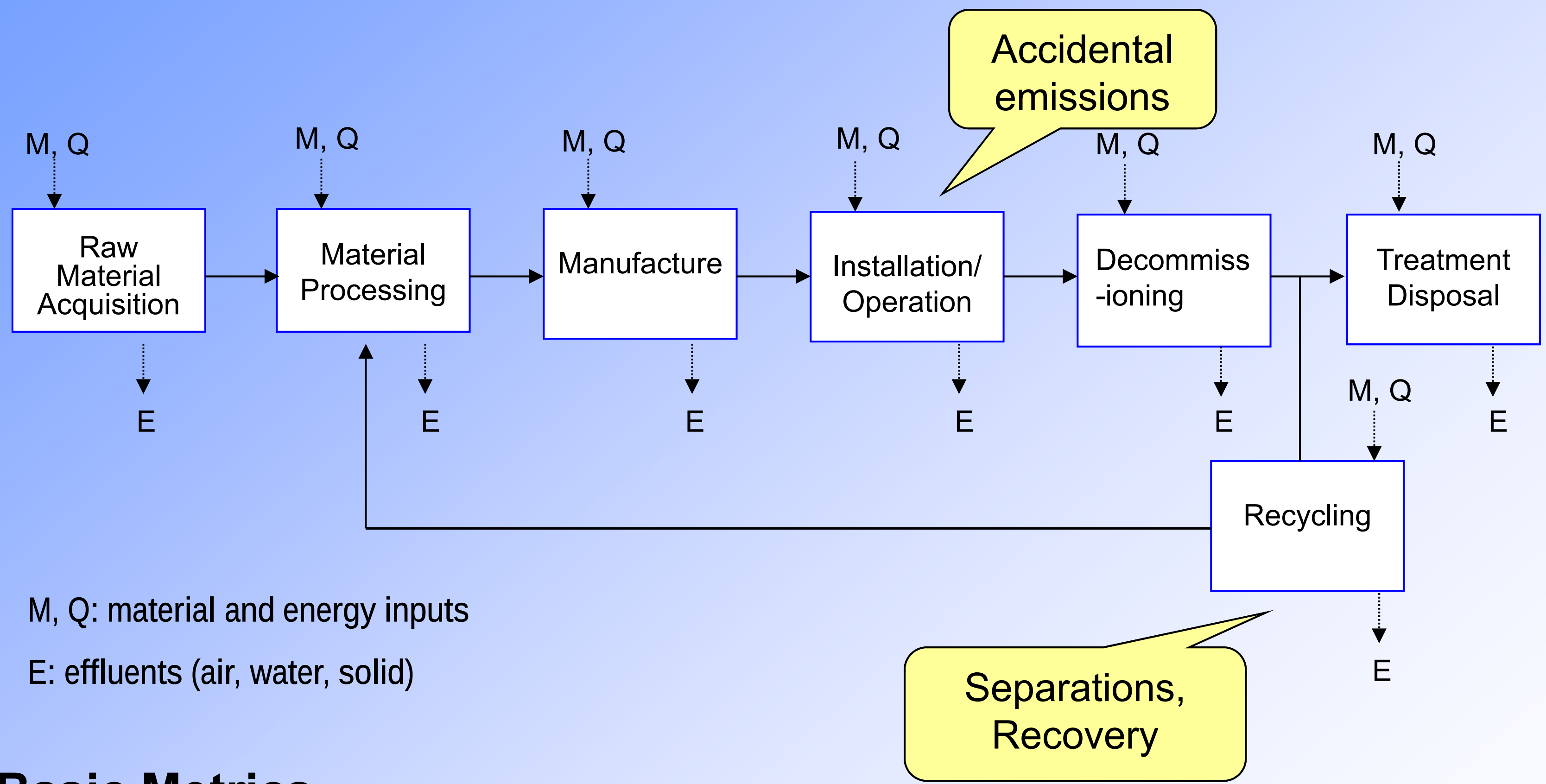
Energy-Environmental Systems Analysis
Example: CdTe PV LCA

Questions to answer:



Life Cycle Analysis

Experimental Research at BNL & CU



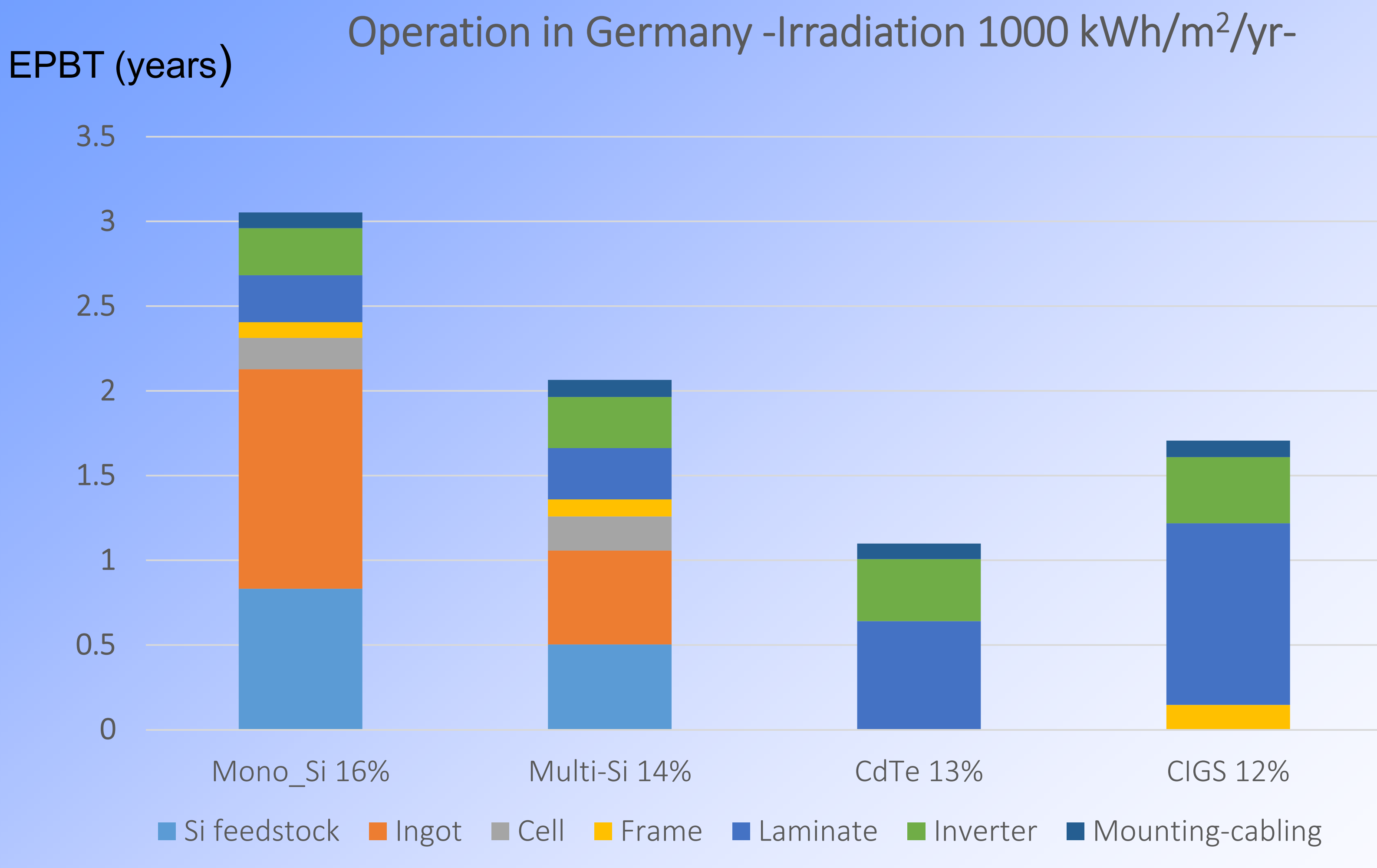
M, Q: material and energy inputs

E: effluents (air, water, solid)

Basic Metrics

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

Energy Payback Times (EPBT)

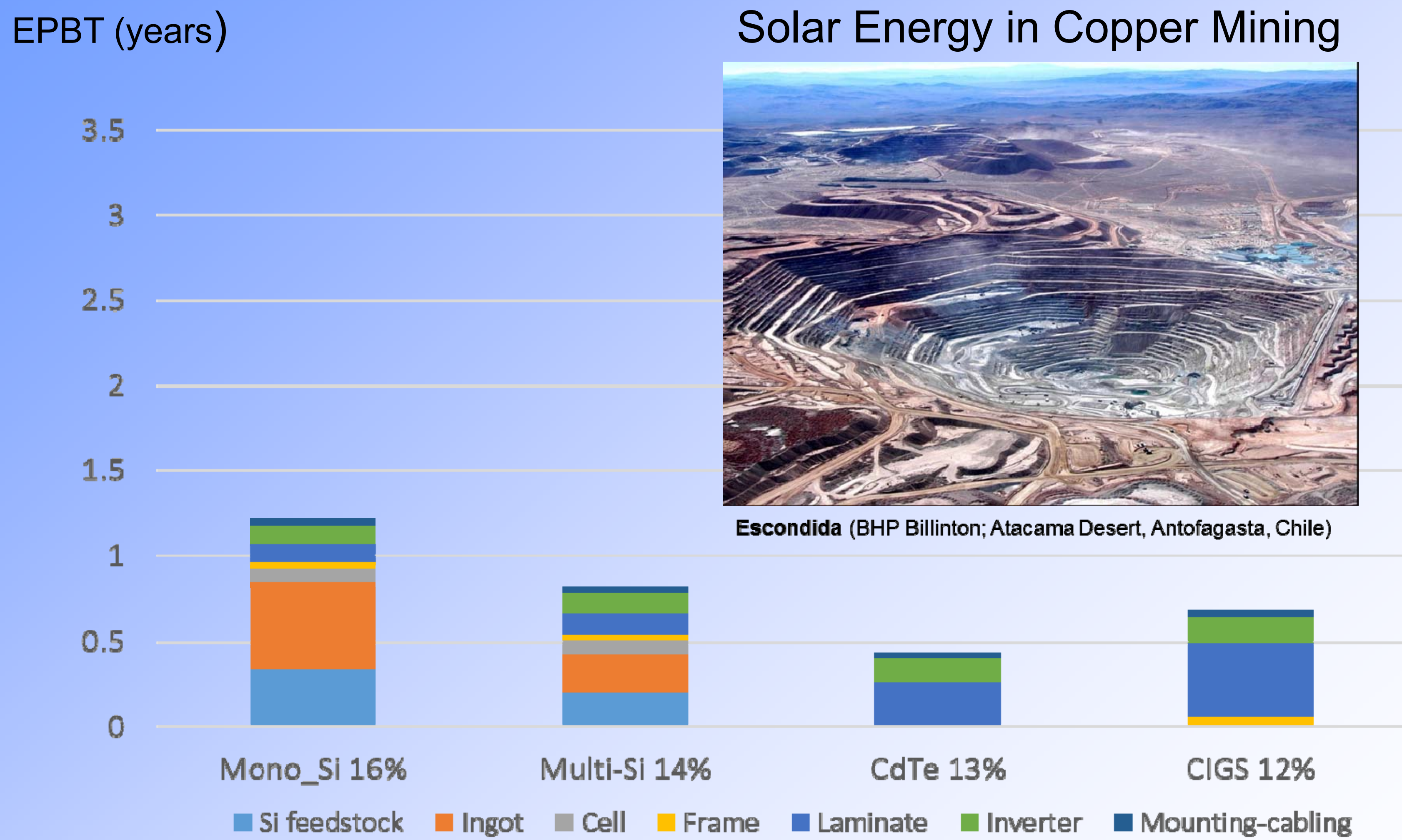


Based on data from 14 manufacturers in Europe, U.S. and Japan

-Fthenakis & Kim, Encyclopedia of Sustainability Science and Technology, 2012; -Fthenakis & Kim, Solar Energy, 2011; -deWild et al., 2009, *EUPV, 2013; Fthenakis et al., EUPV, 2009;* -Fthenakis & Kim, *ES&T, 2008;* - Alsema & de Wild, *Material Research Society, Symposium, 2006;* - Fthenakis & Alsema, *Progress in Photovoltaics, 2006*

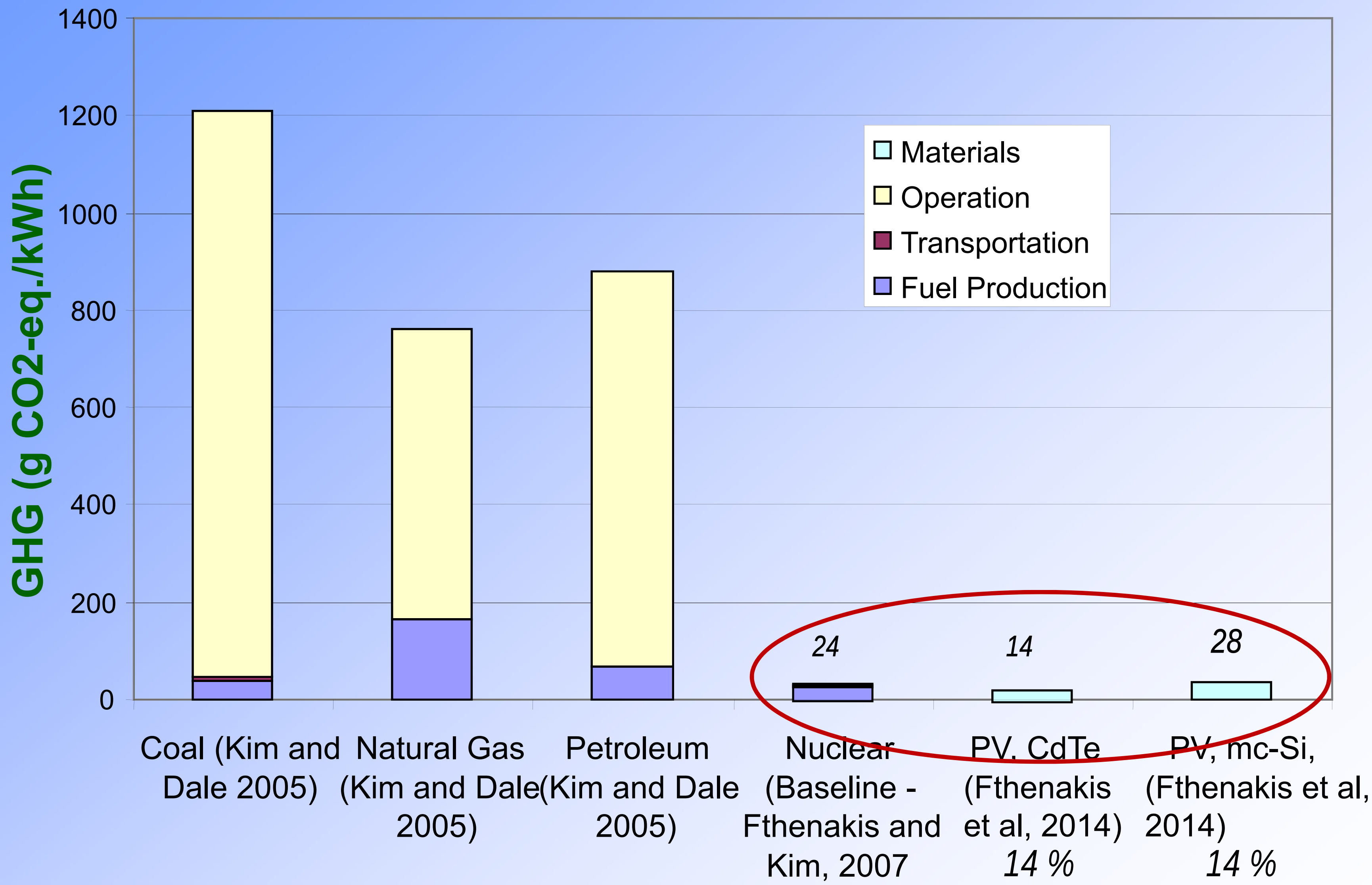
Energy Payback Times (EPBT)

