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# Industrial Decarbonization Workshop - Applications

## U.S. DOE: Solar Energy Technologies Office (SETO)
## Hydrogen and Fuel Cell Technologies Office (HFTO)


*from: San Diego Union Tribune*

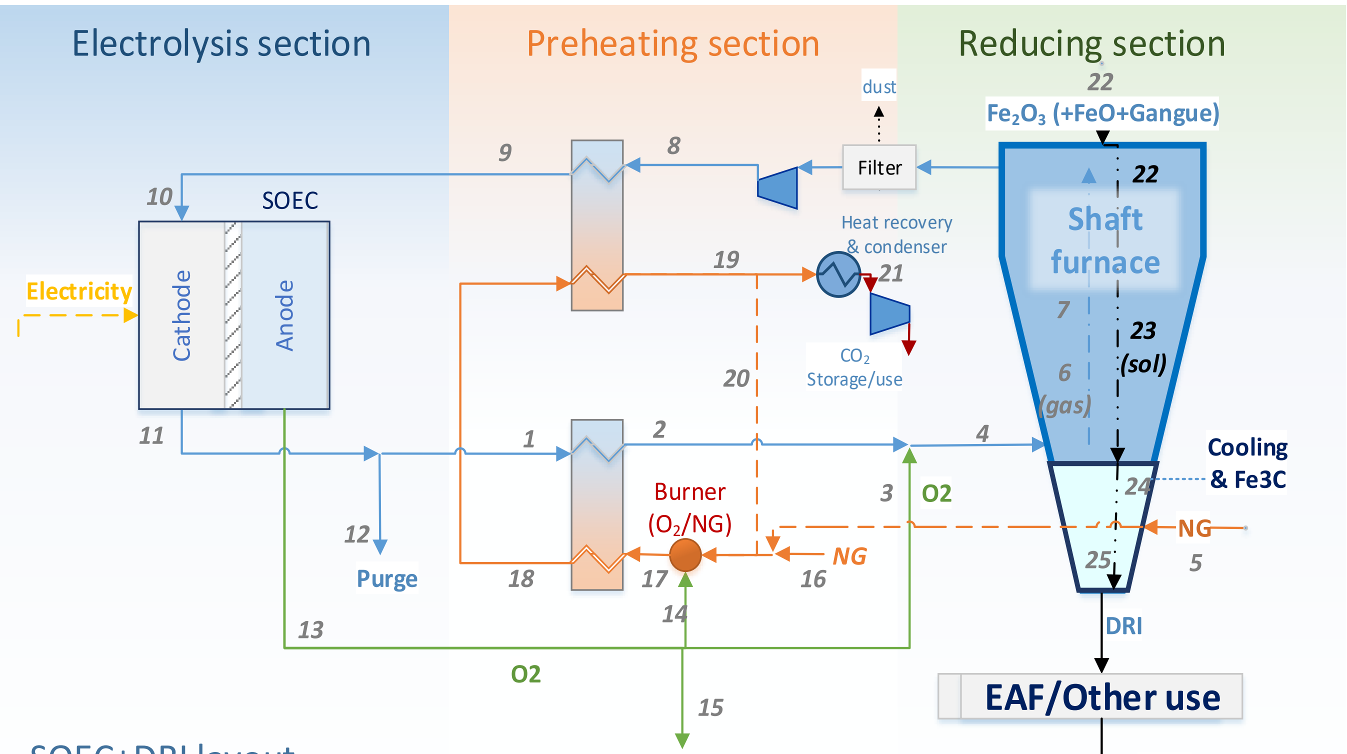
**Prof. Jack Brouwer**
**Director**

**September 14, 2021**

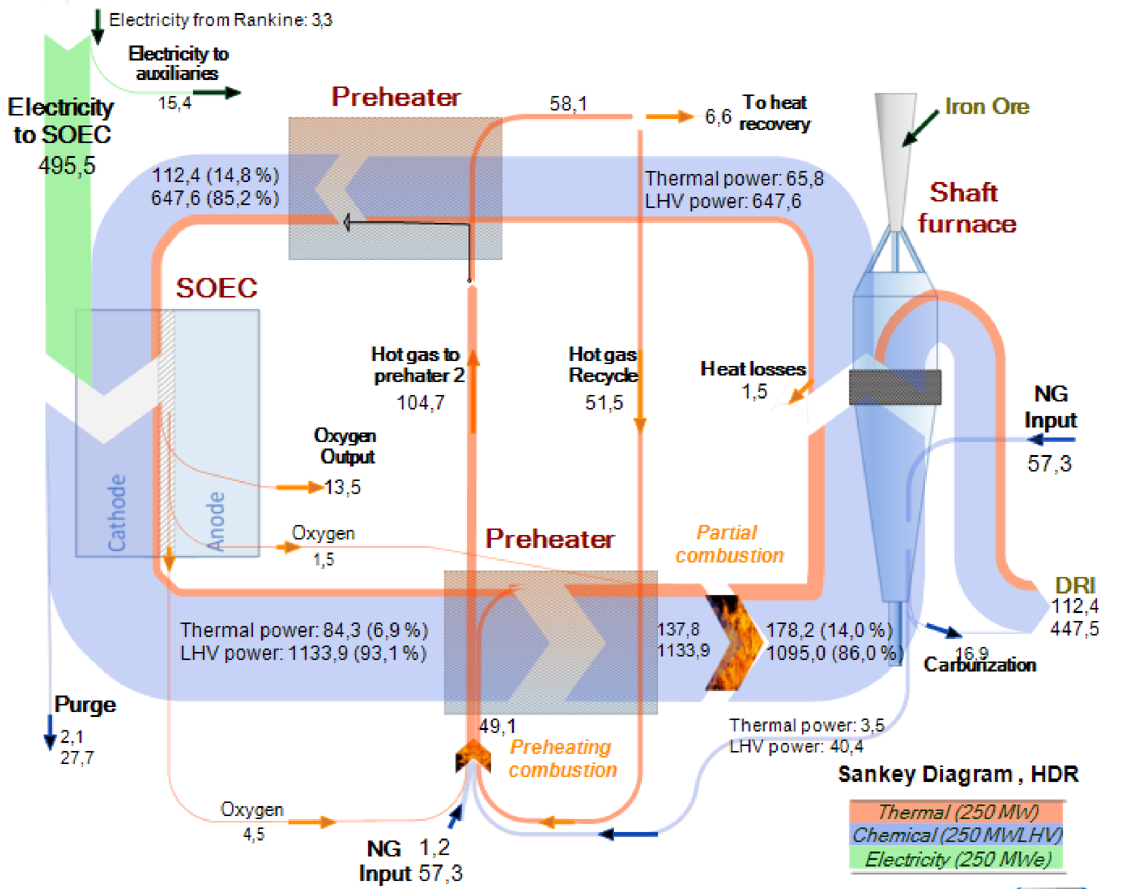
# Integrated SOEC + Direct Reduced Iron (DRI) for Green Steel

Team

