Solar Energy
Future Challenges and Opportunities

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CLCA Columbia University

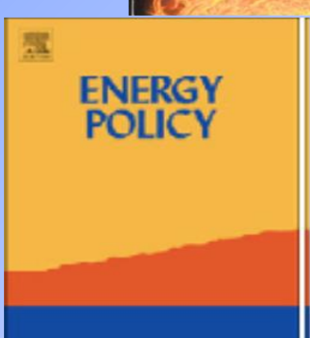
Center for Life Cycle Analysis

Columbia University in the City of New York

www.clca.columbia.edu

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



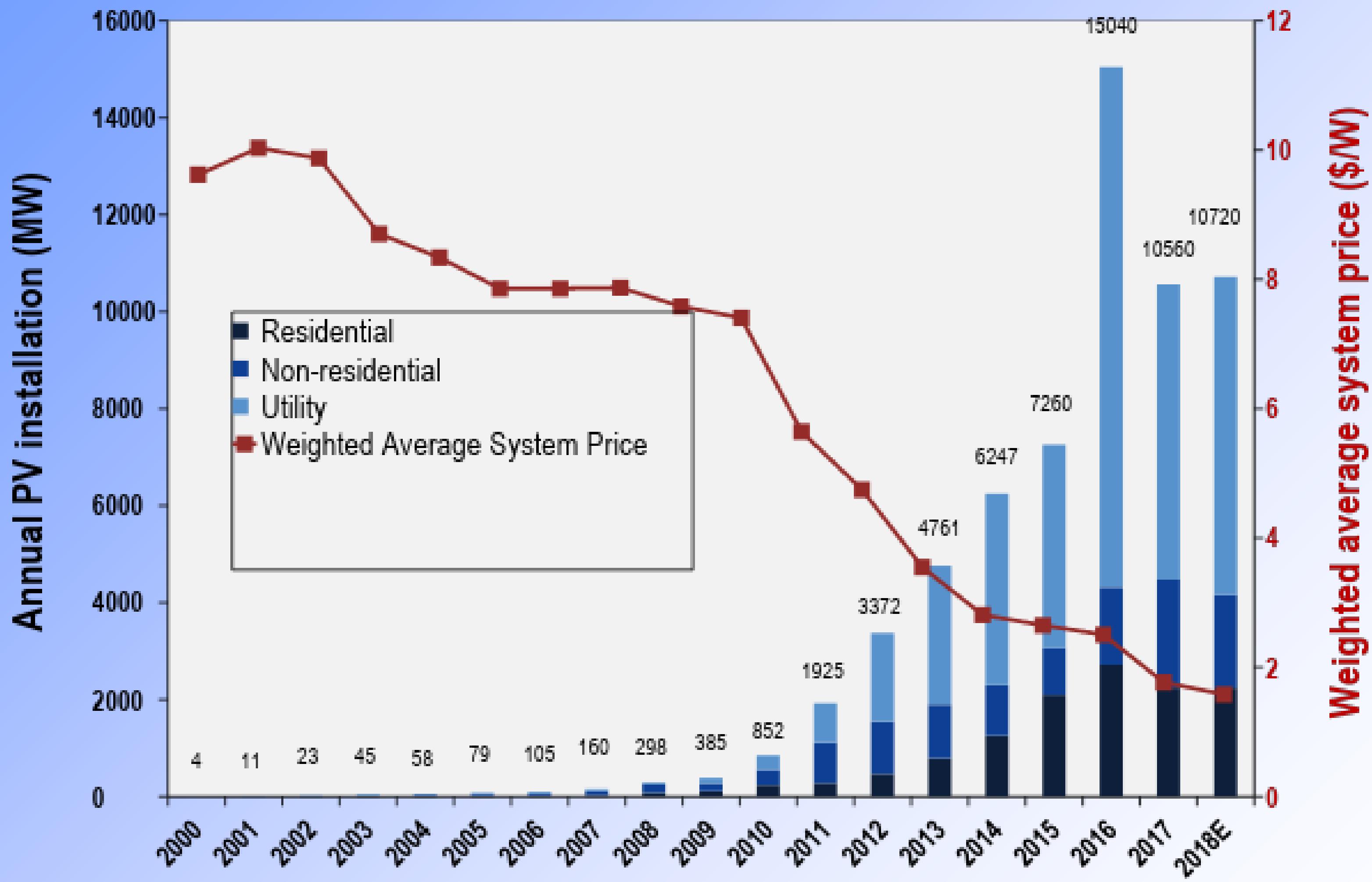
	2020	2030	2050
PV	46	250	2800
Wind	72	210	698
CSP	28	118	1130

Cumulative Deployment (GW)

- Photovoltaics
- Wind
- Concentrated Solar Power
- Energy Storage
- High Voltage DC Transmission
- Hybrid plug-in electric cars

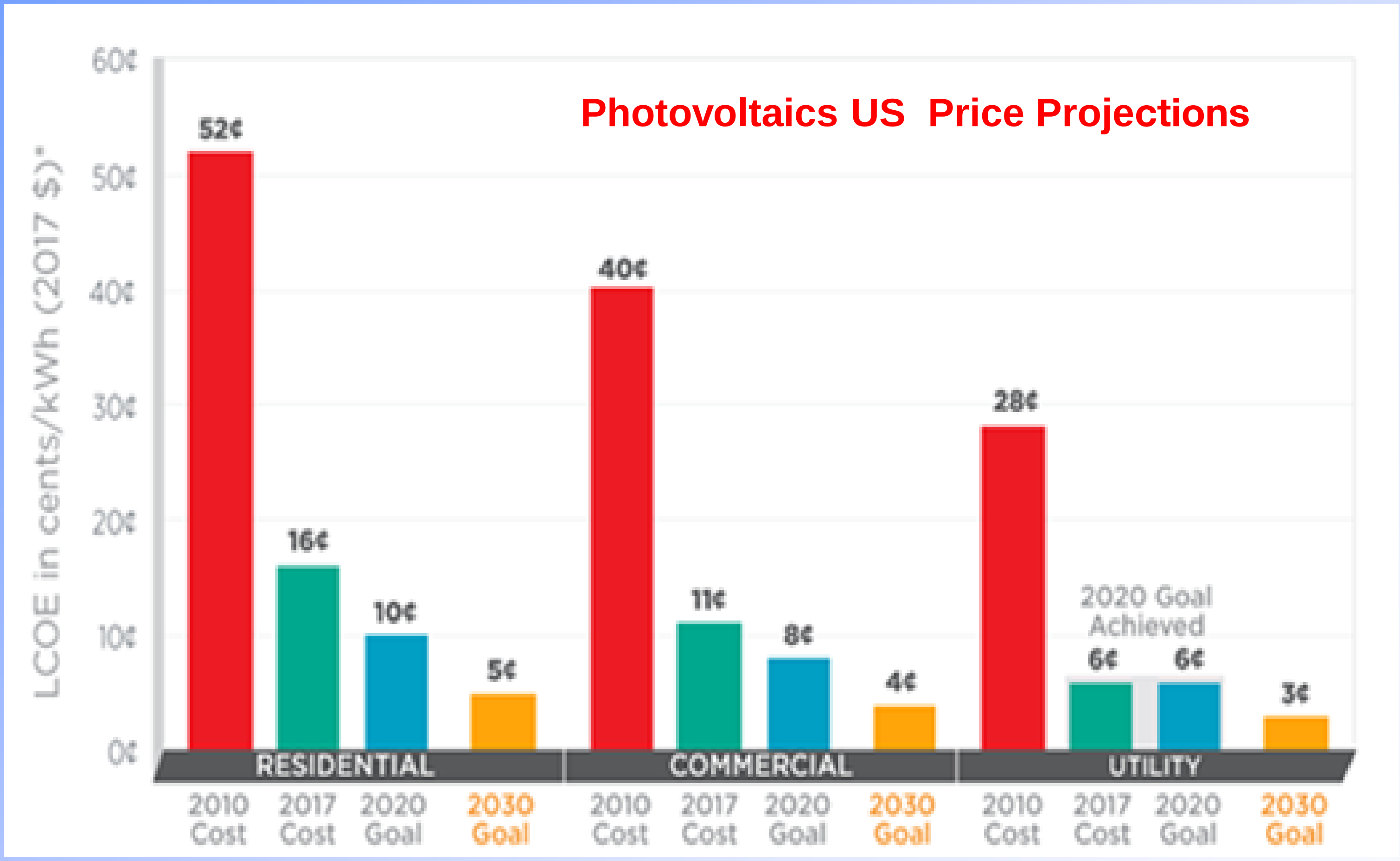
The technical, geographical and economic feasibility for solar energy to supply the energy needs of the U.S.,
Vasilis Fthenakis, James Mason, Ken Zweibel, Energy Policy 37 (2009)

Photovoltaics Current US Status



Cumulative PV installations in the US by 3Q 2018: 60 GW
Cumulative installations World-wide by 1Q 2018: 415 GW

US-DOE-SunShot Vision Study



Utility CSP with 12 hr thermal storage: SunShot 2030 cost target= 5 ¢/kWh

Images: R. Margolis, NREL; from R. Jones-Albertus, et al., Solar on the rise…, MRS Energy & Sustainability, 2018

SunShot Potential Energy, Economic & Environmental Benefits

- Solar will provide 14% of U.S. electricity by 2030; 50% by 2050
- Supporting 300,000 new solar jobs by 2030 and >500,000 new solar jobs by 2050.
- Electric-sector CO2 emissions reduced by 8% by 2030 and 35% by 2050.
- Retail electricity rates reduced by about 0.6 ¢/kWh in 2030 and 0.9 ¢/kWh in 2050, saving consumers $30-$50 billion per year between 2030 and 2050

Although price is an important factor in solar deployment, other factors will also play an important role, including:

- **Access to transmission and ability to expand the transmission network.**
- **Grid-integration challenges.**
- **Siting, environmental, and land-use issues.**
- **Access to capital for manufacturing scale-up and project development.**

Big Solar: Challenges and Opportunities

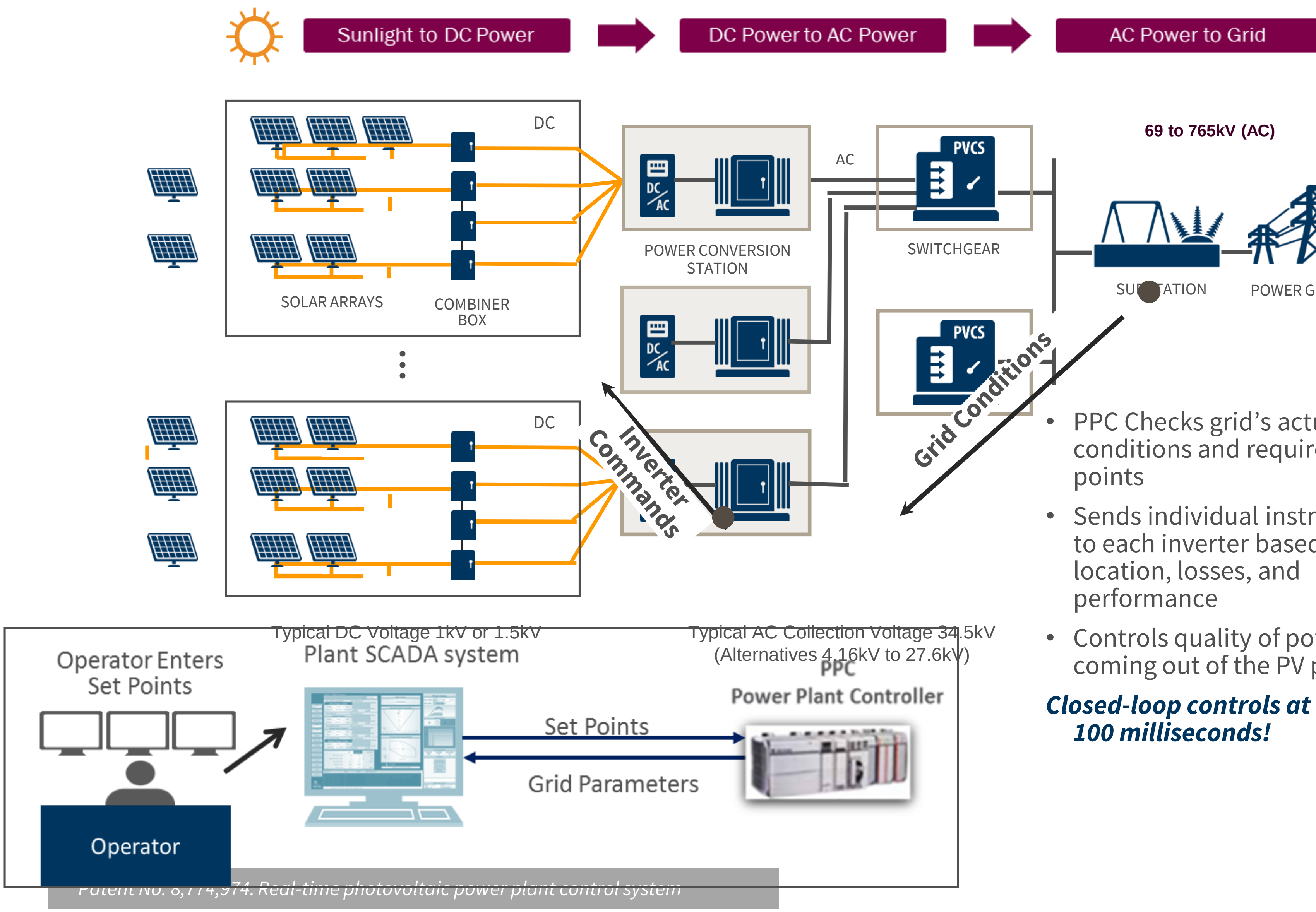
Challenges

- Operational Challenges
  - Variability, Transmission, Grid Reliability/Stability
- Perceptions on Environmental Impact
- Political Foresight
- Cost/Project Financing

New Business Opportunities

- Solar Energy-Water Desalination
- Energy Storage
- Solar Energy Water Nexus in Mining
- Solar Fuels and Chemicals

Operational Challenges?
Plant Control System Enables Grid Support Features



- PPC Checks grid's actual conditions and required set points
- Sends individual instructions to each inverter based on location, losses, and performance
- Controls quality of power coming out of the PV plant

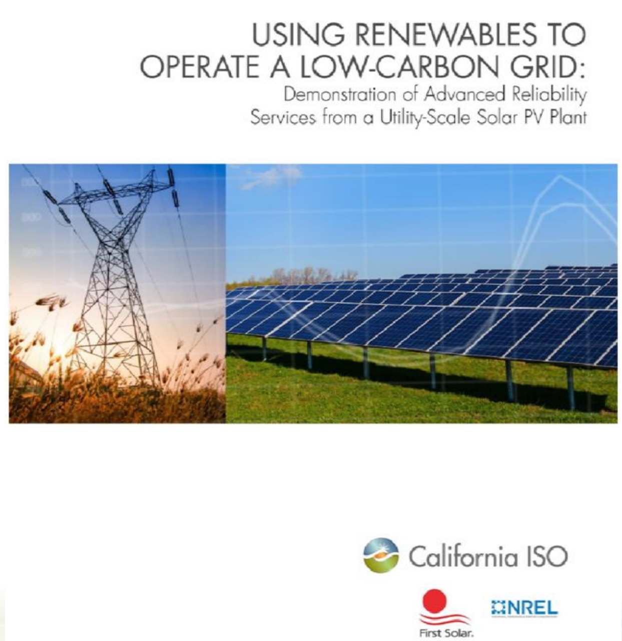
Closed-loop controls at 100 milliseconds!