Operation in Chile -Irradiation 2500 kWh/m^2/yr-
Solar Energy in Copper Mining



Escondida (BHP Billinton; Atacama Desert, Antofagasta, Chile)

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 2014*

Cd Risk Assessment in CdTe PV life-cycle:
Simulations of Accidental Releases during Roof Fires

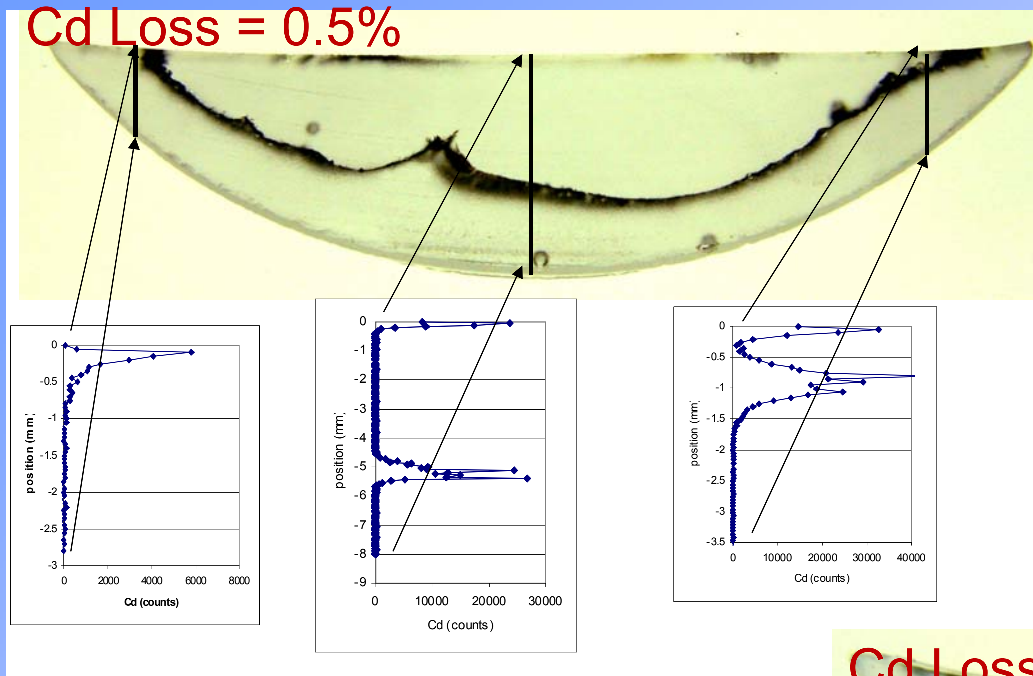
12”x2.5” PV sample burned at 1000 ^{o}C

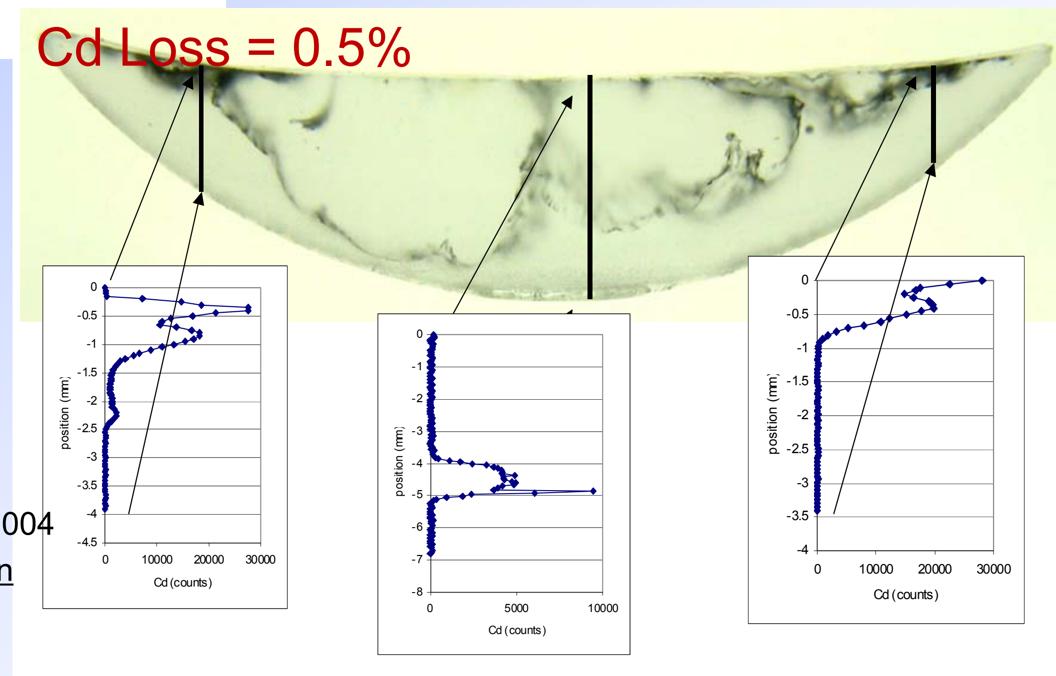
- Weight Loss Measurements
- ICP Analysis of Cd & Te Emissions
- ICP Analysis of Cd & Te in Molten Glass
- X-ray Fluorescence Micro-Spectrometry of Cd in Molten Glass

Fthenakis, Renewable and Sustainable Energy Reviews, 2004

Fthenakis, Fuhrmann, Heiser, Lanzirotti, Wang, Progress in Photovoltaics, 2005

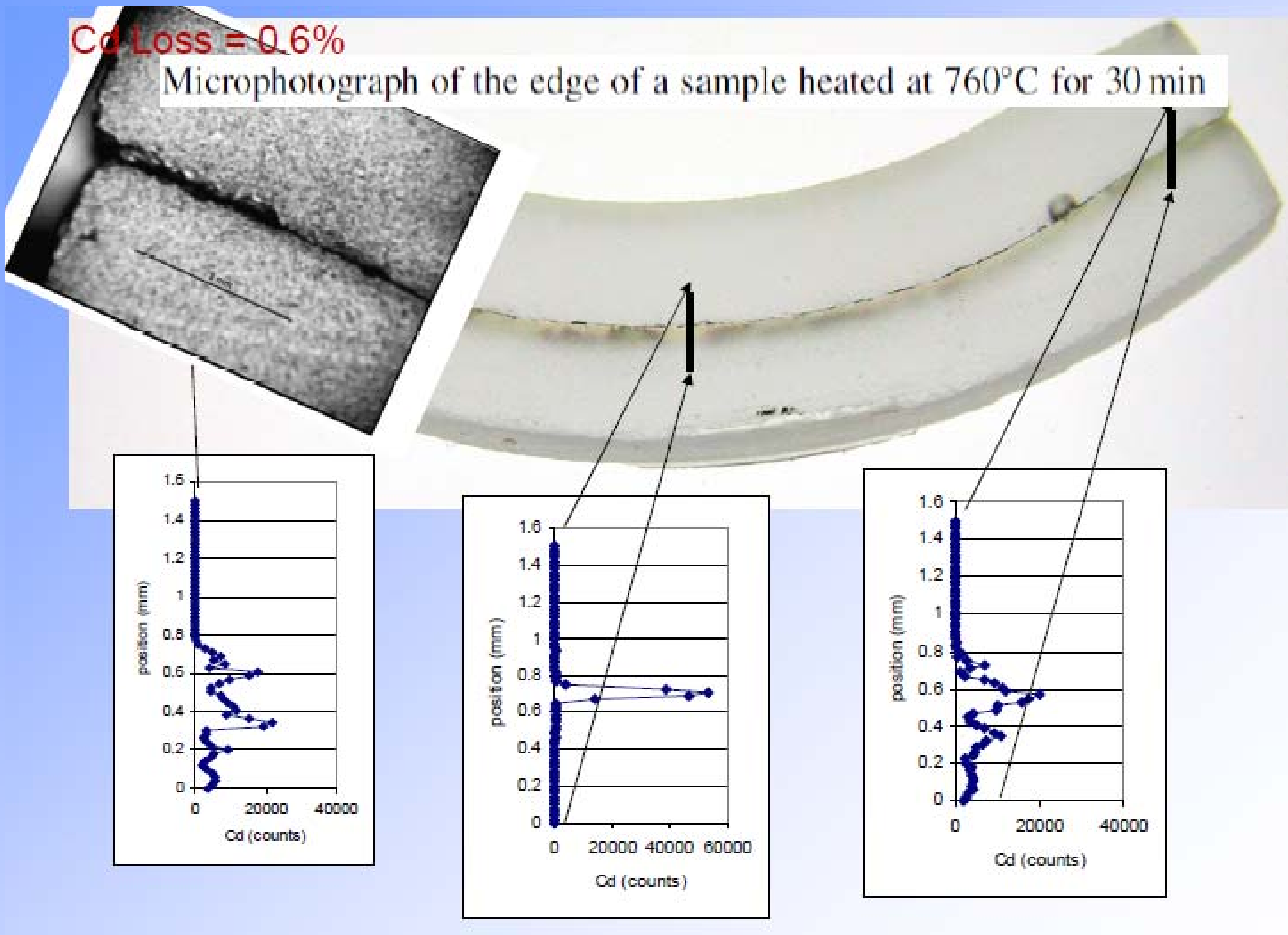
XRF-micro-probe -Cd distribution in PV sample
1000 °C, Sections taken from middle & side of sample





Fthenakis, Renewable and Sustainable Energy Reviews, 2004
Fthenakis, Fuhrmann, Heiser, Lanzirotti, Wang, Progress in Photovoltaics, 2005

XRF Micro-probe-Cd Distribution in PV sample 760 °C, Section from middle of sample



Fthenakis, Renewable and Sustainable Energy Reviews, 2004

Fthenakis et al, Progress in Photovoltaics, 2005

Atmospheric Cd Emissions from the Life-Cycle of CdTe PV Modules –Reference Case

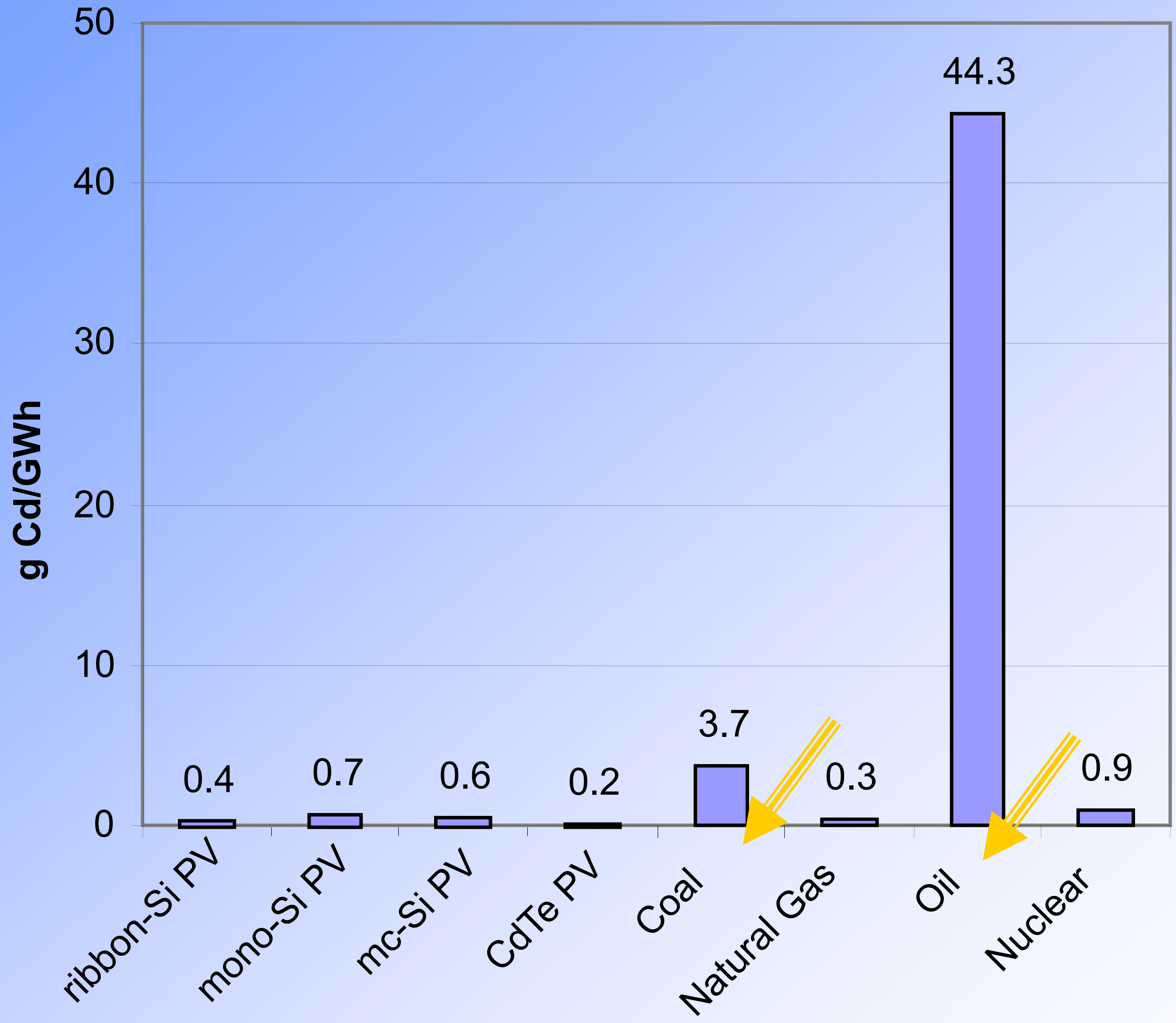
Process	(g Cd/ton Cd*)	(%)	(mg Cd/GWh)
1. Mining of Zn ores	2.7	0.58	0.02
2. Zn Smelting/Refining	40	0.58	0.30
3. Cd purification	6	100	7.79
4. CdTe Production	6	100	7.79
5. CdTe PV Manufacturing	0.4*	100	0.52*
6. CdTe PV Operation	0.05	100	0.06
7. CdTe PV Recycling	0.1*	100	0.13*
TOTAL EMISSIONS			16.55