Advisors



SOEC+DRI layout



Sankey Diagram, HDR

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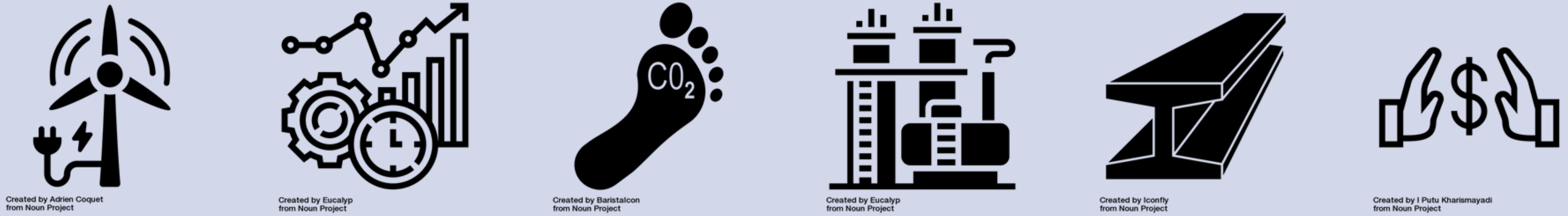
# U.S. DOE Supported *HySteel* Project Goals

Advance, demonstrate and optimize a thermally and chemically integrated Solid Oxide Electrolysis Cell (SOEC) system, as co-producer of $H_2$ and $O_2$, with a Direct Reduction Iron (DRI) plant at 1 ton/week of product scale.