Source: Dr. Mahesh Morjaria, First Solar

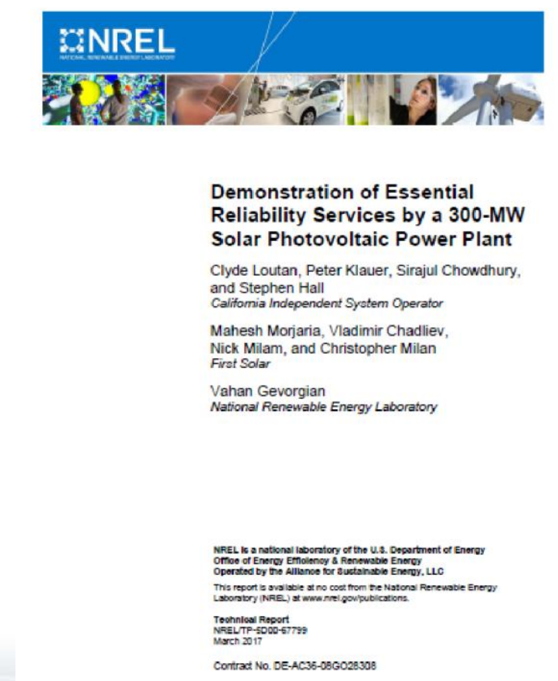
Variable Energy Resources Provide Essential Reliability Services to Reliably Operate the Grid

- **NERC identified three essential reliability services to reliably integrate higher levels of renewable resources**
  1. **Voltage Control (with Reactive Power)**
  2. **Frequency Control**
  3. **Ramping Capability or Flexible Capacity (Automatic Generation Control)**

- **Test results demonstrated utility-scale PV plant has the capability to provide these essential reliability services**


USING RENEWABLES TO
OPERATE A LOW-CARBON GRID:
Demonstration of Advanced Reliability
Services from a Utility-Scale Solar PV Plant

California ISO
First Solar.
NREL


NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant

Clyde Loutan, Peter Klauer, Sirajul Chowdhury, and Stephen Hall
California Independent System Operator

Mahesh Morjaria, Vladimir Chadliev, Nick Milam, and Christopher Milan
First Solar

Vahan Gevorgian
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

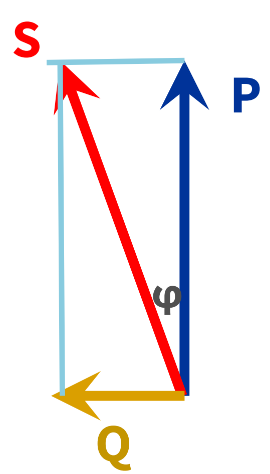
This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Technical Report
NREL/TP-5D00-67799
March 2017

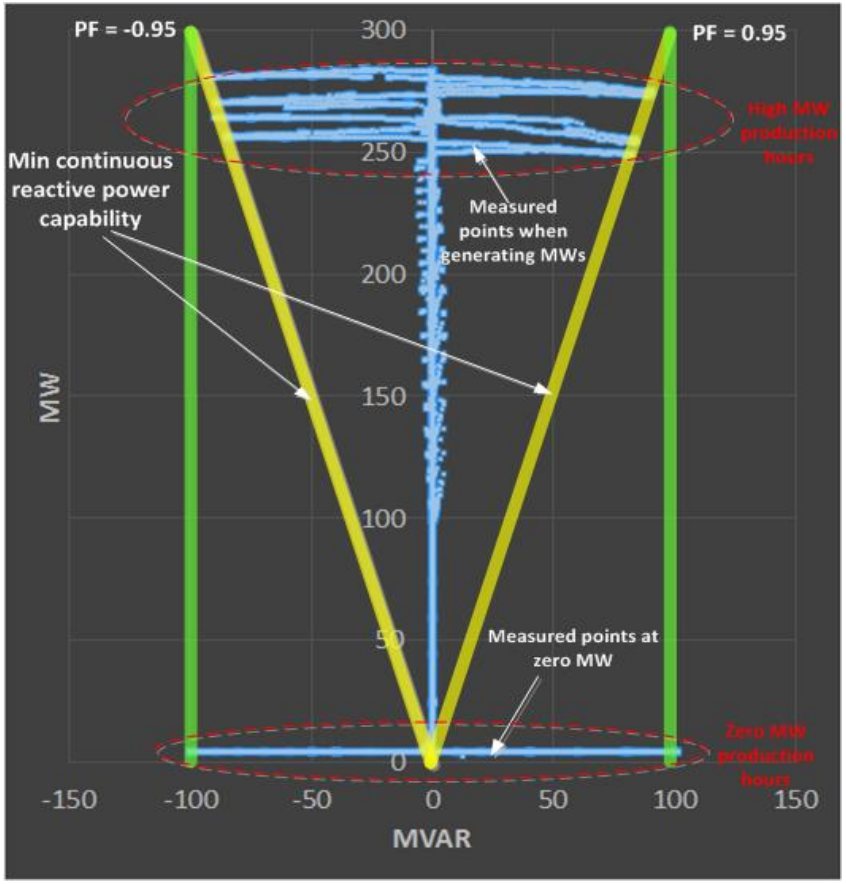
Contract No. DE-AC36-08GO28308

Measured Reactive Power Capability and Voltage

- Example:
  - Actual Power: P_n = 300 MW (80 Inverters)
  - Reactive Power: Q_n = ~100 MVAr
  - Apparent Power: S_n = ~315 MVA
  - Power Factor pf = 0.95
- The PV plant is capable of either producing or absorbing up to 100 MVAr when actual power is from 30 MW to 300 MW



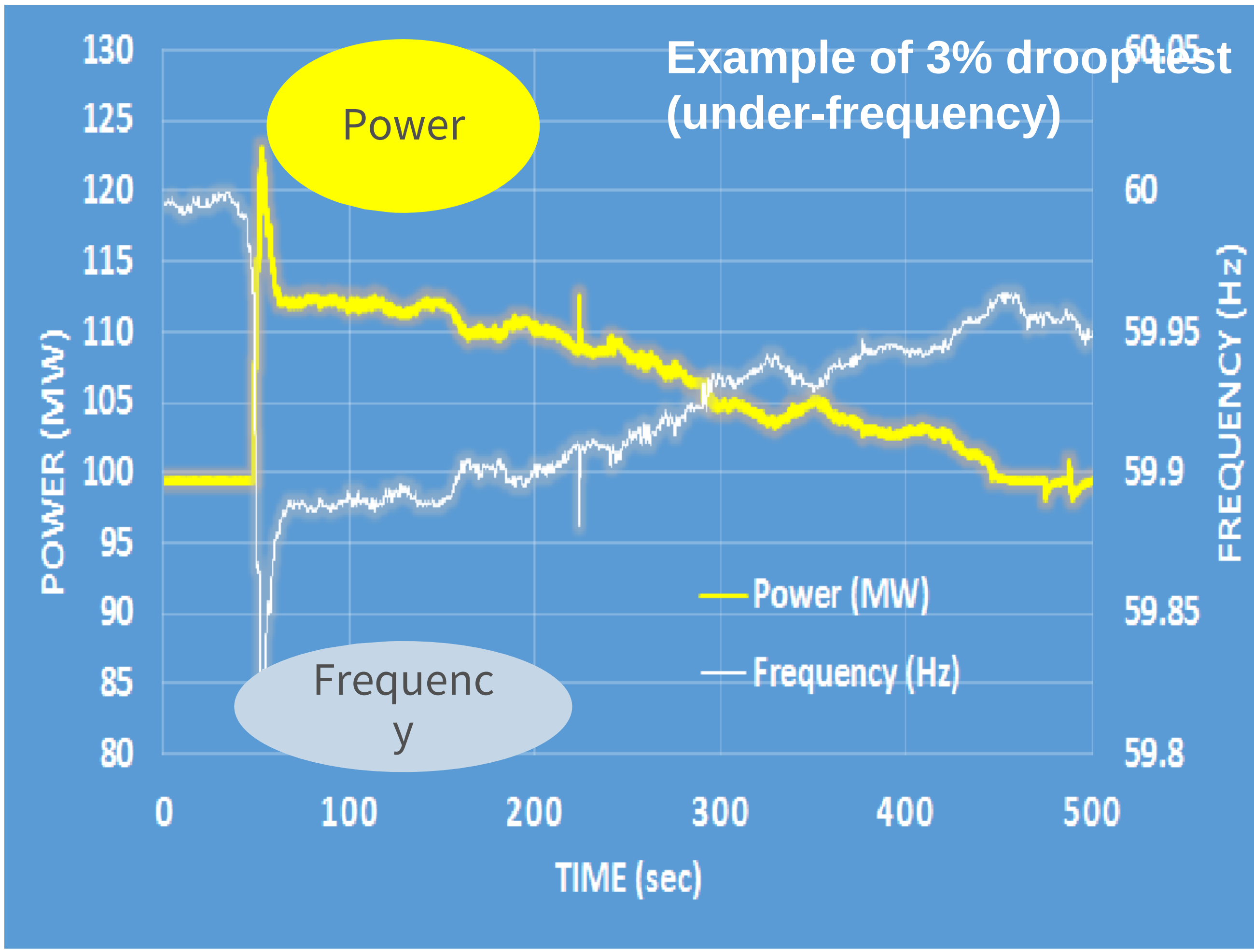
- Reactive power tests at high and low power production levels



By producing reactive power the PV plant increases the voltage on a system, and by switching to absorbing reactive power it can lower the voltage, as needed.

CA-ISO, NREL, First Solar, Using Renewables to Operate a Low-Carbon Grid, 2017

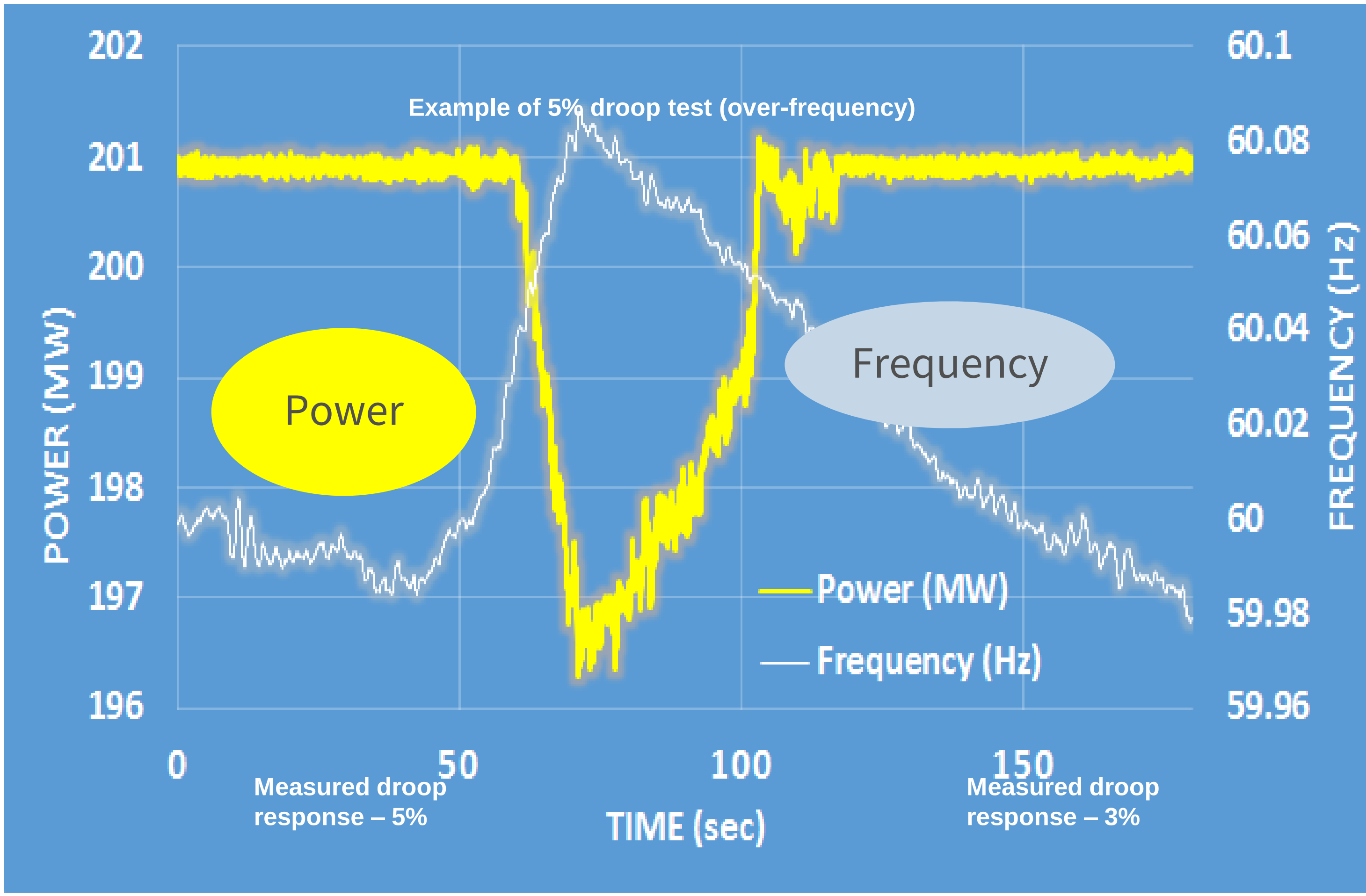
Frequency Droop Tests
Example of Under Frequency Tests