Plus 200 mg Cd/GWh
Indirect Cd emissions
from electricity and
diesel used in life-cycle

* 2011 updates

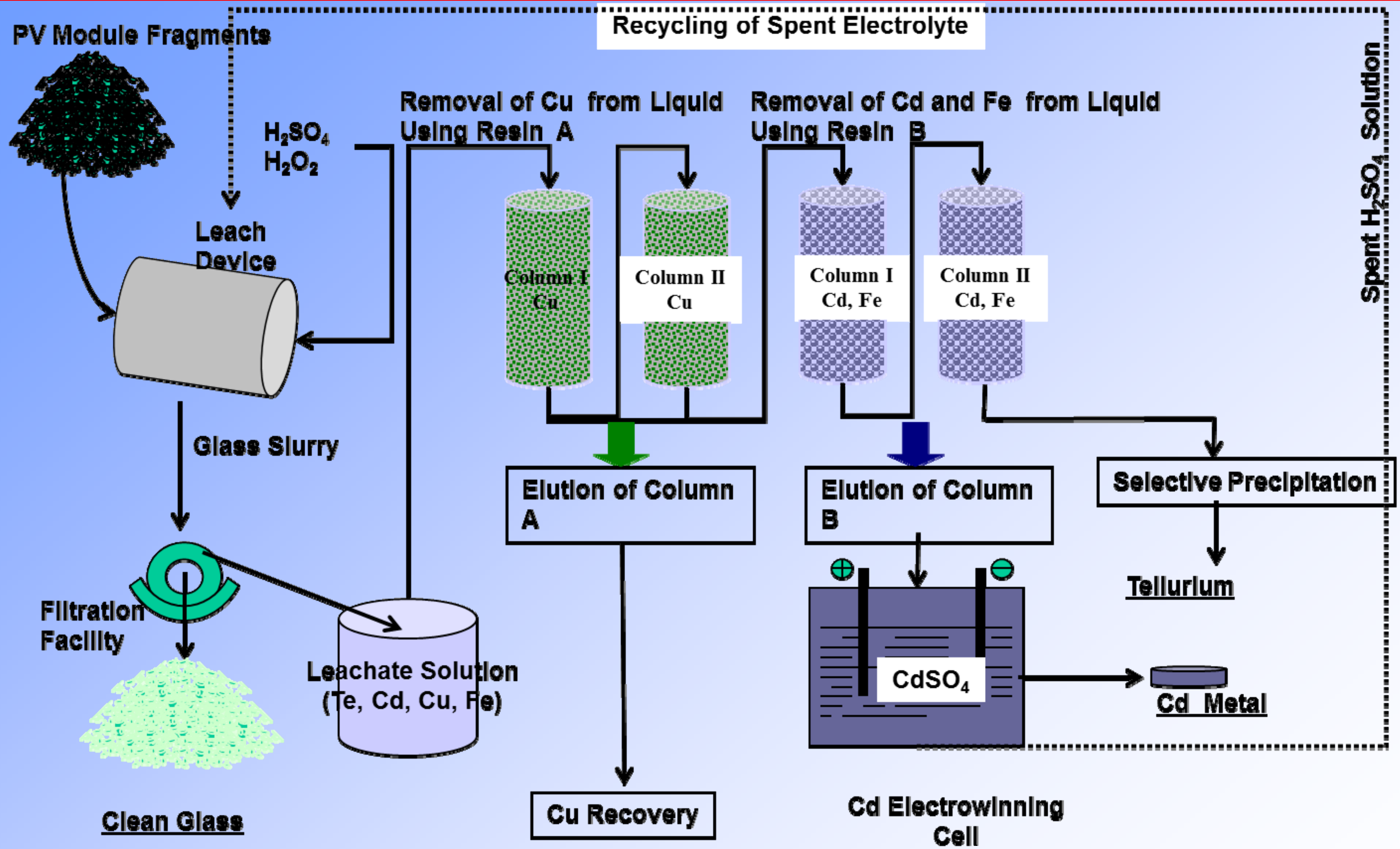
Fthenakis V. Renewable and Sustainable Energy Reviews*, 8, 303-334, 2004*

Total Life-Cycle Cd Atmospheric Emissions



Fthenakis and Kim, Thin-Solid Films, 515(15), 5961, 2007
Fthenakis, Kim & Alsema, Environ. Sci. Technol, *42, 2168, 2008*

Recycling R&D : CdTe PV Modules

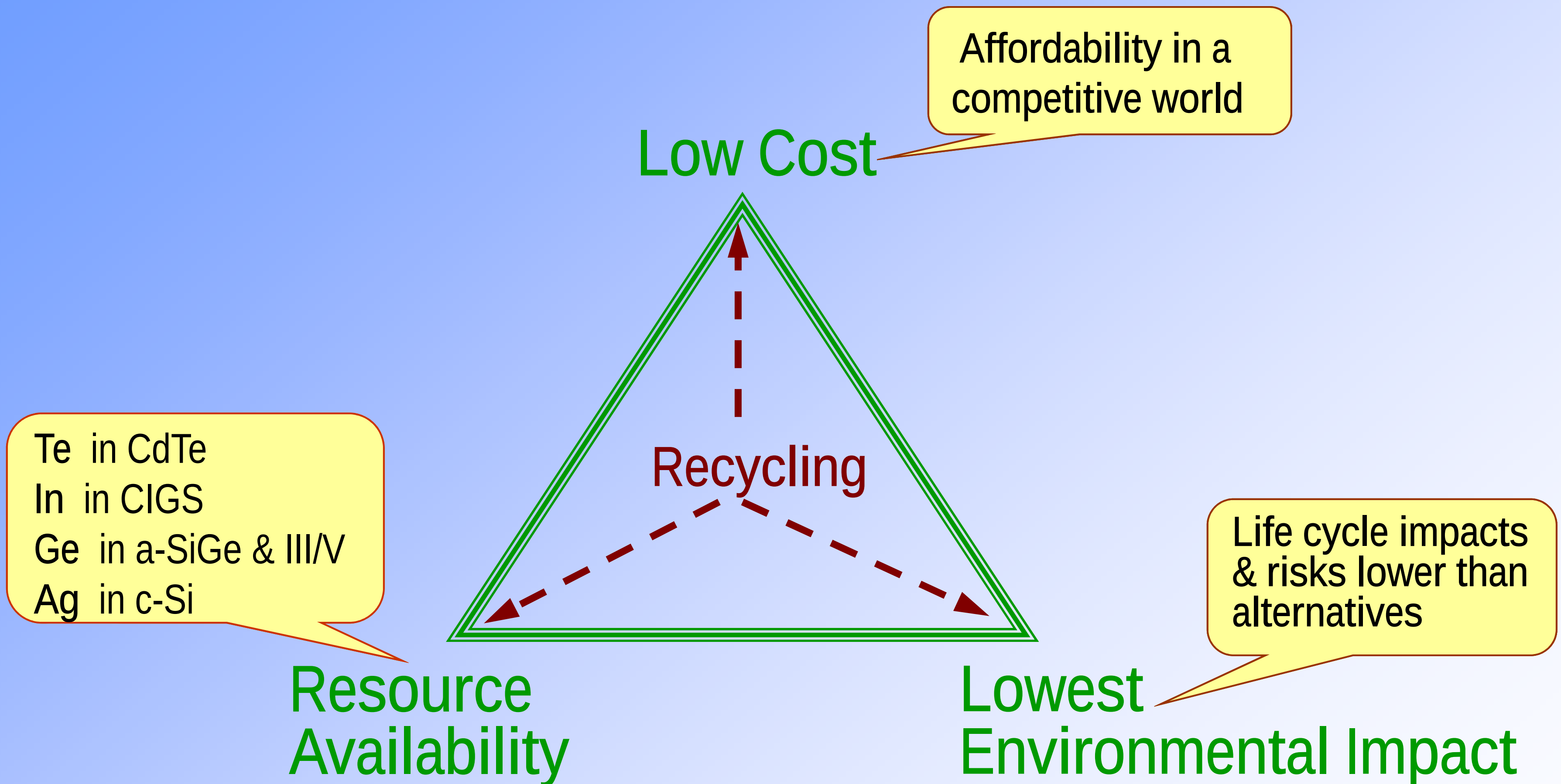


Fthenakis V. and Wang W., Separating Te from Cd Waste Patent No 7,731,920, June 8, 2010

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



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

LCA Guiding Energy Policy

(Expert Peer Reviews of EHS Impacts & Benefits of CdTe PV Technology)

***Expert Peer Reviews by**: US-DOE, 2004; EC-JRC, 2004; German Ministry of the Environment, 2005*

- 2005-European Union
- 2009-France
- 2010-Spain
- 2012-Italy
    - -Germany
    - -Thailand
    - - India
    - -Japan
    - -Middle-East
- 2013-China
    - -Chile
- 2014-Brazil
- 2015-South Africa

LCA Guiding PV Technology Evolution

- Methodology
- Fthenakis, Frischknecht, Raugei, et al., **Methodology Guidelines** on Life Cycle Assessment of Photovoltaic Electricity, 2nd edition, International Energy Agency, Report IEA-PVPS T12-03:2011.
- Si PV Evolution –EPIA Roadmap
- Mann S., de Wild-Scholten M., Fthenakis V., van Sark W., Sinke W., The energy payback time of **advanced crystalline Si PV modules in 2020**: a prospective study, Prog. Photovolt: Res. Appl. 2014
- Nano & Organic PV
- Kim & Fthenakis, Comparative Life Cycle Energy Payback Analysis of multi-junction a-SiGe and **nanocrystalline** /a-Si modules, Prog. Photov: Res. and Applications, 2011.
- Kim & Fthenakis, Journal of Industrial Ecology, Life Cycle Energy and Climate Change Implication of **Nanotechnologies**: A Critical Review, Journal of Industrial Ecology, 2013.
- Fthenakis & Anctil, Life Cycle Assessment of **Organic** Photovoltaics, in Third Generation Photovoltaics, InTech, 2012.
- Buildings
- Asdrubali, Baldassarri & Fthenakis, LCA in the Construction Sector: **Guiding the Optimization of** Conventional Italian **Buildings**, Energy and Buildings, 2013.

Resource Availability: Land, Water, Materials

Land

Fthenakis & Kim, **Land Use and Electricity Generation**: A Life Cycle Analysis, Ren. and Sustainable Energy Reviews, 2009.

Water

Fthenakis & Kim, **Life-cycle of Water in U.S. Electricity Generation**, Ren. and Sustainable Energy Reviews, 2010.

Critical Metals

Fthenakis, Wang & Kim, **Life Cycle Inventory Analysis in the Production of Metals** used in Photovoltaics, Ren. and Sustainable Energy Reviews, 2009.

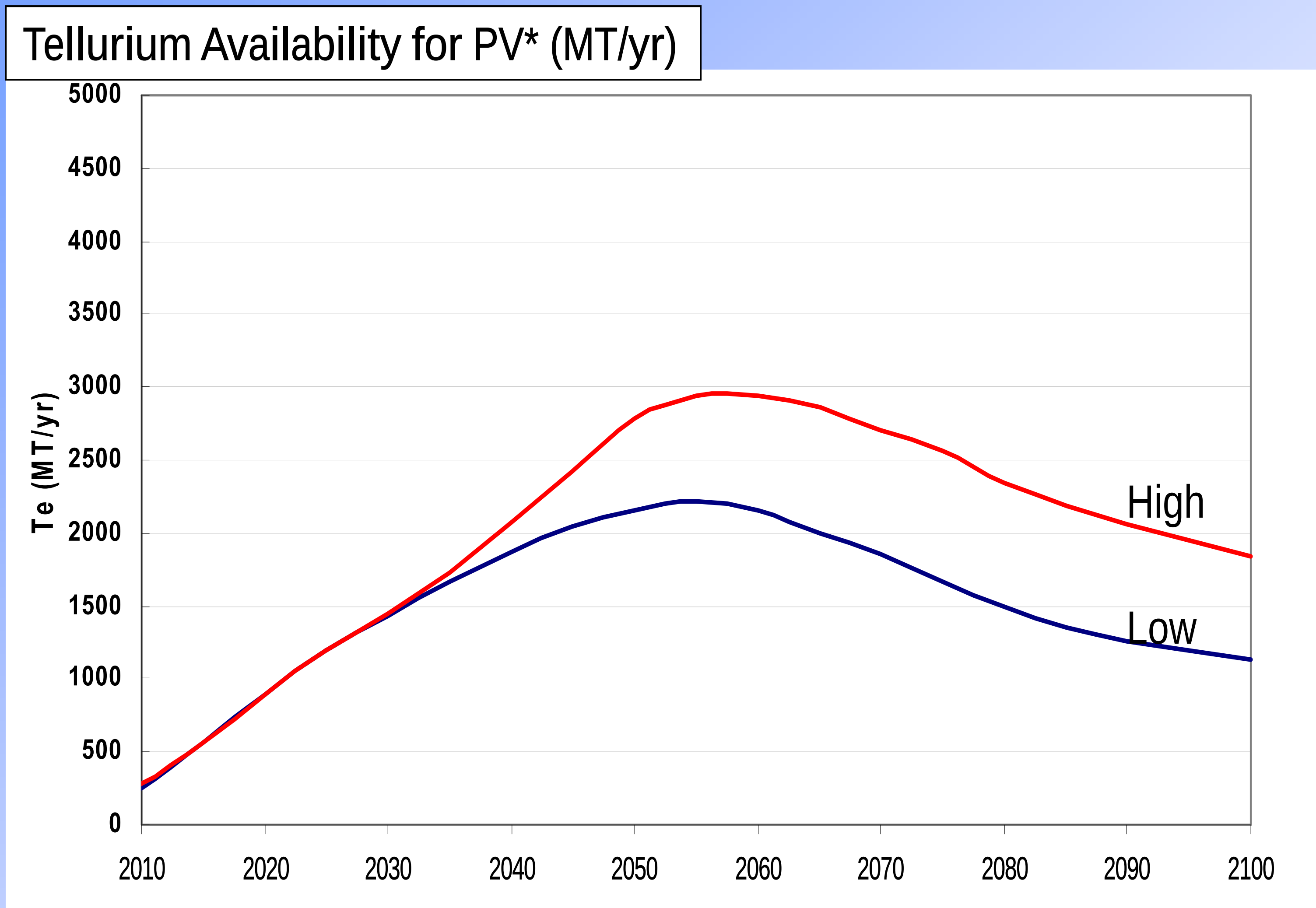
Matsuno, Hur & Fthenakis, **Dynamic Modeling of Cadmium Flow with Zinc and Steel** in Japan, Resources, Conservation and Recycling, 2012.

Anctil & Fthenakis, **Critical metals** in strategic photovoltaic technologies: **abundance versus recyclability**, Progress in Photovoltaics: Research and Applications, 2013

Wang & Fthenakis, **Feasibility of Recycling** of CdTe Photovoltaics, The Minerals, Metals & Materials Society, 2005.

Wang & Fthenakis, **Recovery of Tellurium** from CdTe Photovoltaic Module Manufacturing Scrap & other Sources, The Minerals, Metals & Materials Society, 2006.

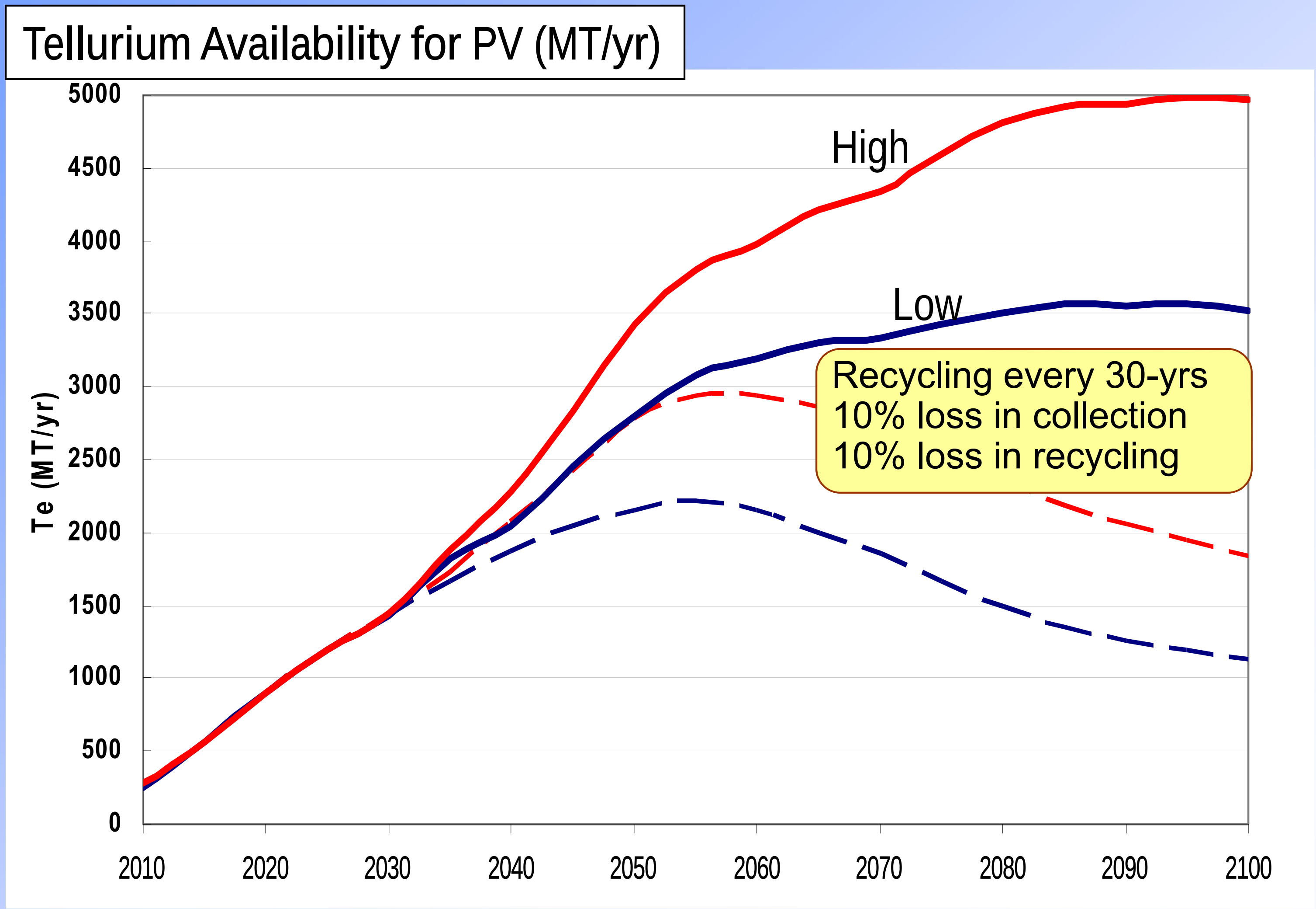
Tellurium for PV* from Copper Smelters



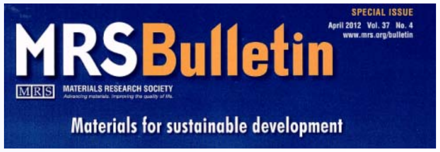
•Global Efficiency of Extracting Te from anode slimes increases to 80% by 2030 (low scenario); 90% by 2040 (high scenario)

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

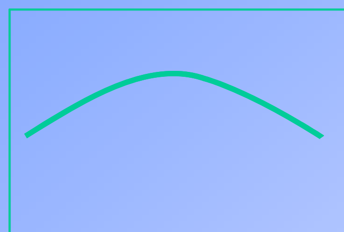
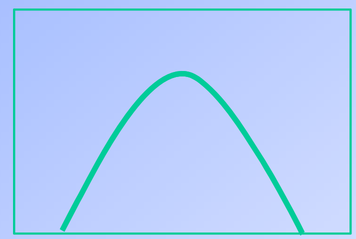
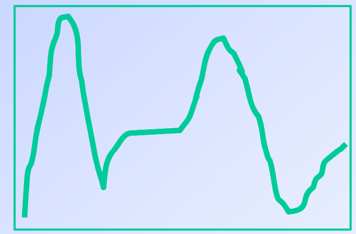
Te Availability for PV: Primary + Recycled



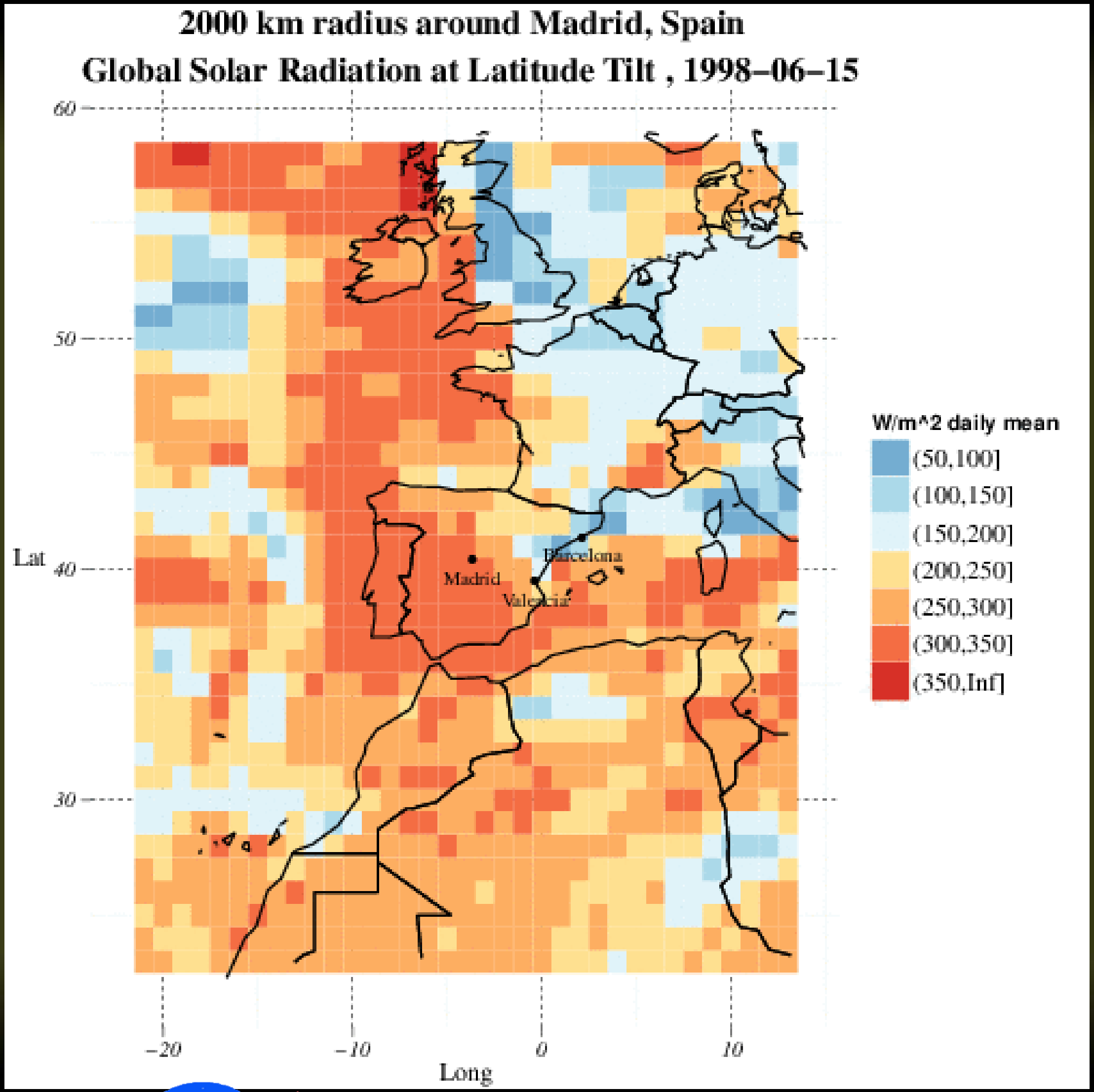
Fthenakis V., Renewable & Sustainable Energy Reviews 13, 2746, 2009
Fthenakis V., MRS Bulletin, 37, 425, 2012



Area 2: Renewable Energy Systems Integration
Solar Variability Solutions: Cost Optimization

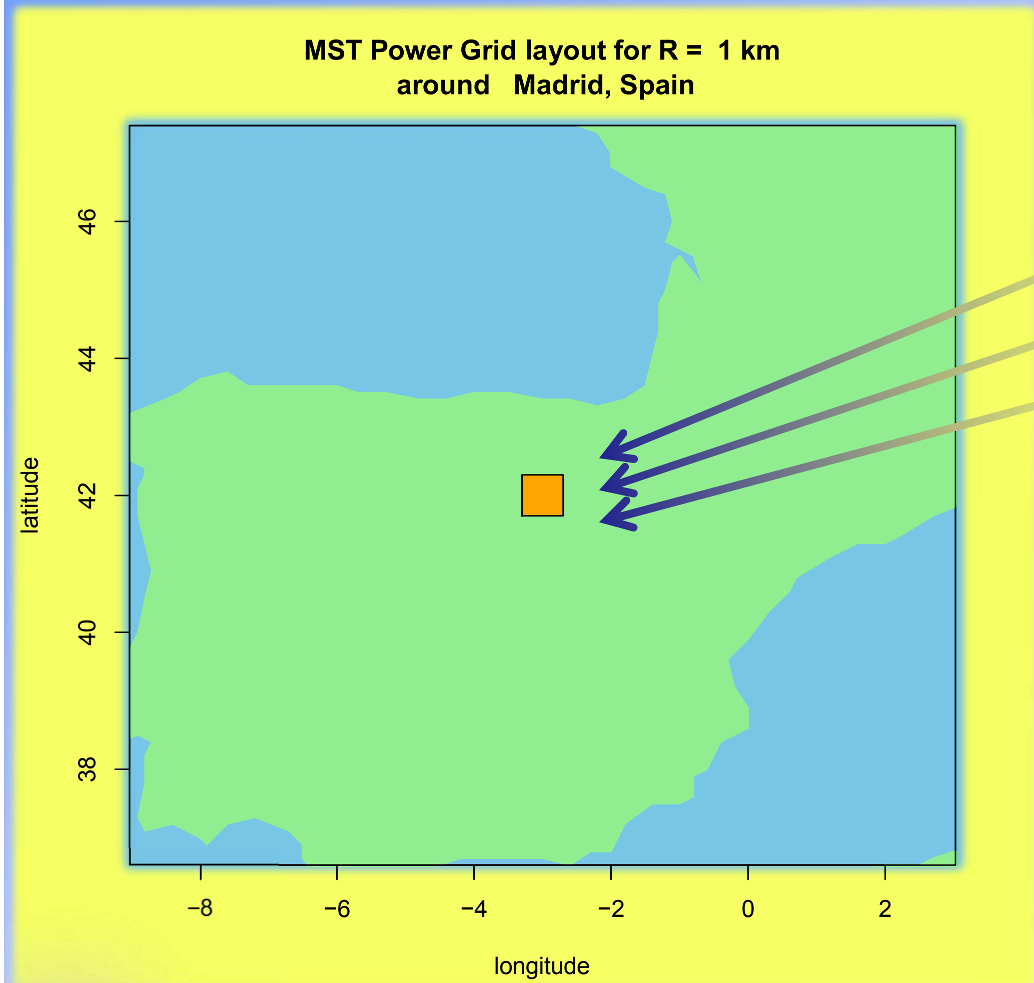
Type:	Seasonal	Diurnal	Cloud-induced
	P  months	P  hours	P  minutes
Solutions:	System oversizing Long-distance Transmission Storage (Hydro, CAES)	Storage (Hydro, CAES, Batteries)	Forecasting, Geographic dispersion, Storage (Flywheels, capacitors, batteries)
Markets*:	Energy market →	Energy market (day-ahead)	Load Following, Frequency Regulation