- **Used actual frequency event time series measured in the U.S. Western Interconnection**

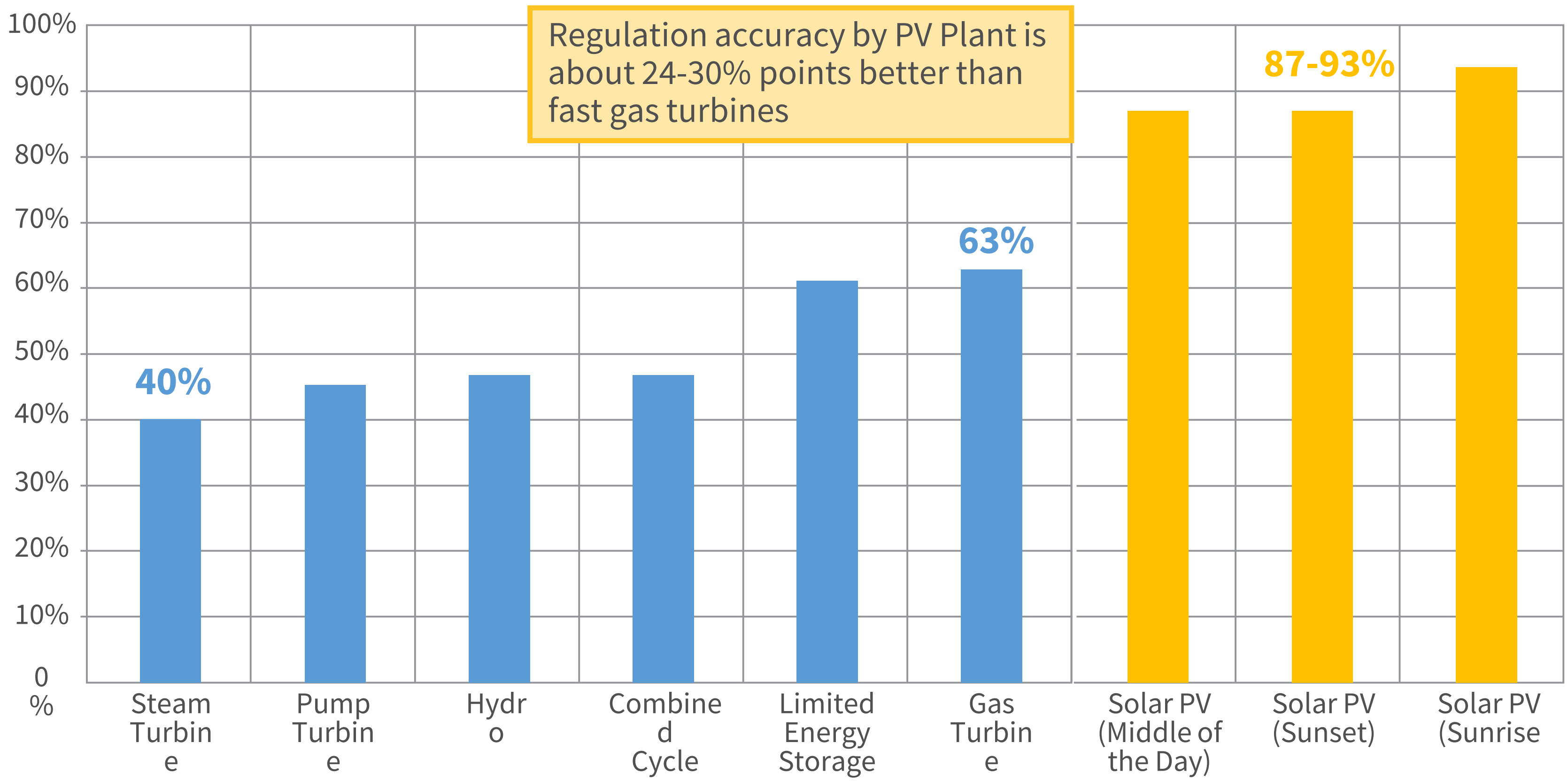
CA-ISO, NREL, First Solar, Using Renewables to Operate a Low-Carbon Grid, 2017

Example of Over-Frequency Droop Tests



CA-ISO, NREL, First Solar, Using Renewables to Operate a Low-Carbon Grid, 2017

PV Plants Outperform Conventional Generators in Frequency Regulation



California ISO

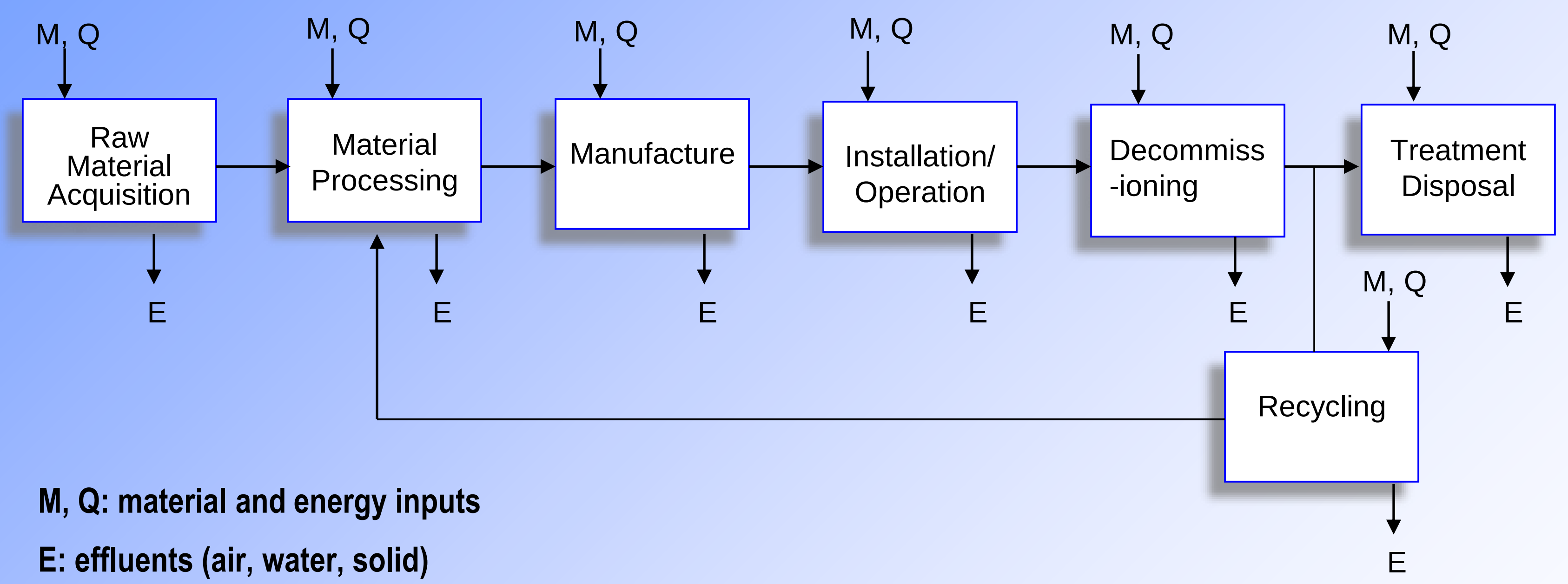
CA-ISO, NREL, First Solar, Using Renewables to Operate a Low-Carbon Grid, 2017

http://www.caiso.com/Documents/TestsShowRenewablePlantsCanBalanceLow-CarbonGrid.pdf

Addressing Perceptions on Environmental Impact

- **PV Energy Return on Energy Investment is too low**
- **PV deployment uses too much land**

Energy-Environmental Life Cycle Analysis



M, Q: material and energy inputs

E: effluents (air, water, solid)

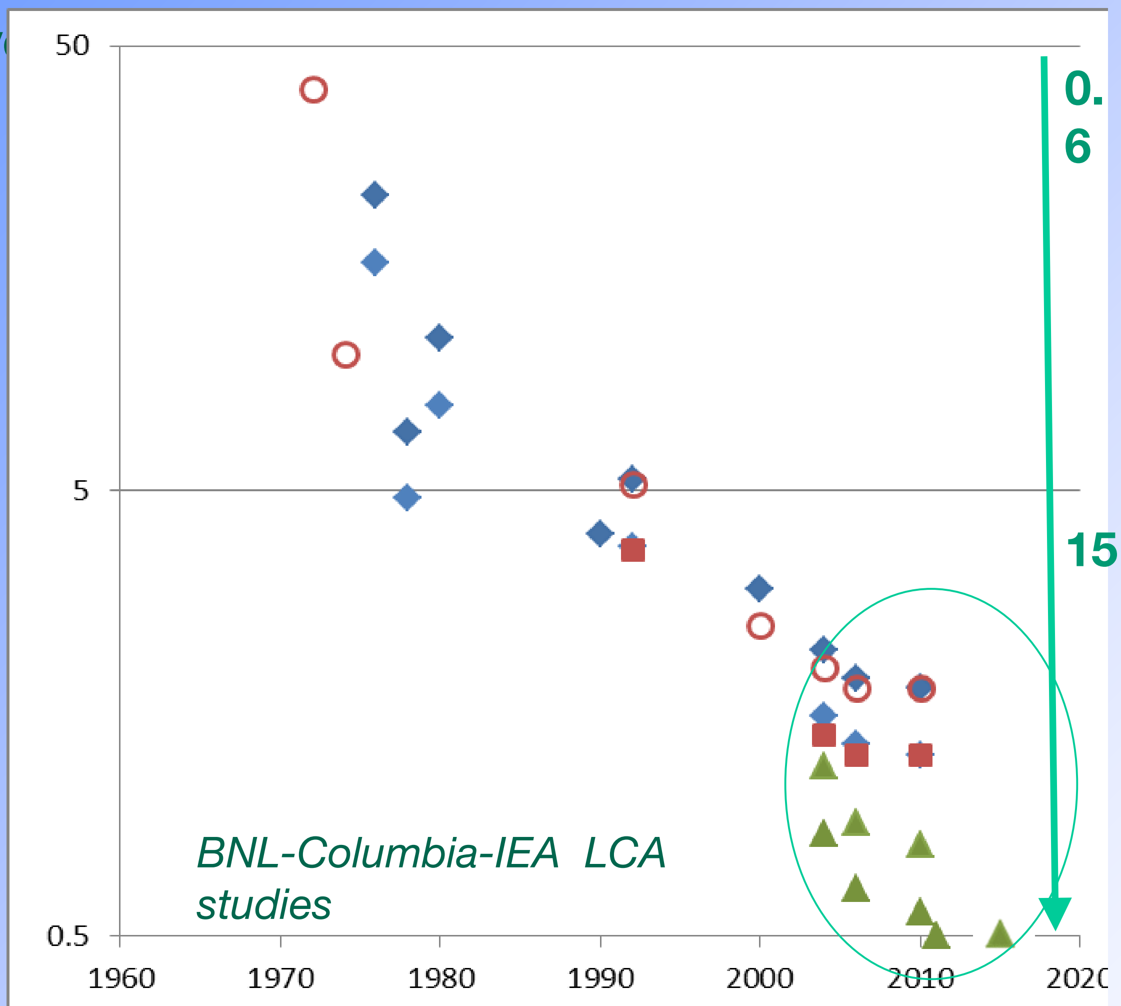
Basic Metrics

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

Energy Payback Times (EPBT) & Energy Return on Energy Investment (EROI) Historical Evolution