Daily Tilted-plane and tracking Radiation Simulations anywhere on the planet



Marc Perez, Doctoral Work, 2014

PV-Storage-Transmission Model Applied to Madrid, Spain

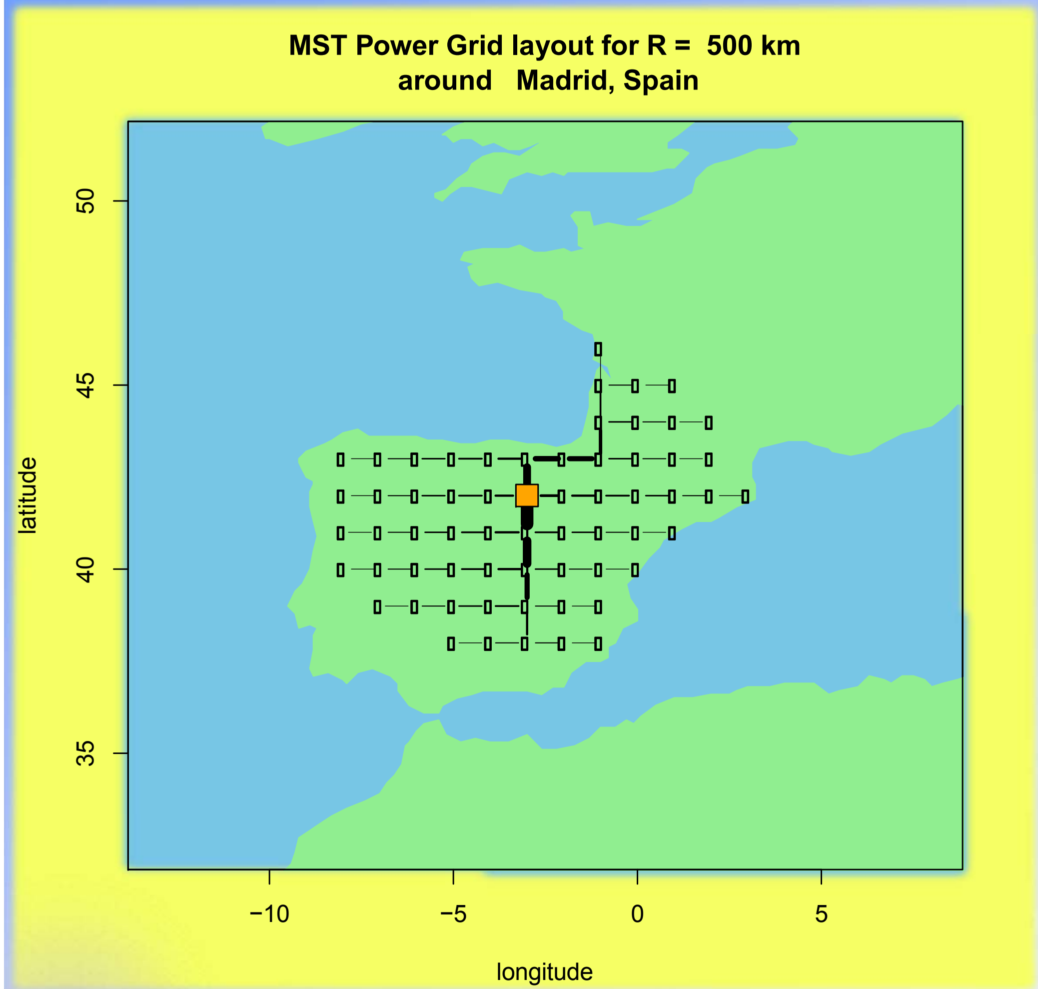


10 GW_{DC}

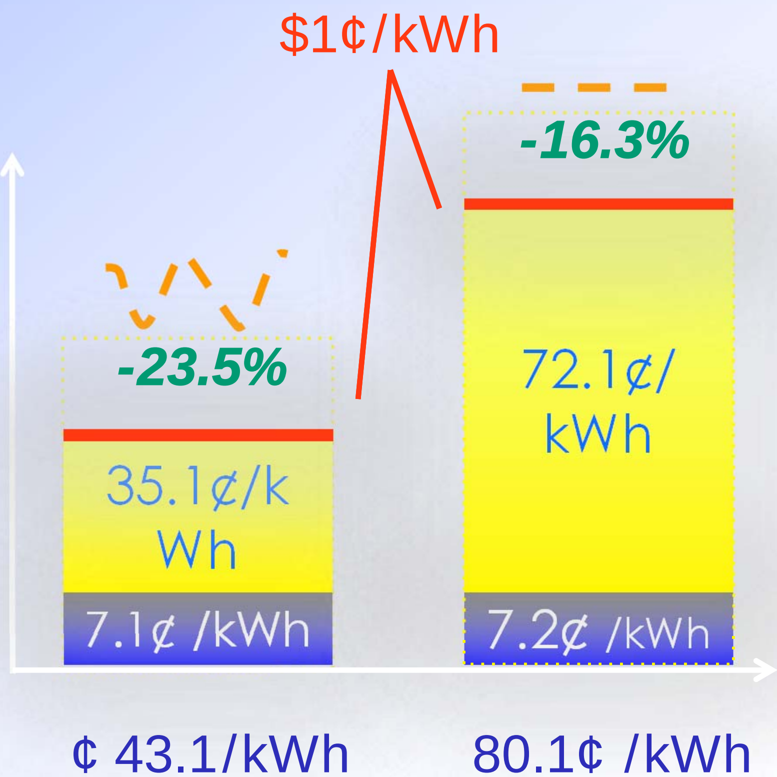
Co-located
Load,
PV
Storage

- Marginal Storage Cost
- Marginal PV Cost

PV-Storage-Transmission Model Applied to Madrid, Spain

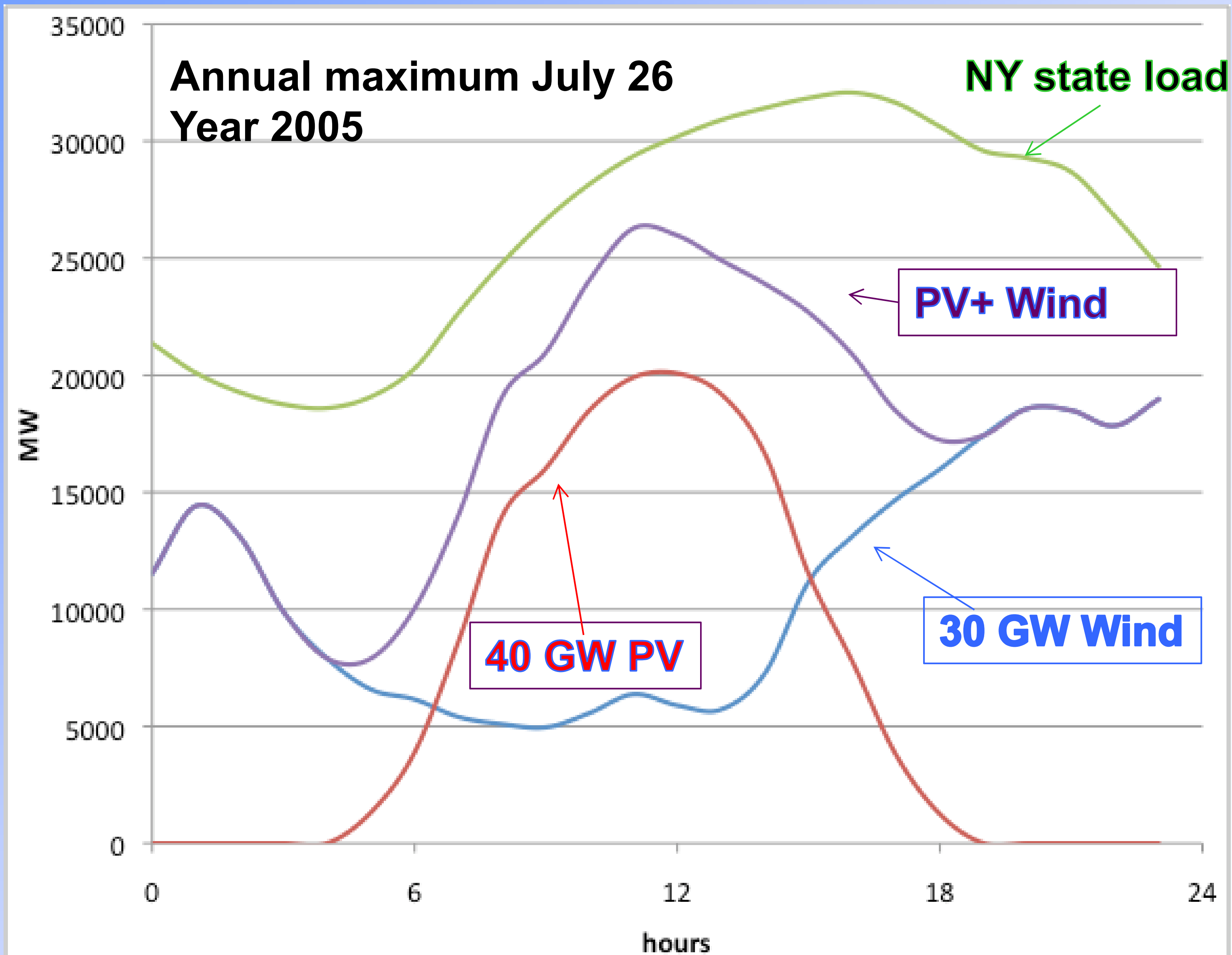


Interconnected *PV across 500km*



- Marginal Storage Cost
- Marginal PV Cost
- Marginal Interconnection Cost

The Synergy of Combining PV and Wind

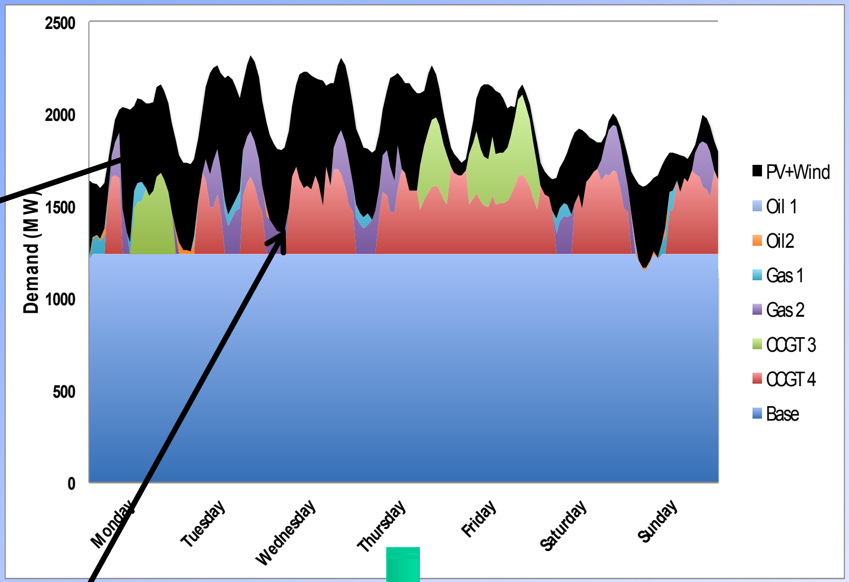


Nikolakakis and Fthenakis, Energy Policy, 39(11), 6972-6980, 2011

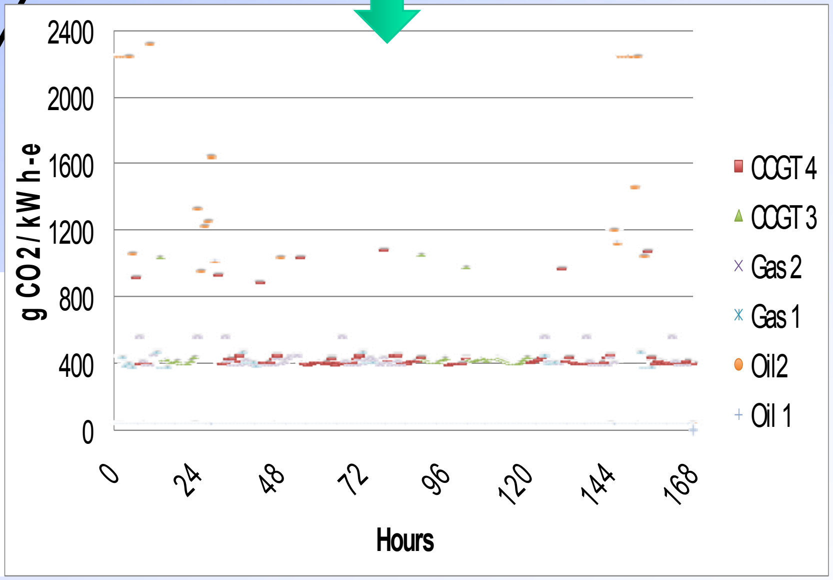
Modeling the Dispatch of Fossil-fuel Generators to Balance the Solar+Wind Variability