EPBT (y

ERO



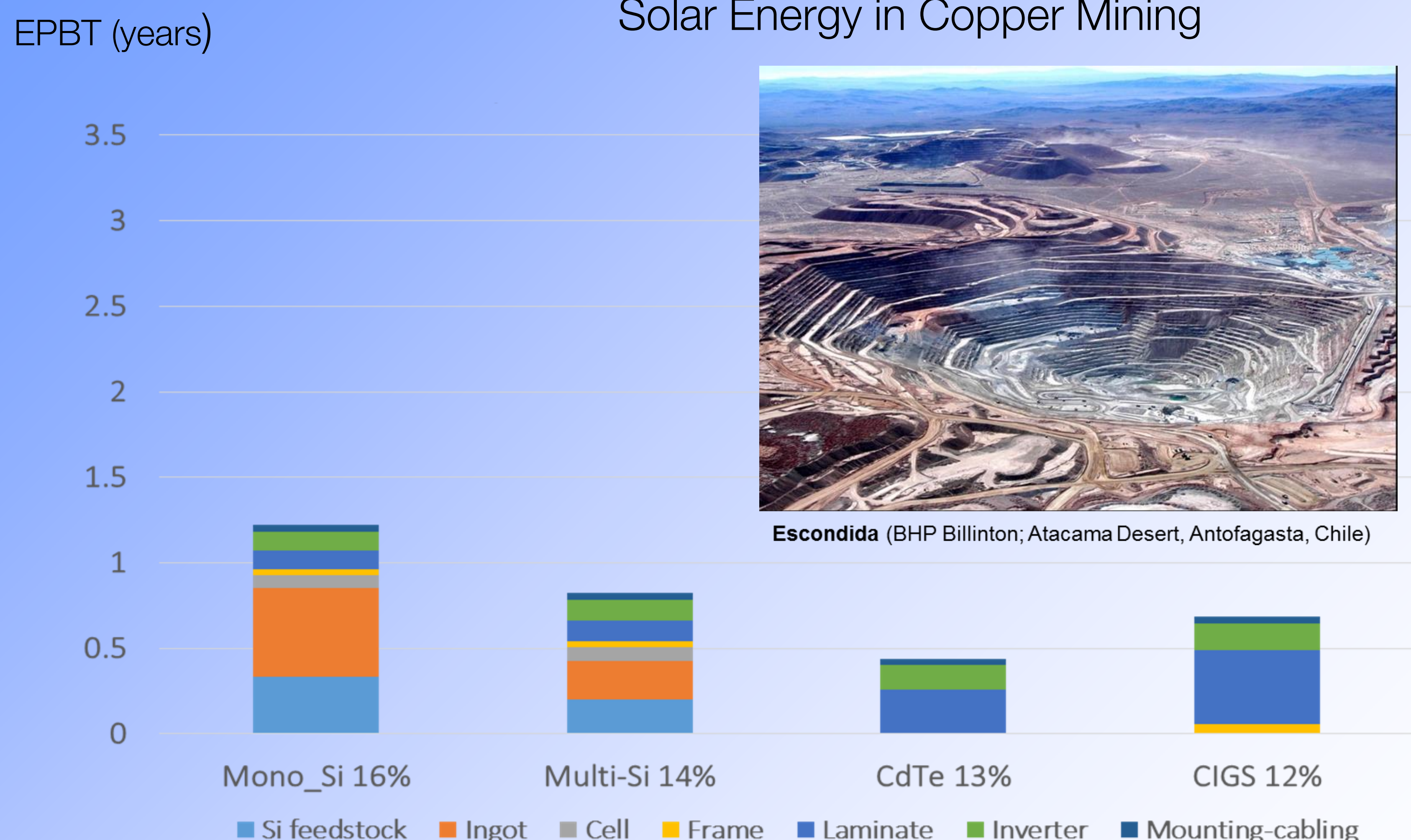
Irradiation of 1700 and 2400 kWh/m²/yr

60

Fthenakis et al., Methodology Guidelines on LCA of PV Electricity, IEA PVPS, Nov. 2011
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

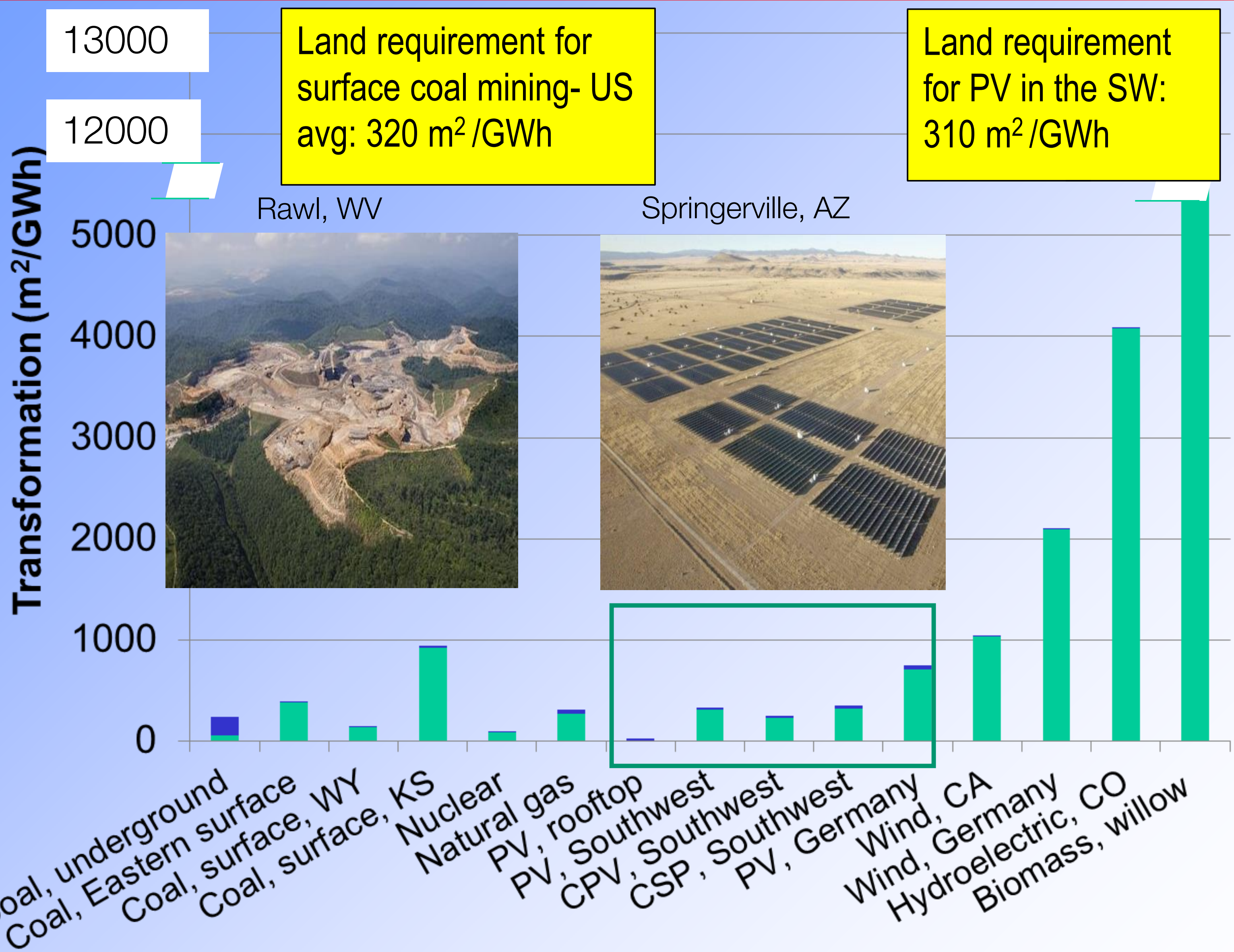
Energy Payback Times (EPBT)

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



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

PV Uses less Land than Coal



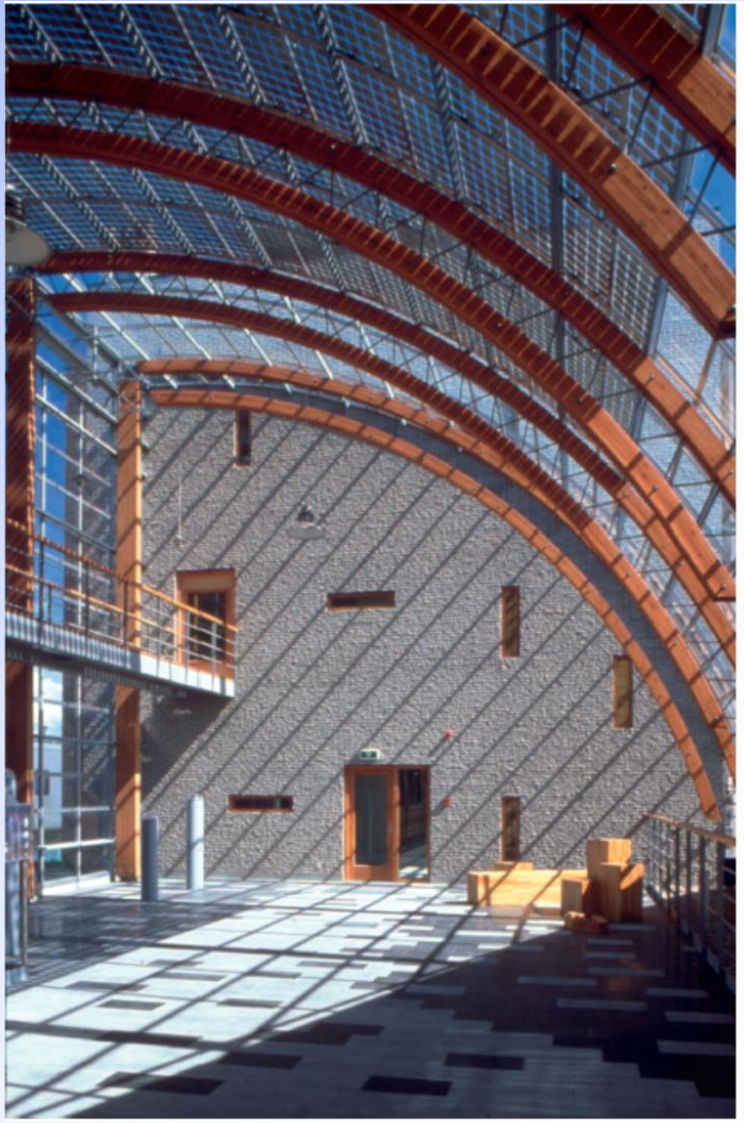
Fthenakis and Kim, Renewable and Sustainable Energy Reviews, 2009;
Burkhardt et al (2011)

…and does not disturb the Land

...dual Use of Land

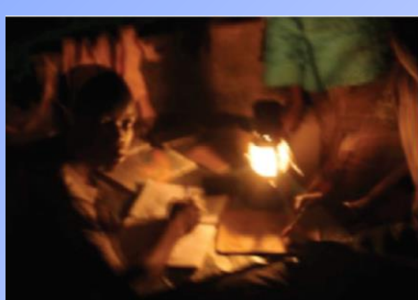
19

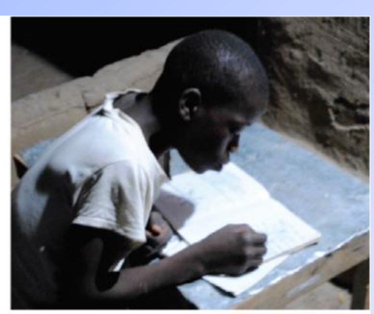
…combines Usefulness and Beauty



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

and Changes Lives in the Developing World





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

Affordable & Abundant Solar Enabling New Industries

Solar +

- + Storage, desalination, fuels, chemicals

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

First Commercial Solar Desalination Plant
Solar Still–Las Salinas, Chile, 1872

- **Clean Inexhaustible Solar Energy became cost competitive**
- **Regions of Water Stress are Rich in Solar Irradiance**
- **Desalination uses a lot of fossil-fuel-based energy that generates carbon emissions**

Low-carbon Water Desalination relying on Solar Energy is a sensible approach

Integration of Solar and Desalination Technologies

Solar Technologies

Desalination Technologies

Solar Still

Photovoltaics (PV)

Reverse Osmosis (RO)

Electrodialysis (ED)

Concentrated Solar Power (CSP)

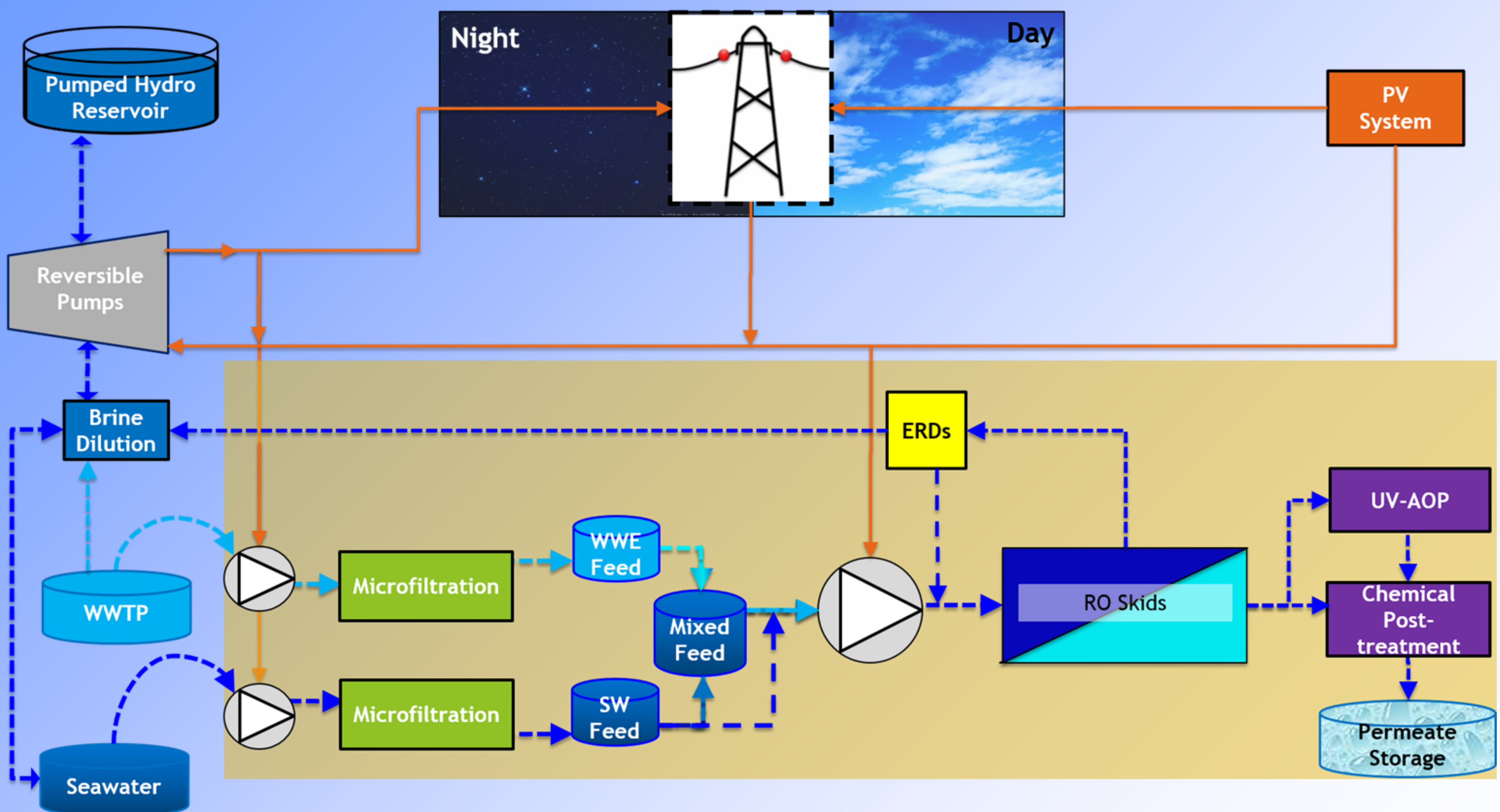
Multi-effect Distillation (MED)
MED-TVC; MED-AHP; MED-ADHP

Flat plate collector (FPC)
Evacuated tube collector (ETC)

Multi-stage Flash (MSF)

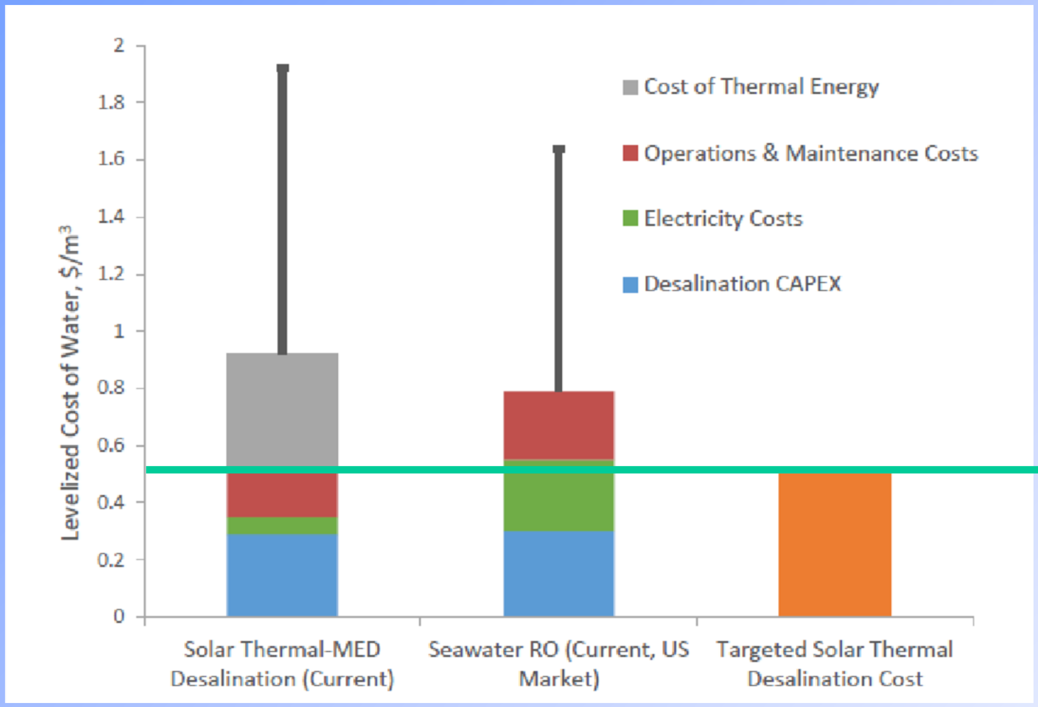
Membrane Distillation (MD)

Active-Salinity-Control PV RO Desalination System



- **RO desalination system that can handle a wide range of feed salinity**
- **System provides ancillary services to the grid**
- **Winner US-Israel Integrated Energy-Desalination Design Competition, 2018**

US-Department of Energy (DOE)
Solar Thermal Desalination Program 2019-2021



Target:
Seawater desalination below $0.50/m3

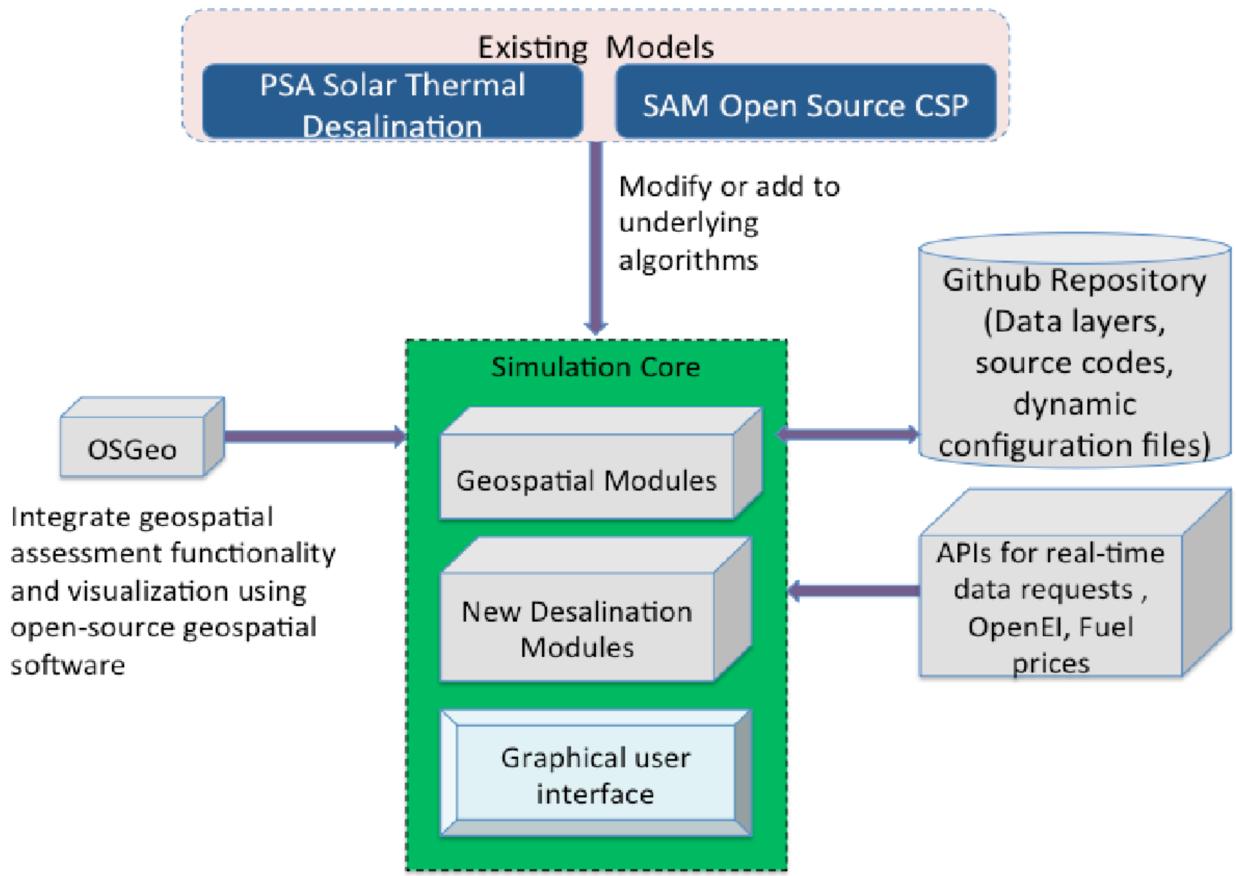
R&D Topic Areas:

1.Innovations in thermal desalination technologies
2.Low-cost solar thermal heat
3.Integrated solar desalination systems
4.Analysis for solar thermal desalination

-Develop analytical tools that will simplify the planning, design, and valuation of solar thermal desalination systems.

Source: DOE-EERE FOA, 2018

GIS-based graphical user interface tool analyzing solar thermal desalination systems and high-potential implementation regions

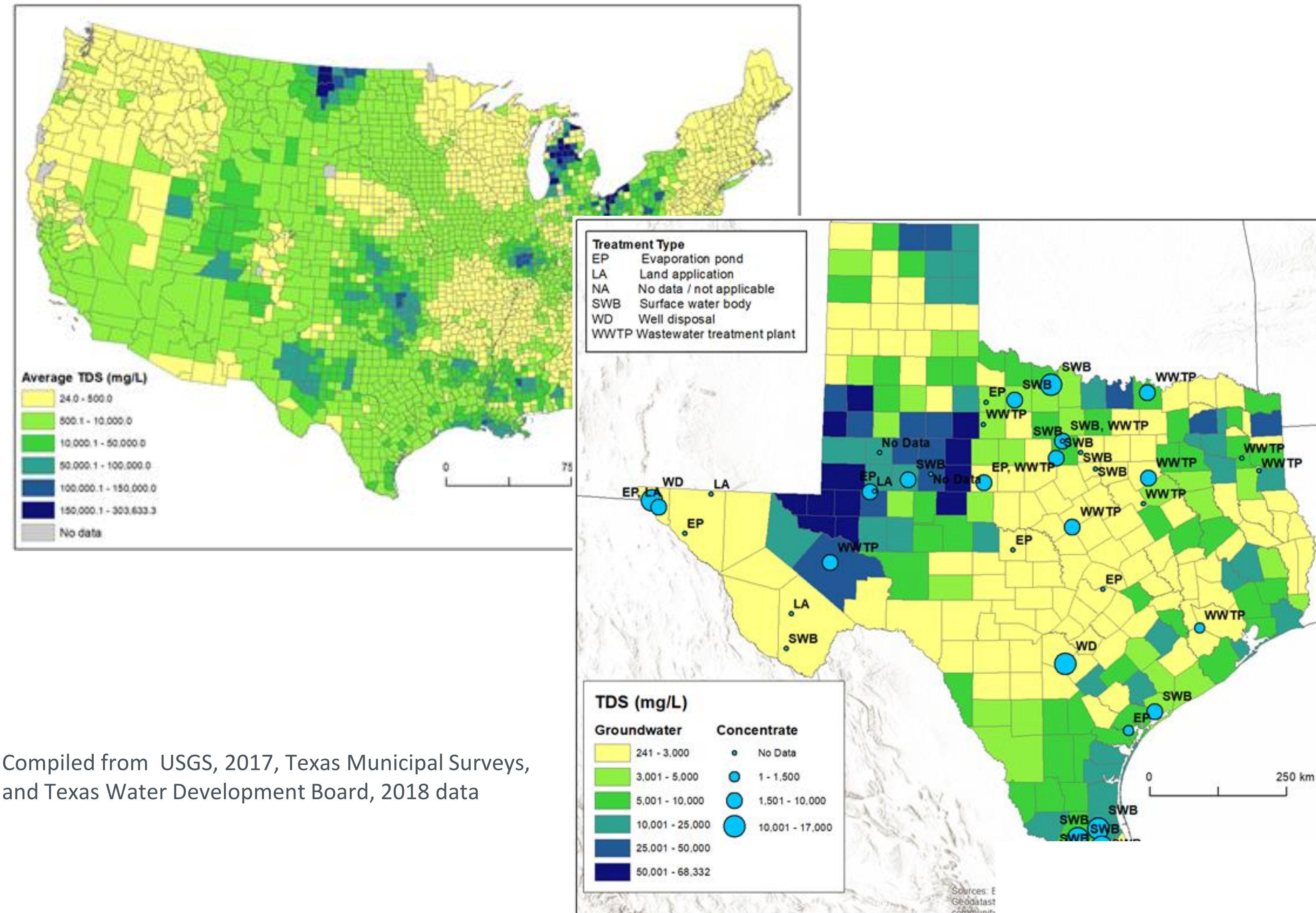


- **Reference Desalination models: MSF, MED, MED-TVC, RO**
- **New Technologies & Potential Hybrids: MD, RO-MED, RO-MD, crystallization for ZLD.**
- **The analysis tool design will be Open Access, Expandable, using a Modular Architecture**

US-DOE Award, 2018-2021
PSA: Plataforma Solar de Almeria
SAM: NREL System Advisory Model