Variable Generation

Dispatchable Generation



Unit Commitment and Economic Dispatch

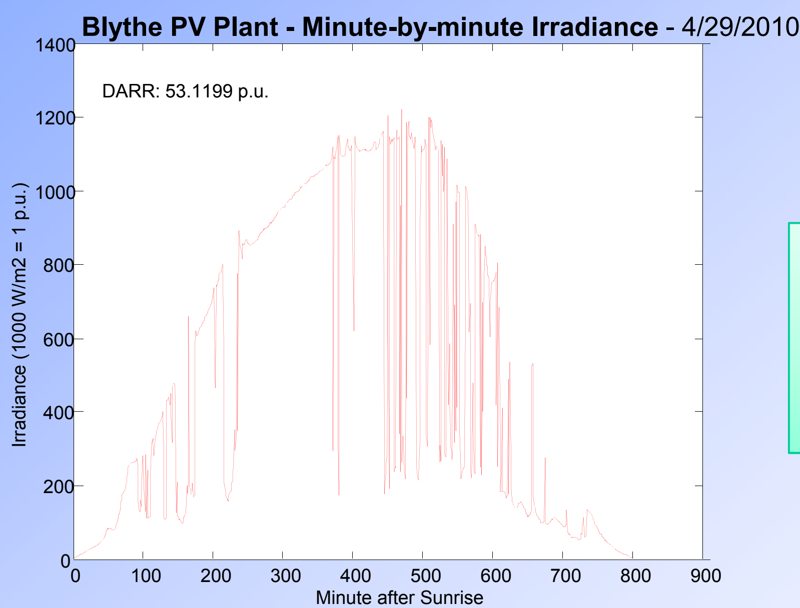


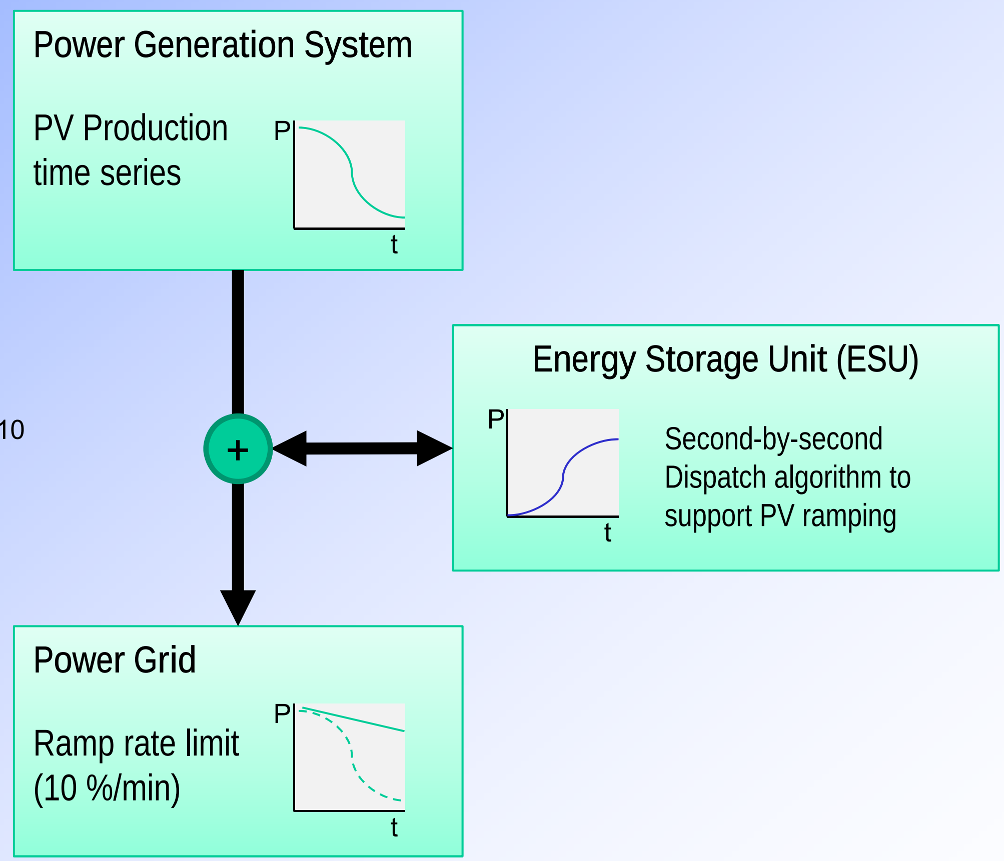
- **Fuel consumption & associated emissions**
- **Start-up emissions**
- **Start-up & operational fuel costs**
- **O&M & wear of equipment costs**

Nikolakakis, Fthenakis, Modeling the Environmental Impact of PV and Wind Large-scale Integration in Regional Grids, *39th IEEEPVSC*, 2013

PV Power Plant Ramps Induced by Clouds: Energy Storage for Ramp Rate Control

Development of models for simulating dispatch of Energy Storage Units to control PV plant ramp rates (based on 1.5 billion data from 9 PV power plants)

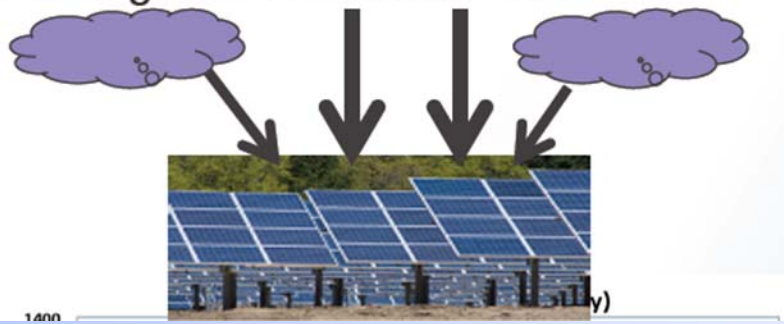




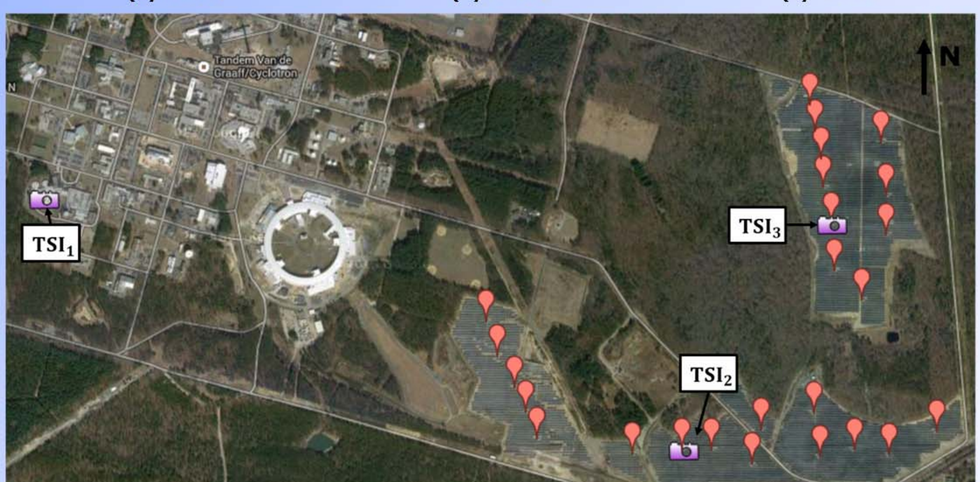
van Haaren, Morjaria, Fthenakis, Empirical Assessment of Short-term Variability from Utility Scale Solar-PV Plants, Progress in Photovoltaics Research and Applications, *22(5), 548-559, 2014*

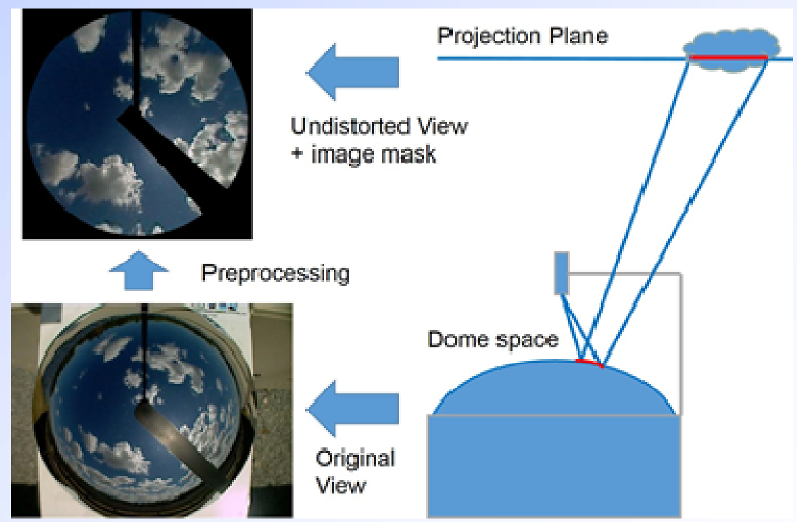
BNL Research on Improving Solar Energy Prediction via Sky-Imaging

- Long Island Solar Farm (LISF), a 195 acre, 32MW (AC) flat panel photovoltaic solar power generating facility, currently the largest in the eastern U.S.



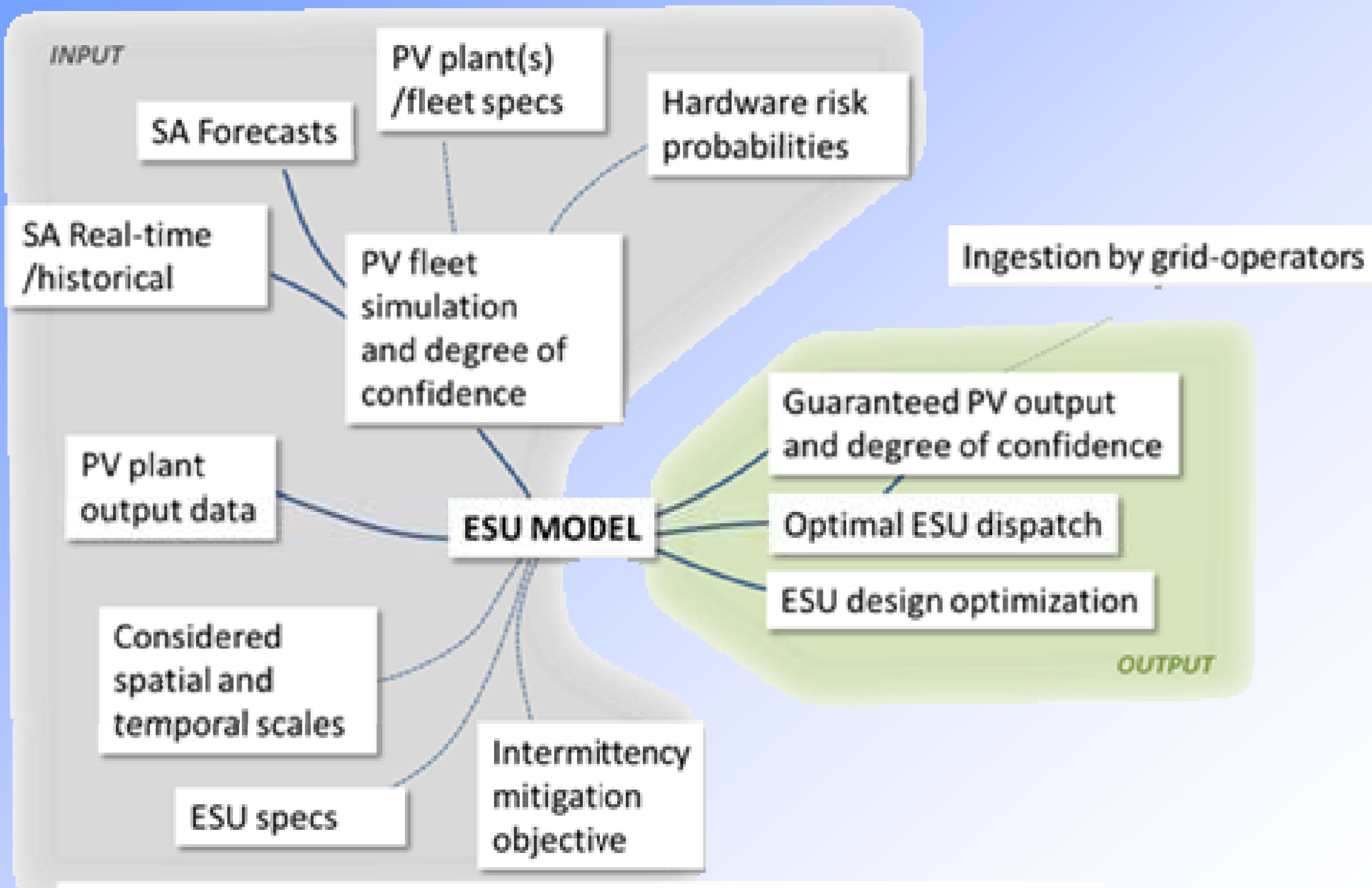
(a) TSI_1 (b) TSI_2 (c) TSI_3





Courtesy: Dantong Yu, BNL

Smart Solar Forecast-enabled Dispatching of Storage Systems to Provide Solar Output Certainty to Grid Operators, while Minimizing Variability and System Costs



Fthenakis V. , Perez R., Hoff T., proposal to DOE SunShot, concept paper under review

Inexpensive & Reliable Solar Energy Empowering the Mining and Industrial Mineral Industries

By:

- Reducing energy costs
- Minimizing electricity production emissions
- Using solar energy for water desalination

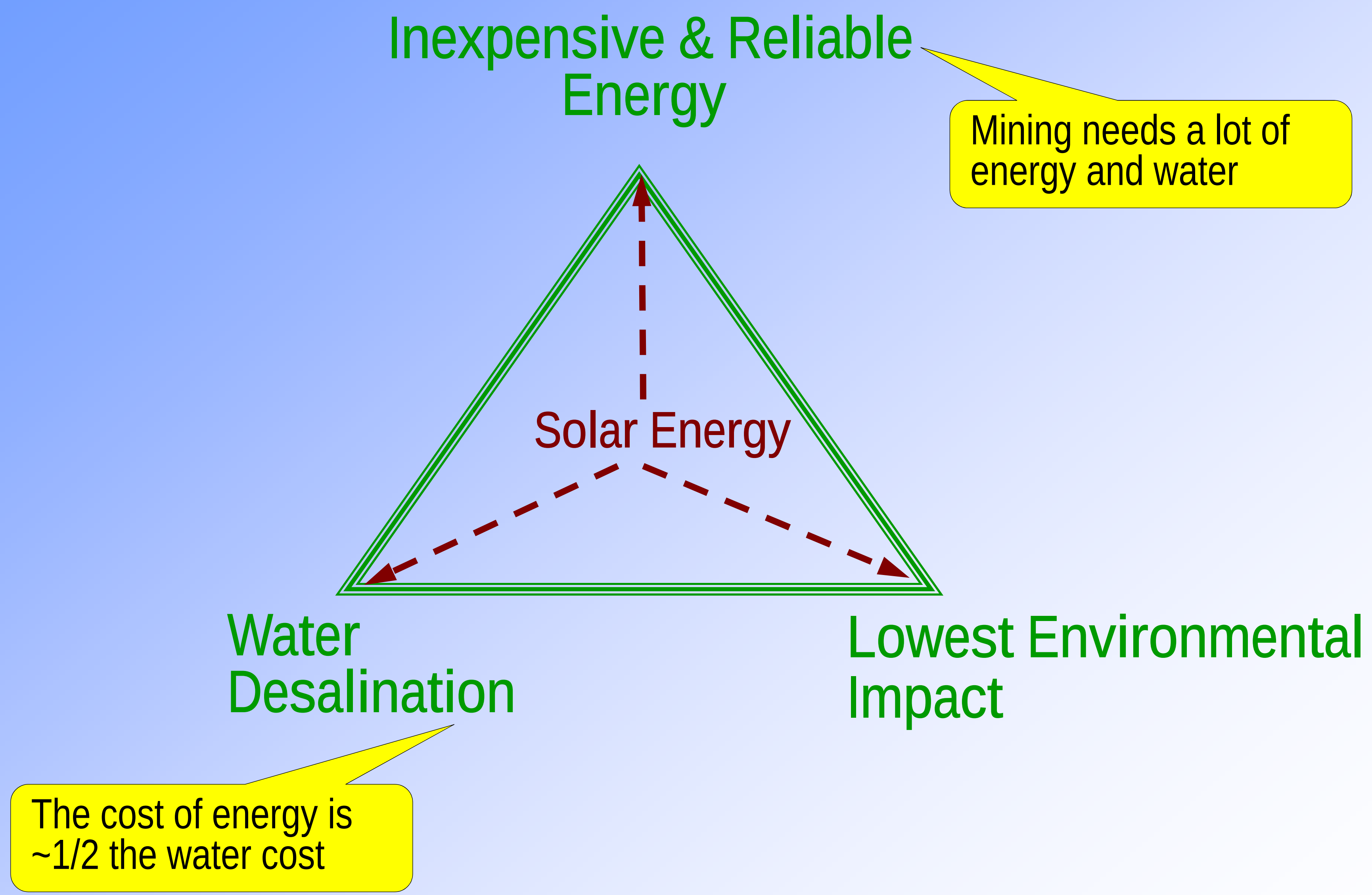
Challenge:

- Solar energy dispatchability

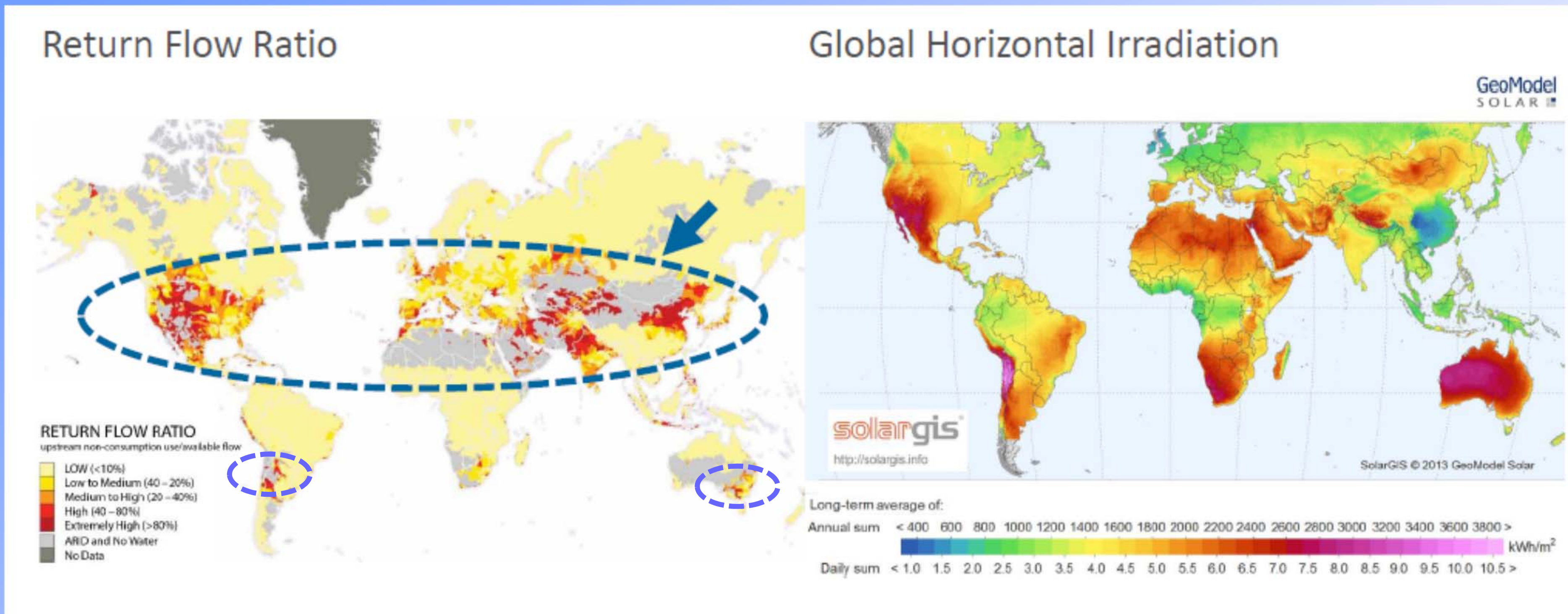
Synergies of Mining and Solar Industries:

- Using of waste materials in CSP thermal storage
- Using Li, Mg and S in electricity storage
- Using Te and Se in PV

Solar Energy-Water-Environment Nexus in Mining



Regions of Water Stress are Rich in Solar Irradiance & often Rich in Metal & Mineral Resources

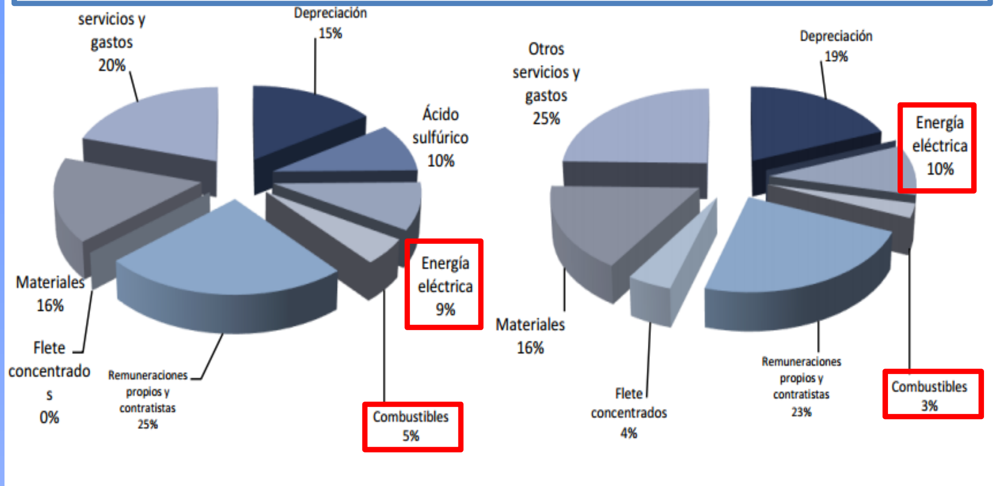


- Sustainable seawater desalination relying on solar energy is a sensible approach

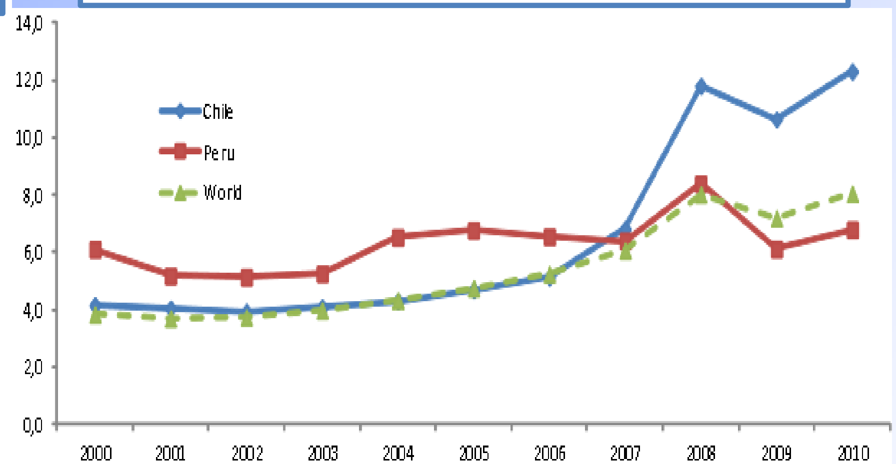
Energy-Water Nexus in Cu Mining –Chile

Solution: Solar Water Desalination

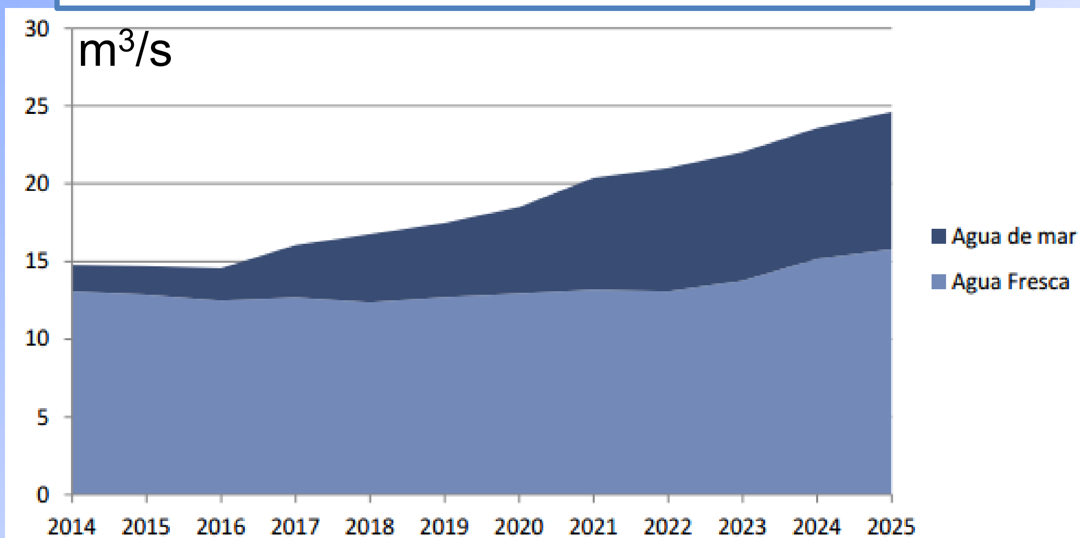
Cu Production Operational Cost Breakdown
-Leaching- -Concentration-



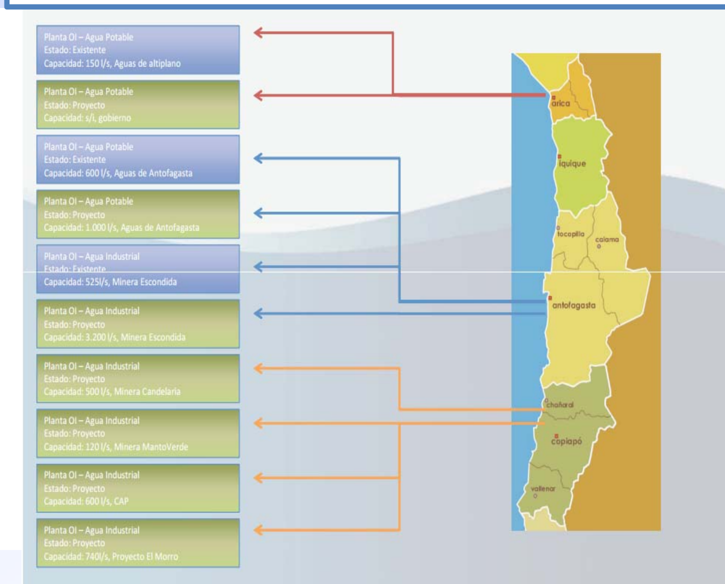
Cost of Energy (US₵/lb of Cu)



Projected Water Consumption in Cu mining



Seawater RO Desalination Plants



Source: COCHILCO various reports

Studies with Solar Energy Research Center of Chile:
Solar Energy and Water in the Mining Industries

- **Non-metallic mining industry.**
  Water for mining camps and chemical process for brine to solid salts
- **Copper industry.**
  Solar electricity to displace imported fossil-fuels
- **Water Treatment using Solar Energy**
  Solar can provide the desalination energy needs
- **Thermal storage using salts, electricity storage using pumped-hydro and Li-ion batteries**

1st and 2nd International Workshop in Lithium, Industrial Minerals and Energy
Antofagasta, Chile, IWLiME 2014 and IWLiME 2015

Motivation

- The exports from the mining industry in Chile totalled $45.2 billion in 2013[1]
- The Chilean production of Cu becomes less competitive; one reason is high electricity prices.
- The metal production is mainly located in northern Chile which has the best solar resource in the world.

Escondida (BHP Billinton; Atacama Desert, Antofagasta, Chile)

Metal	North Chile % of national production
Copper	69.4
Gold	75.9
Silver	62.2
Iron	83.7
Molybdenum	31.0

[1]*ANUARIO DE LA MINERÍA DE CHILE 2013 (versión corregida), ISSN 0066-5096, Inscripción No 240.099, SERNAGEOMIN*

[2] *our elaboration based on ref* 1

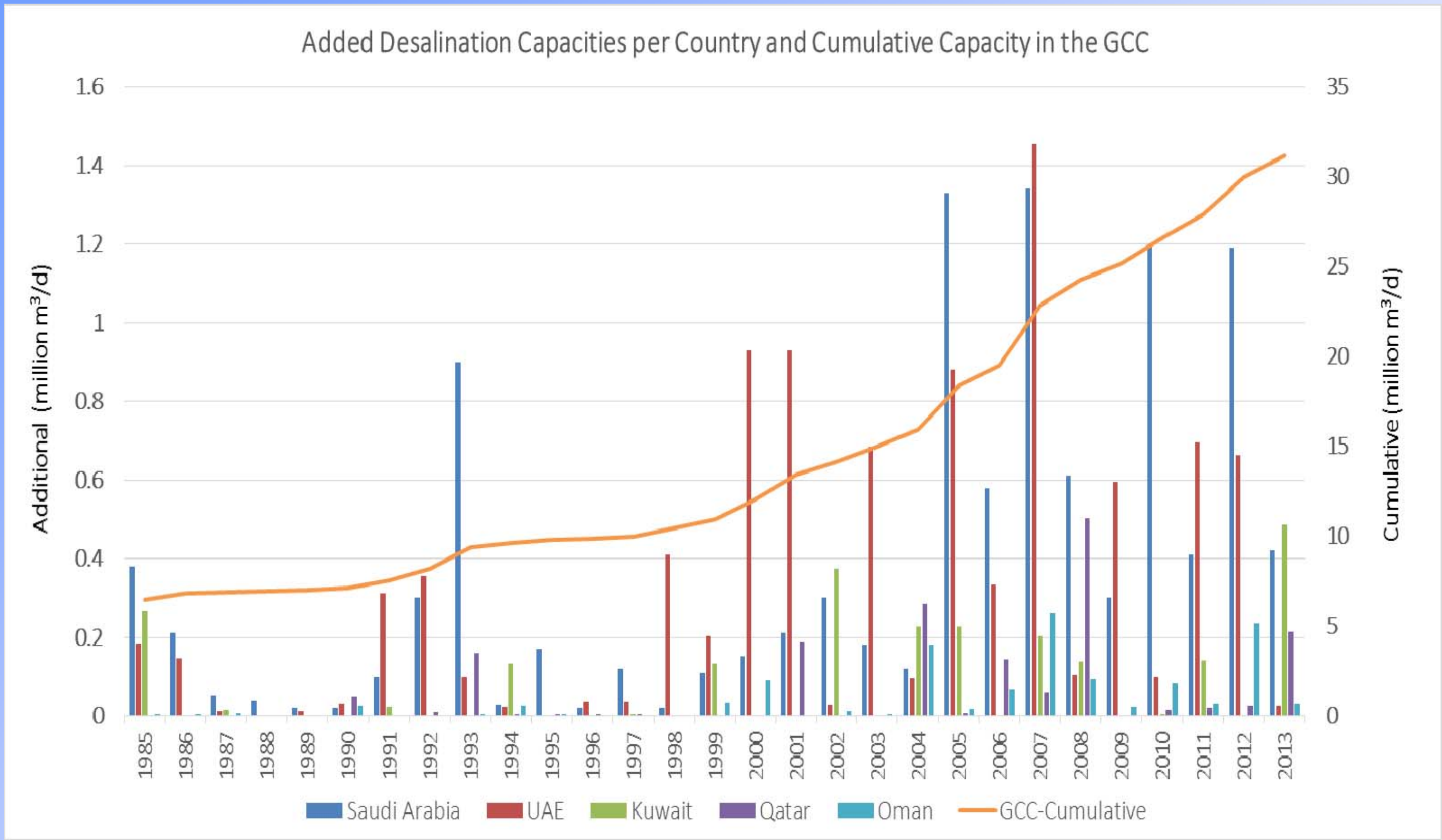
Energy-Environment Nexus in Cu & Li Mining

Solution: Mining Waste to be Used for Thermal Energy Storage in Concentrated Solar Power

- The huge metal mining industry leaves tons of accumulated wastes with no applications to date.
- An Andasol 50 MWe CSP with 7.5 hr thermal energy storage (TES) required 28,000 tonnes of nitrate salts.