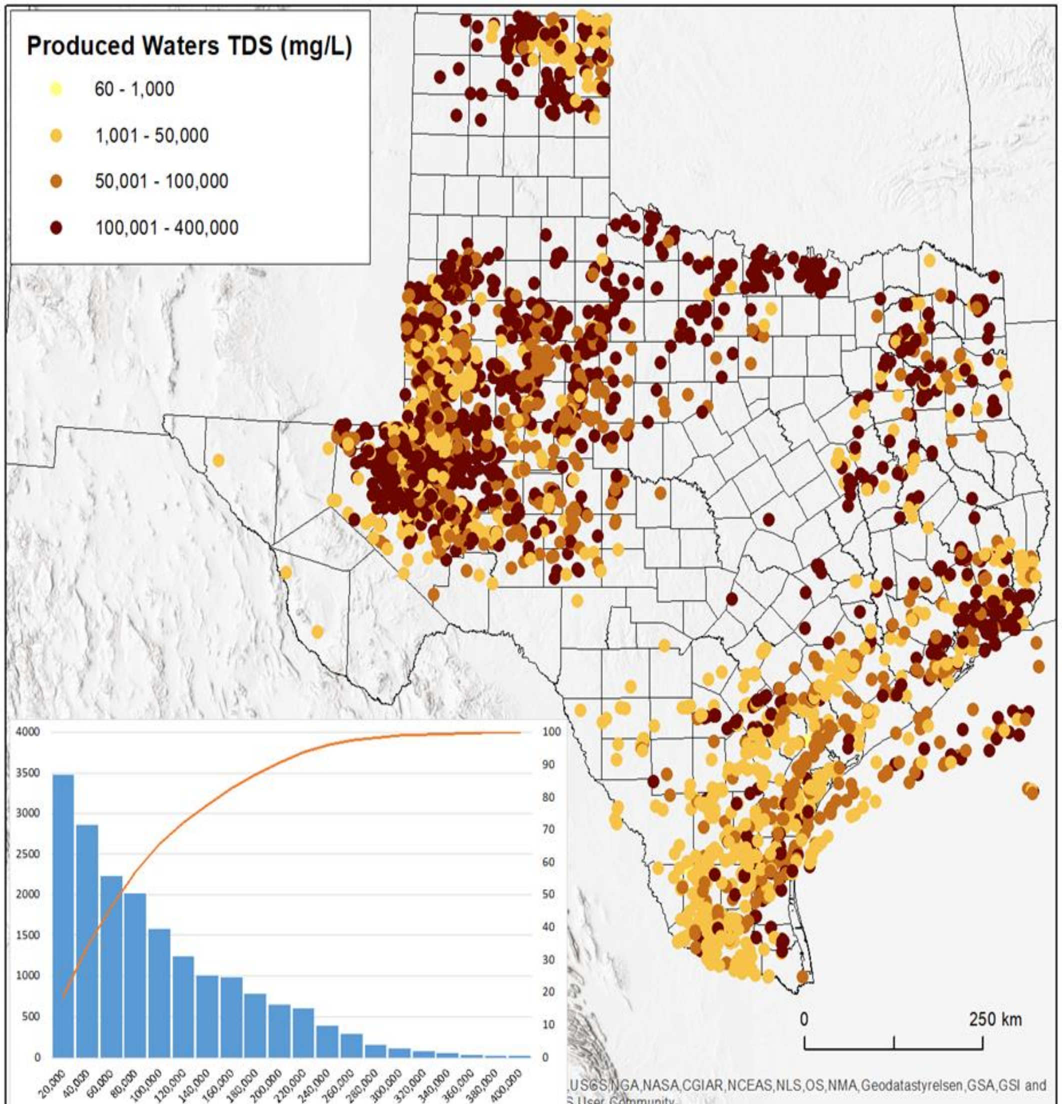
Development of Alternative Water Database
Brackish Water

Total Dissolvable Solids (TDS) Concentration (mg/L)



Compiled from USGS, 2017, Texas Municipal Surveys, and Texas Water Development Board, 2018 data

Development of Alternative Water Database
Produced Oil & Gas Water

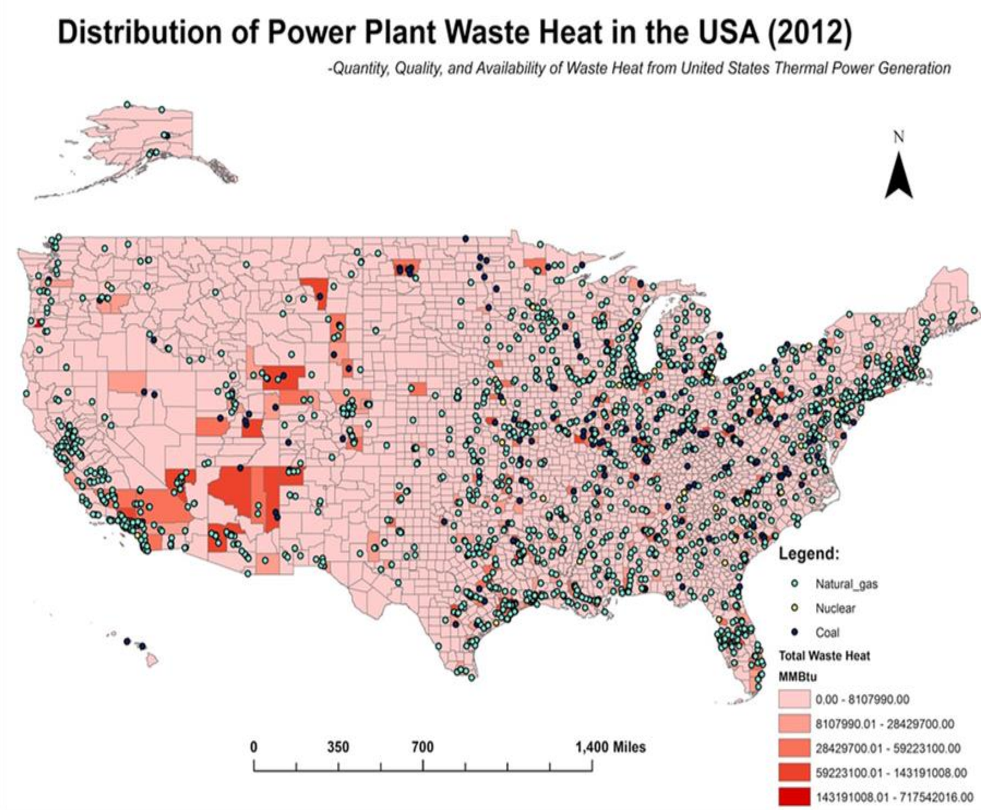


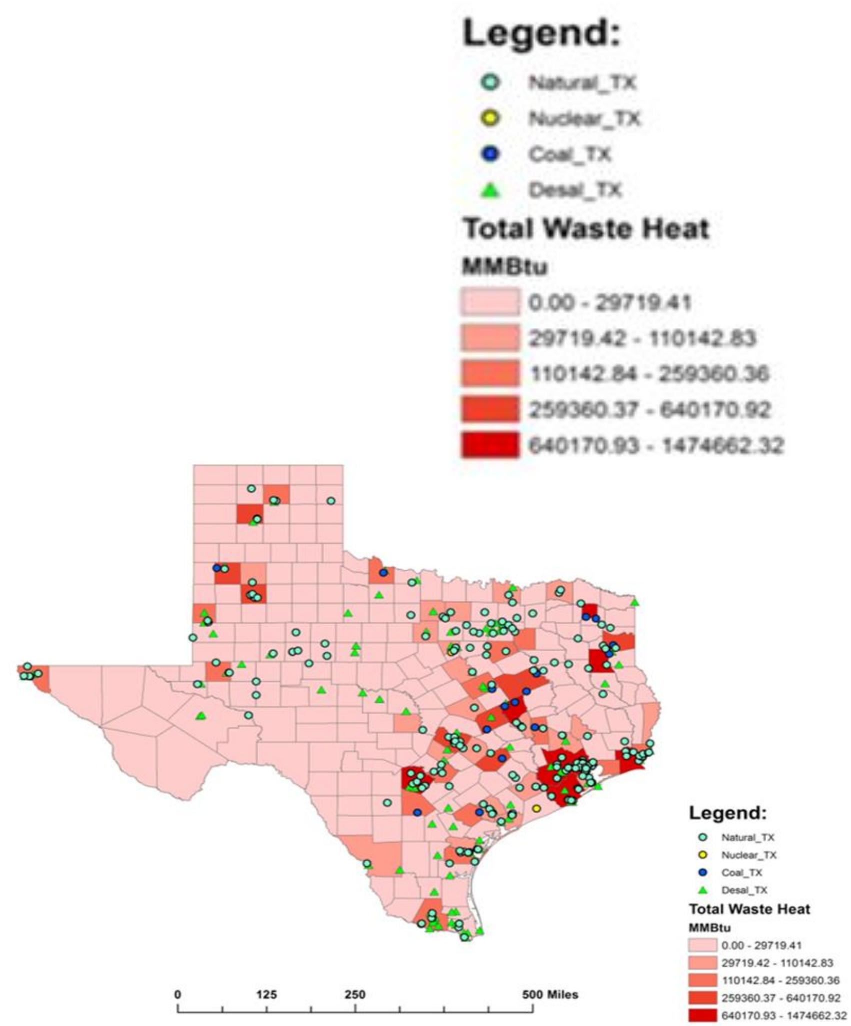
✓ Treatment of industrial wastewater

✓ Solar desalination of seawater and brackish water

Compiled from USGS Produced Water data, 2018

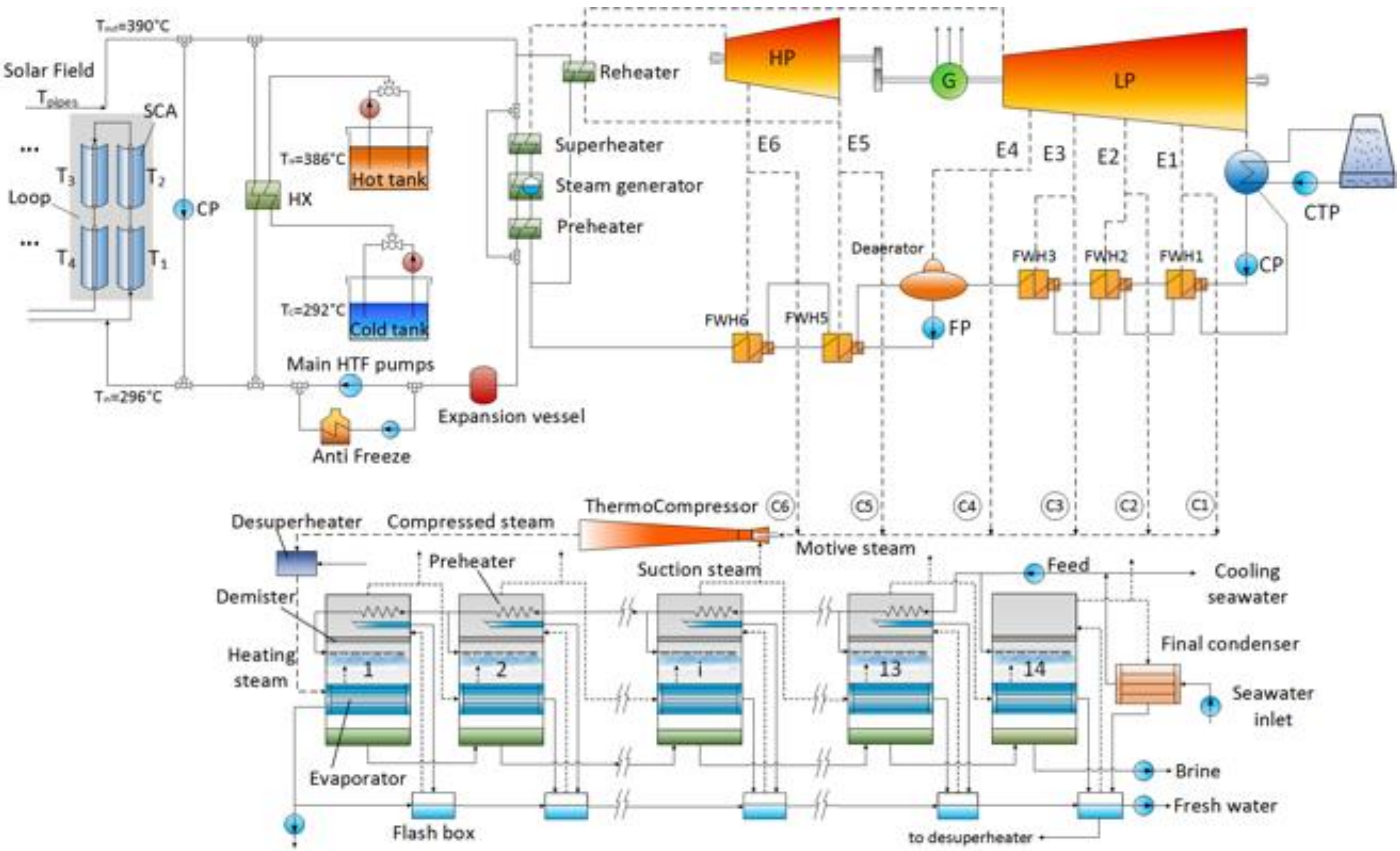
Development of Heat Source Database
Power Plant Waste Heat





Compiled from 2012 EIA data

Example Model: TVC-MED integrated with CSP



Ortega-Delgado, Palenzuela, Alarcon-Padilla, *Desalination* 394, 2016

Closing Remarks

- ❑ Solar energy can supply a large fraction of our energy needs.

- ❑ Inexpensive solar energy is an enabler for resolving water and environment challenges.

- ❑ Solar can enhance grid resiliency.

- ❑ Energy policy & climate change. The next 5 years are critical for our choices.

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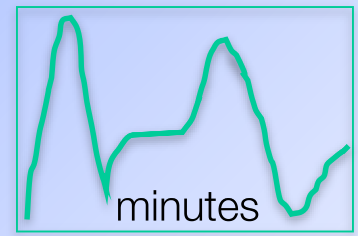
Area 2: Renewable Energy Systems Integration
Solar Variability Solutions: Cost Optimization

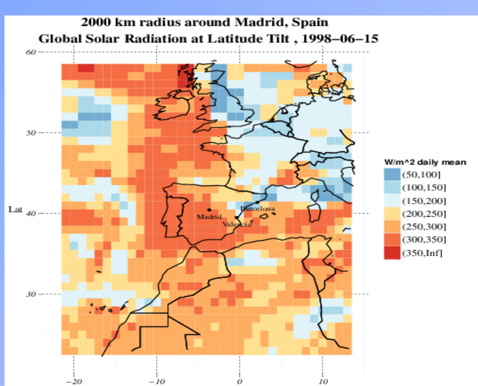
Seasonal

Diurnal

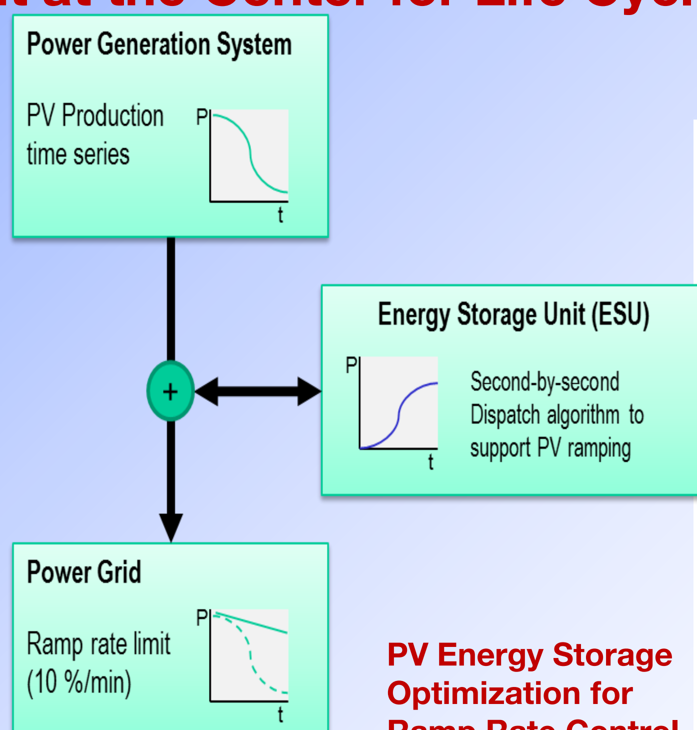
Cloud-induced



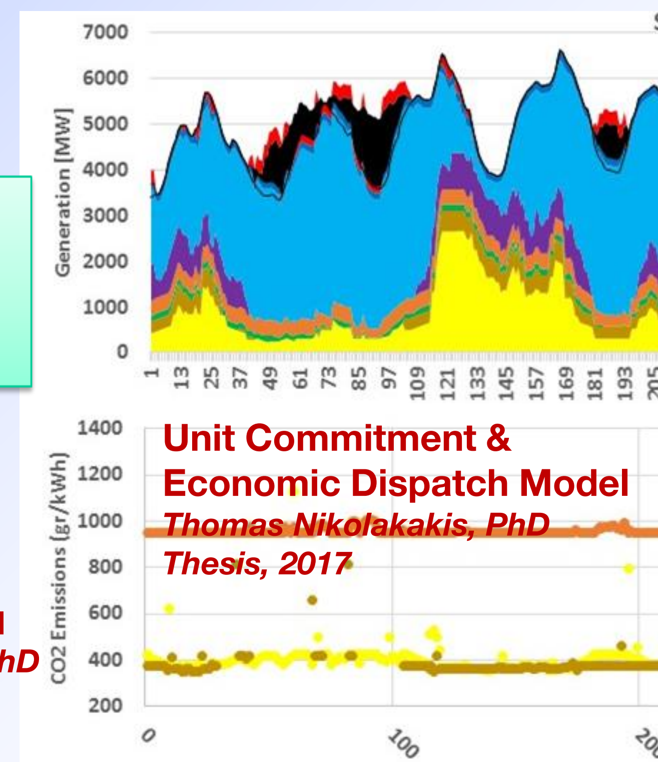
Model development at the Center for Life Cycle Analysis (CLCA)



PV Generation, Curtailment, Transmission and Storage Optimizer
Marc Perez, PhD Thesis, 2014



PV Energy Storage Optimization for Ramp Rate Control
Rob van Haaren, PhD Thesis, 2014



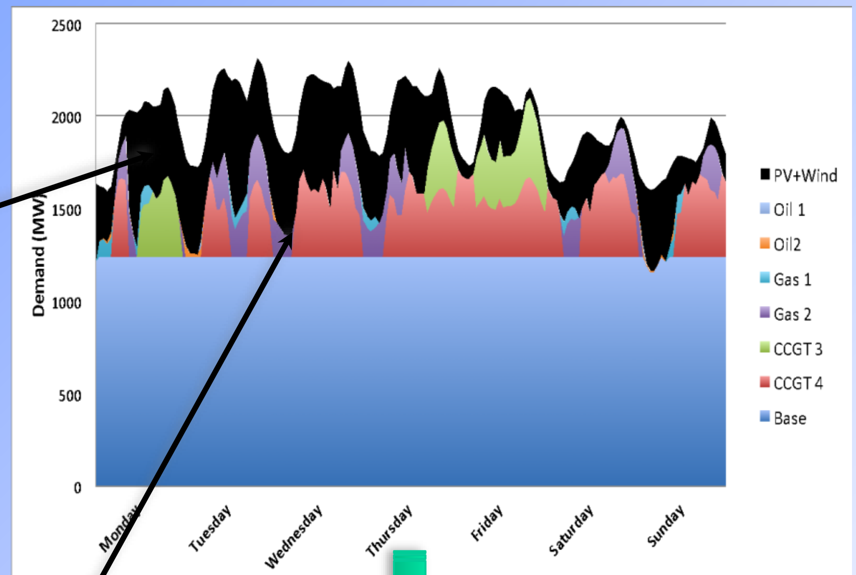
Unit Commitment & Economic Dispatch Model
Thomas Nikolakakis, PhD Thesis, 2017

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

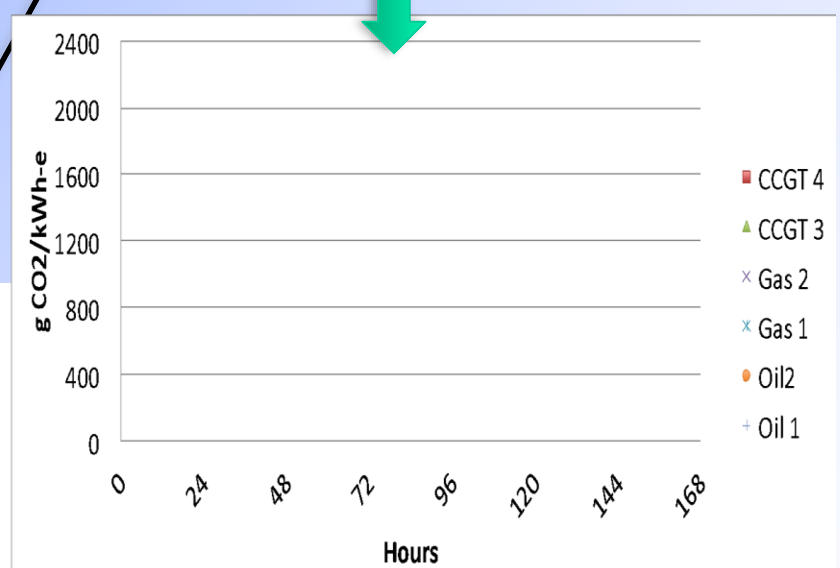
Variable Generation

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, *39th IEEEPVSC,* 2013

Columbia- SERC-Chile: Proposed Joint Studies

1. Solar Energy Storage

    Thermal using salts, electricity using pumped hydro, Li-based batteries and combinations

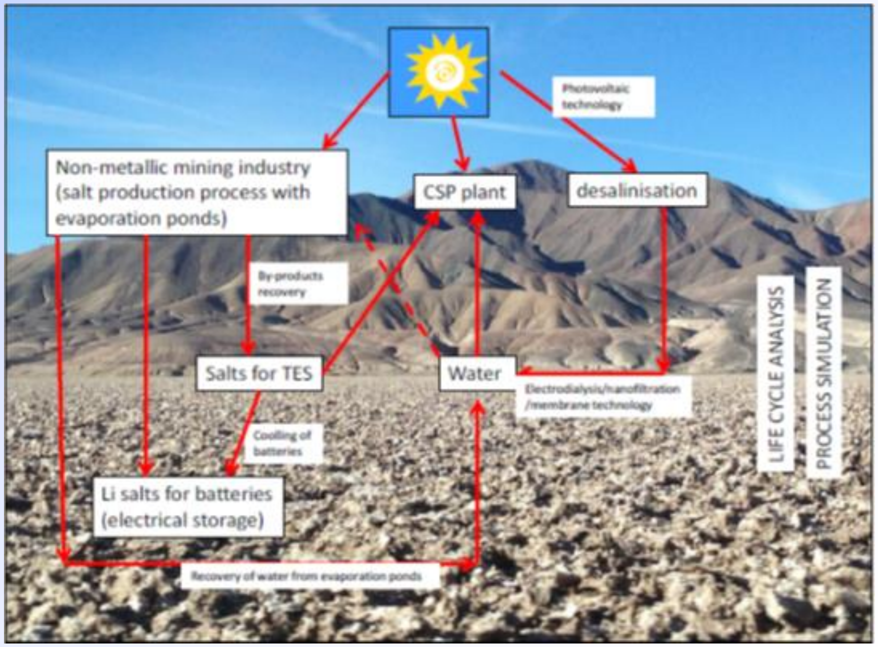
2. Water Treatment using Solar Energy

    Decontaminating natural water, treating industrial wastewater, desalination of sea & brackish-water

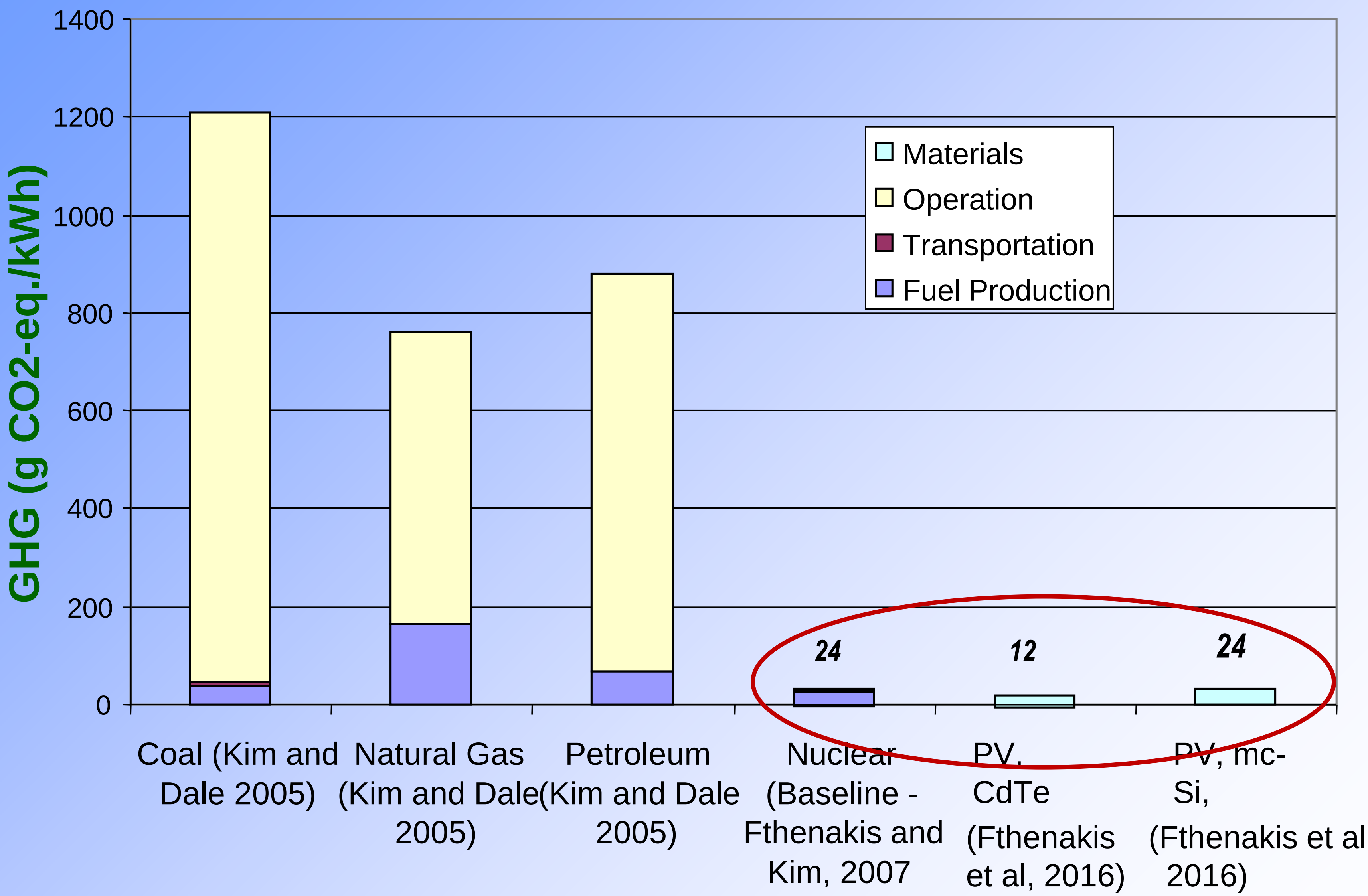
3. Solar Energy and Water in the Mining Industries

- Non-metallic mining industry. Evaporation ponds to concentrate salt brines.
  Water for mining camps and chemical process for brine to solid salts.
- Copper industry. Solar electricity to displace imported fossil-fuel energy.
- Desalinization industry. Solar can provide the desalination energy needs.
- CSP plants. Water availability is a challenge; on the other hand they can satisfy constant loads via thermal storage.