- Objective: Develop TES systems based on mining wastes and establish the feasibility and sustainability of implementation of such systems via Life Cycle Analysis.

Water-Energy Nexus: Desalination Capacities

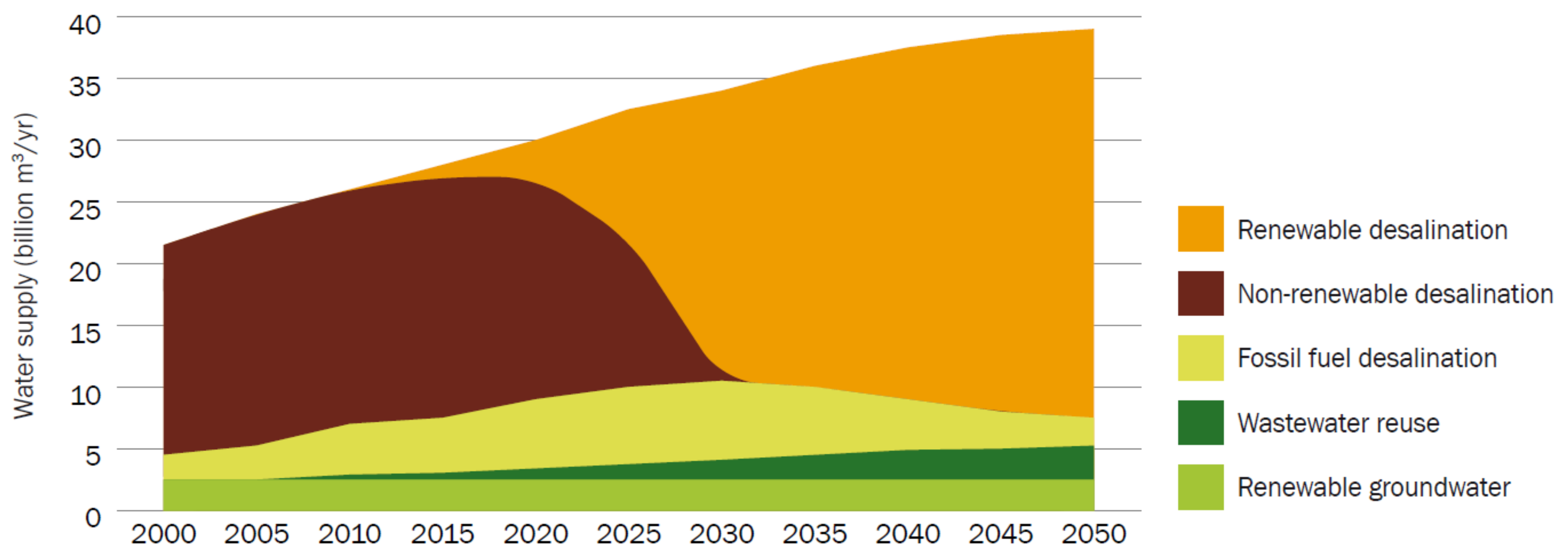


Fthenakis V., Solar Energy-enabled Water Desalination in the Gulf Cooperation Council, Prepared for IRENA, in review

Water-Energy Nexus: Low-carbon International Desalination Initiative for COP21

- An alliance of non-governmental actors and possibly governments to foster technology development and solutions sharing to drastically reduce CO2 emissions in water desalination
- Investment in R&D&D (additional $100M/yr)
- Effort led by Masdar Institute, UAE.
- Endorsed by IRENA
- To be endorsed by the Government of the United Arab Emirates (UAE)
- The Initiative shall be launched at the United Nations Climate Change Conference COP21 December 2015 in Paris
- U.S. Contributors: Columbia-CLCA and NREL
-

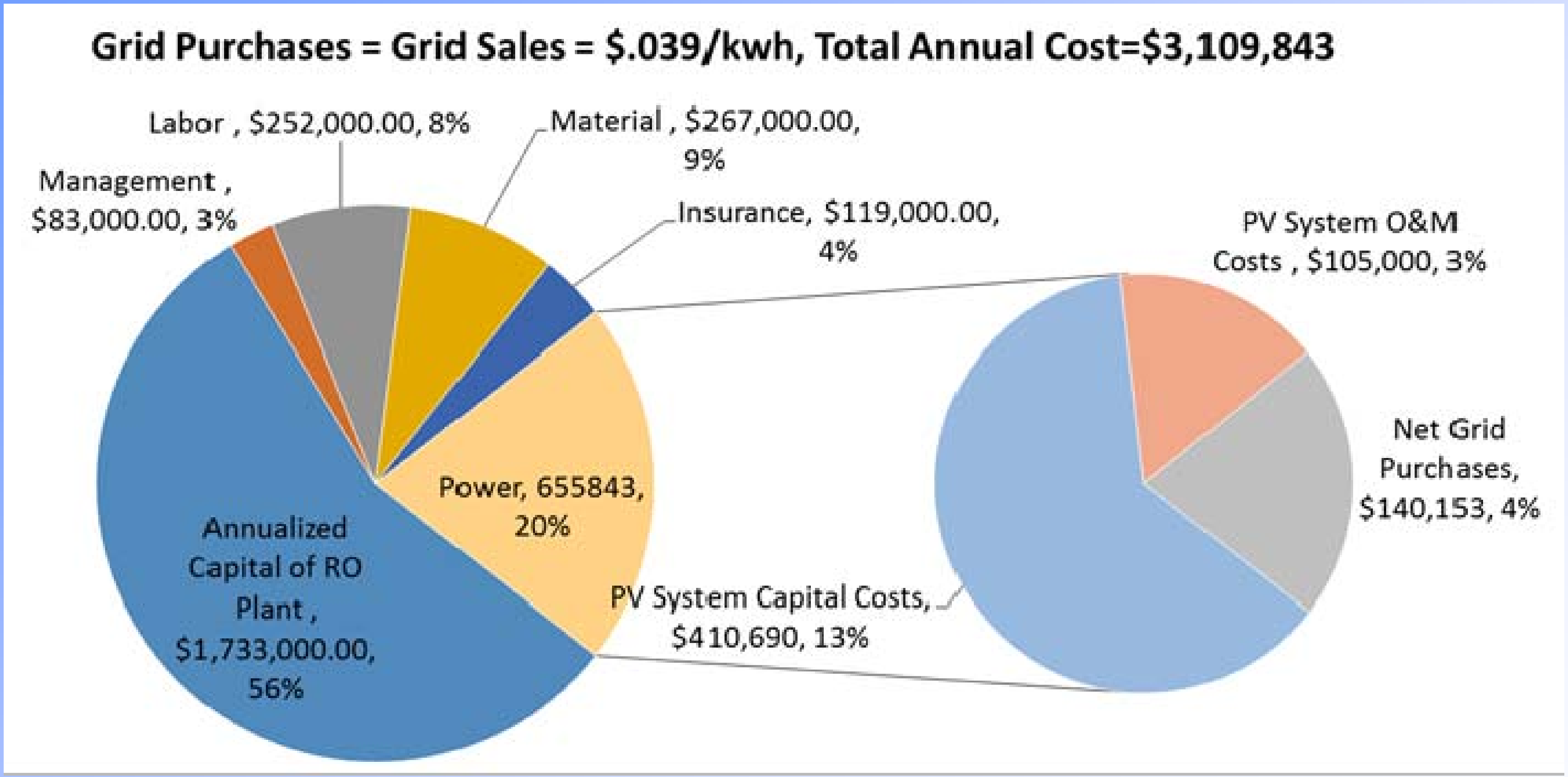
Figure 16.13 Projections on Saudi water supply by source



Source: KACST

Water-Energy Nexus: Solar Desalination Feasibility Studies

Grid Connected Systems



Fthenakis, Atia, Morin, Bkayrat, New Prospects for PV Powered Water Desalination Plants: A case study in Saudi Arabia, Progress in Photovoltaics: Research and Applications, in press

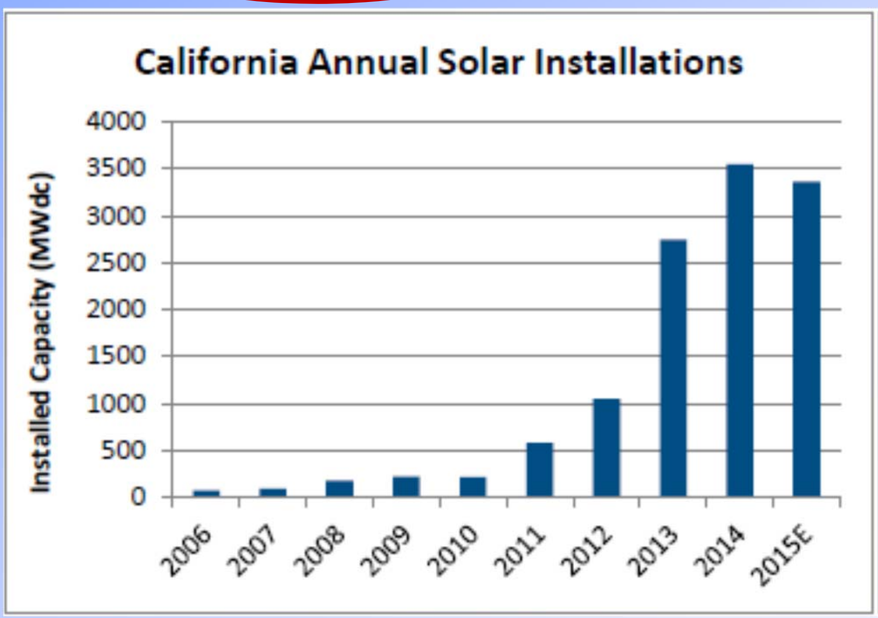
Atia, Fthenakis, Bkayrat, Techno-economic Evaluation of Stand-Alone PV-Powered Seawater Desalination Plants in Saudi Arabia,, Proc. 29th European Photovoltaic Solar Energy Conference, 2014.

Adam Atia, NSF GRF 2015-18: Flexible, Solar Powered, Water Desalination/Decontamination

Problems and Integrated Solutions

Top 10 problems of Humanity for Richard Smalley (1943- 2005)

1. Energy
2. Water
3. Food
4. Environment



29 April 2015

California launches most ambitious climate targets in North America

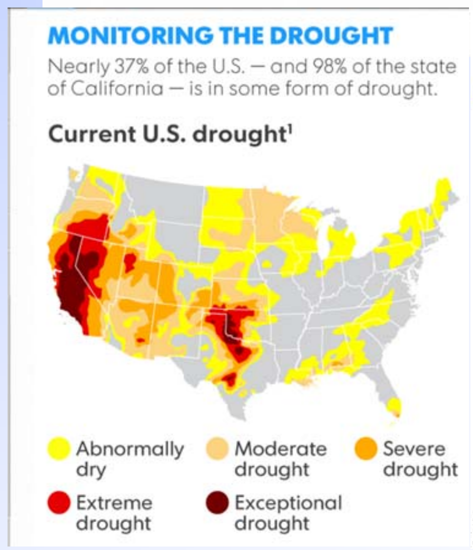
North America, Carbon Reduction, Policy, Sustainable Energy

California Governor Jerry Brown issued an ambitious executive order on Wednesday that aims to reduce the states greenhouse gas emissions by 40 per cent below 1990 levels by 2030.

Four-term Governor Brown called it the most aggressive emissions reduction target by any North American government in history.

Under Brown's leadership, California has made impressive steps to combat climate change, which has impacted the state with severe water shortages.

California's Gov. Brown sounds the alarm on drought



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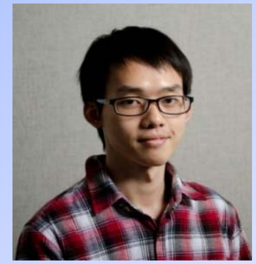

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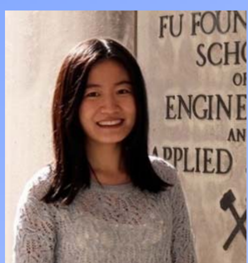

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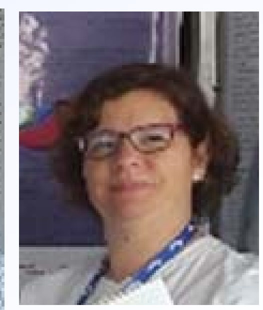

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Problems awaiting Solutions

Need for integrated solutions on Energy-Water-Environment

EAEE can address bigger multi-faceted problems by strengthening linkages among faculty and among departments

- Lall & Gentine –Water Management/Modeling
- Modi –Microgrids, CSP-thermal storage LCA
- Yip & Durning –Membrane-based Water Desalination
- Somasundaran & Xi –Nanomaterials LCA
- Schlosser & Sachs –RE Solutions to Climate Change
- Themelis/Bourtsalas –WTE LCA
- Farrauto –Fuel-cell systems analysis
- Park –Solar-synthetic fuel LCA
- Yin –LCA of hybrid solar panels
- Culligan –Building LCA
- Deodatis –Integrated Risk and Life-Cycle Assessment