4. Microgrids for Rural Communities

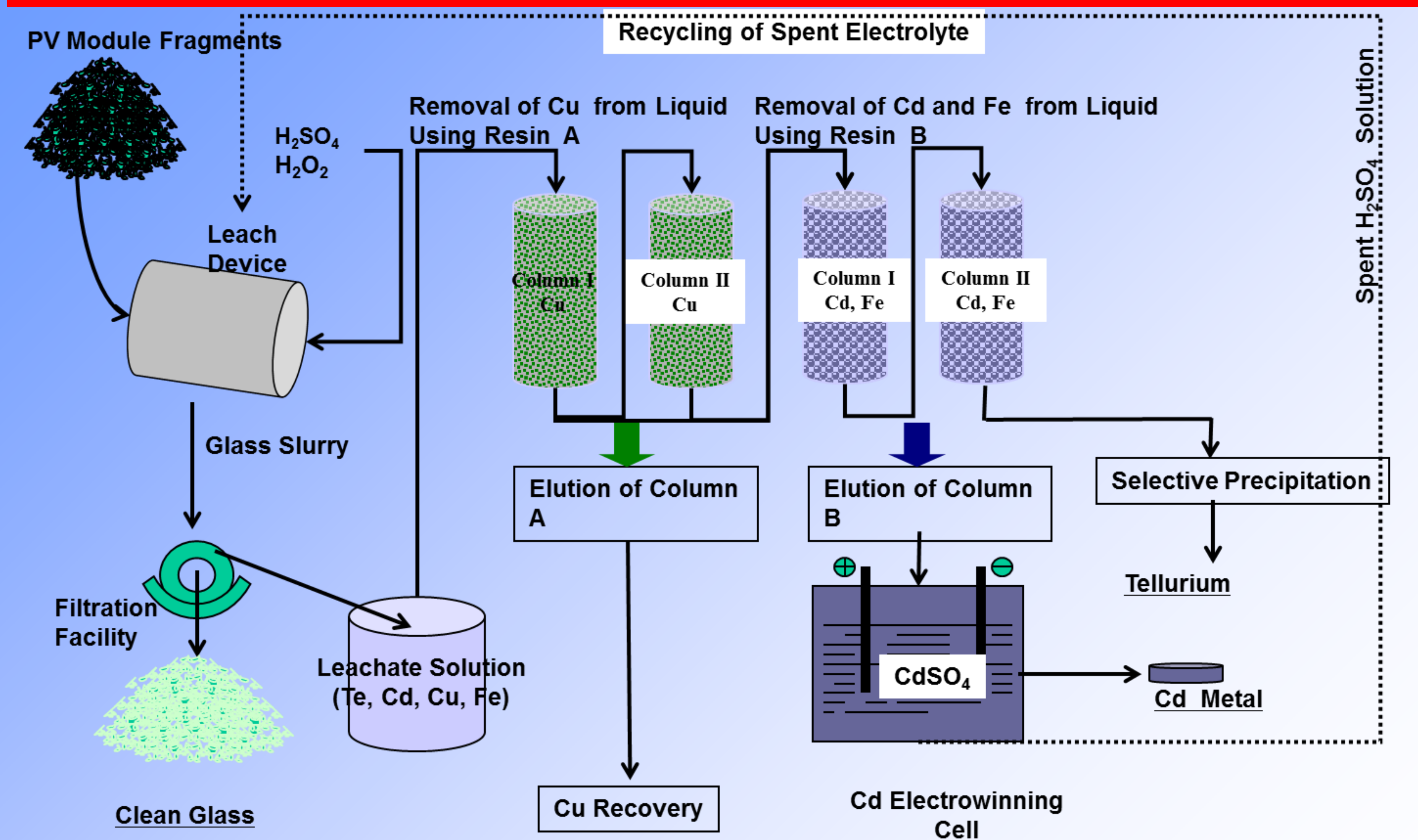


GHG Emissions from Life Cycle of Electricity Production: Comparisons



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*

Recycling R&D : CdTe PV Modules

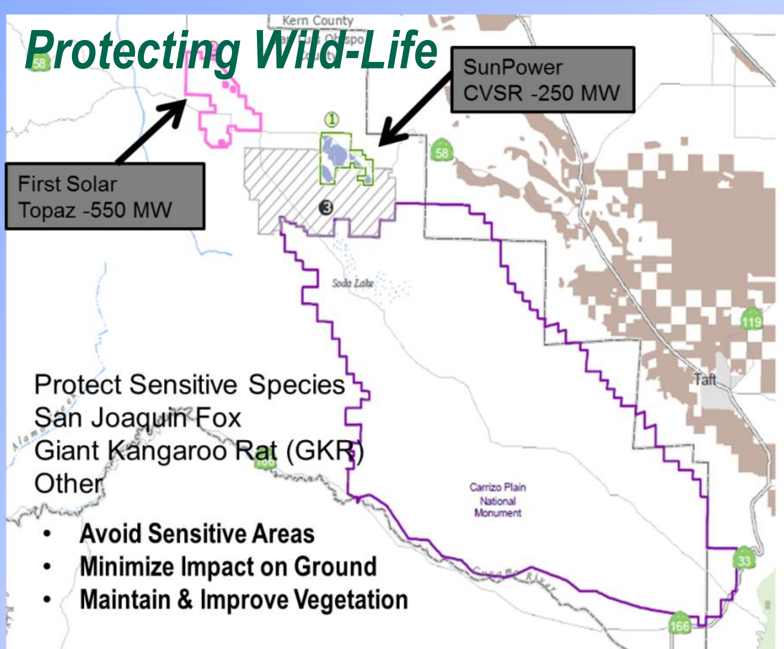


Fthenakis V. and Wang W., Separating Te from Cd Waste Patent No 7,731,920, June 8, 2010

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.

Use of Land is Environmentally Friendly



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

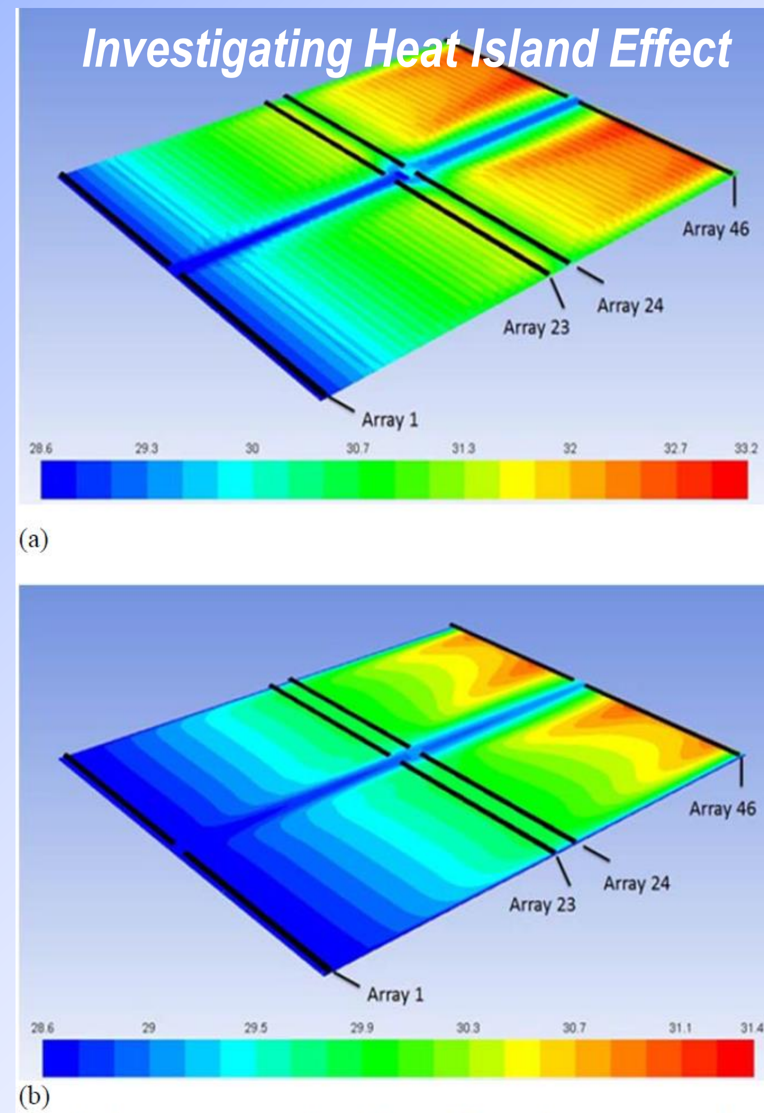
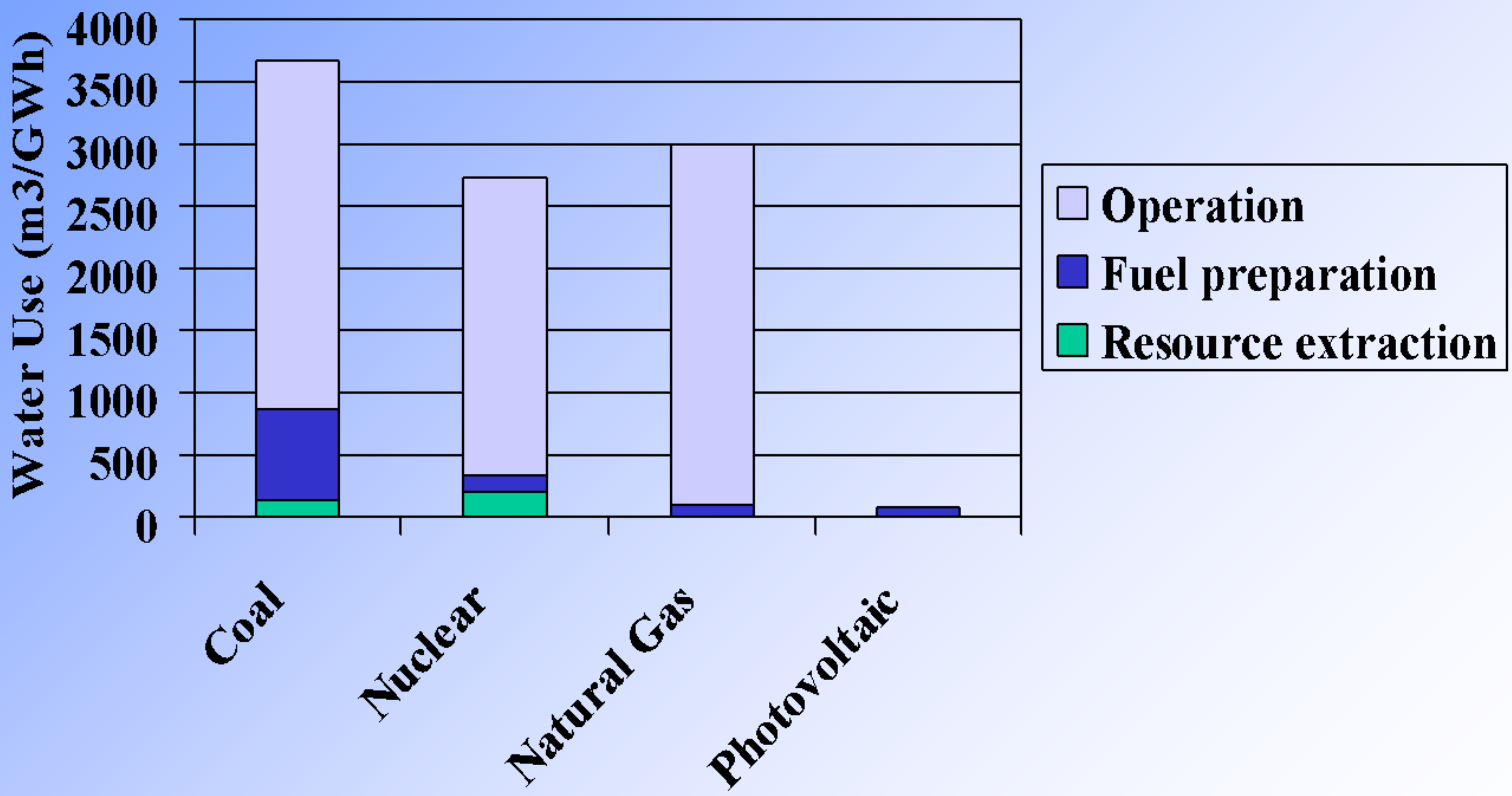


Fig. 11 Air temperatures from 3-D simulations during a sunny day. a) Air temperatures at a height of 1.5 m; b) air temperatures at a height of 2.5 m.

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

PV Uses much less water than other power cycles



Fthenakis and Lynn, Electricity from Sunlight, Photovoltaic-Systems Engineering and Sustainability, Wiley, 2018

Need for Full Cost Accounting: Environmental Cost Benefits of PV

- Environmental benefits for displacing fossil fuel-based electricity
  - Relative to coal PV would prevent the emissions of
  - SO_2: 8 ton/GWh
  - NOx: 3 ton/GWh
  - $PM_{10,\ 2.5}$: 0.4 ton/GWh
  - CO_2: 1000 ton/GWh
- PV by displacing coal also prevents health, safety and environmental impacts in mining; the later would increase with CCS
- PV Environmental Health and Safety cost and benefits need to be monetized and included in the overall cost comparisons

  Estimates of External Costs of Coal
  - National Research Council, NAS. 2010: 1-15 c/kWh
  - Epstein et al, Harvard Medical School, 2011: 8-19 c/kWh

Large Scale PV –Triangle of Success