**Specific primary energy consumption <8 $GJ/t_{DRI}$**

**Electric-to-hydrogen efficiency for an SOEC stack of <35 kWh/kg of $H_2$ produced**

**Specific $CO_2$ emissions rate < 90 kg $CO_2$/ton DRI product w/o oxyfuel**

**Pilot system at production capacity of 1 ton/week and TRL 4**

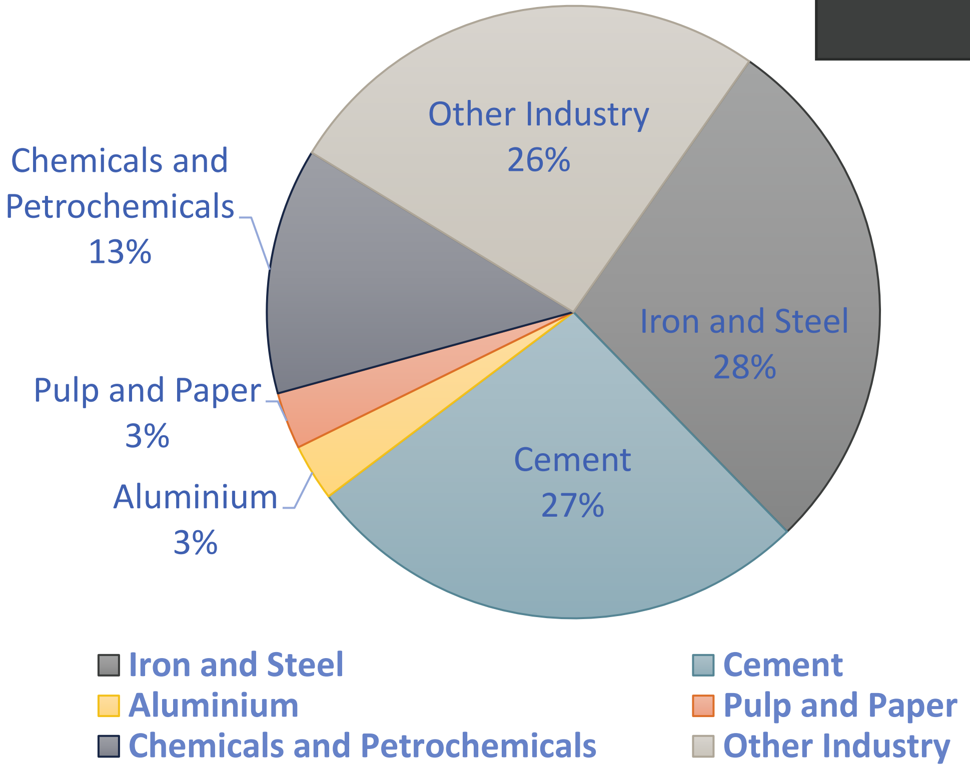
**Scale-up design for a 2 Mton/year DRI product capacity**

**Total capital specific cost < $200/ton equivalent pig-iron per year**

Total Project Budget: $5,664,862.00 – Total DOE Share: $4,043,993.00 – Total Cost Share: $1,620,869.00

# *HySteel* Relevance & Potential Impact

**Direct Industrial CO2 emissions**




WorldSteel association – World steel in figures 2020
International Energy Agency (IEA)

**Steel industry:**
World total 1869 $Mton_{steel}$
6-6.5% of total anthropogenic $CO_2$ emissions

Blast Furnace + Basic Oxygen Furnace (BF+BOF)
Hydrogen Direct Reduction (HDR)
Hybrid Hydrogen Direct Reduction (Hybrid HDR)

| | Units | BF+BOF | HDR | Hybrid HDR |
|---|---|---|---|---|
| Energy intensity | $GJ/ton_{crude\ steel}$ | 19-20 | <8 | <9 |
| Specific emissions | $ton_{CO2}/ton_{crude\ steel}$ | 1.8-1.9 | <0.09 | <0.09 |
| Specific cost | $\$/ton_{eq\ pig\text{-}iron}\ yr$ | 210 | 200* | 200* |
| Electric load | $GJ_{el}/ton_{crude\ steel}$ | - | <7 | <7 |
| *At 2 Mton/yr scale | | | | |

| | Units | Ref SOEC | HDR | Hybrid HDR |
|---|---|---|---|---|
| Hydrogen Eff. | kWh/kg | 40 | 35 | - |
| Syngas Eff. | kWh/kg | 45 | - | 40 |
| Oxygen Eff. | kWh/kg | 6.5 | <5 | <5 |

# *HySteel* Project Work Packages

**WP1: System integration and thermodynamic analysis**

- *Plant conceptualization and thermodynamic analysis*
- *DRI kinetics at high $H_2$ concentrations*
- *Assessment of product quality*

**WP2: SOEC module design and control**

- *SOEC module sizing and nominal load design*
- *SOEC thermal management*
- *SOEC control strategy development*

**WP3: SOEC prototype design, construction and testing**

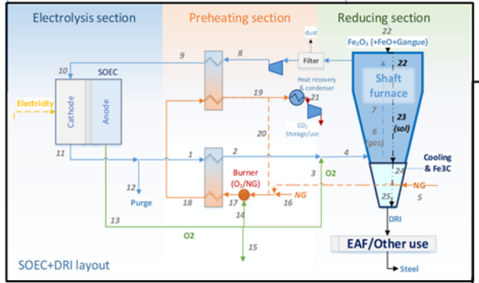
- *Testing in relevant conditions for DRI operation*
- *SOEC prototype design*
- *SOEC prototype fabrication*

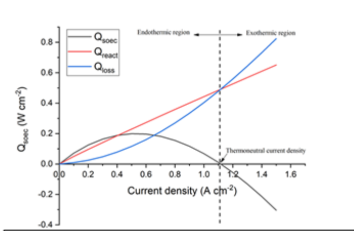
**WP4: Design and characterization of pilot-scale SOEC+DRI process**

- *Design and commissioning of DRI simulator*
- *Integration and commissioning of SOEC module into DRI test bench*
- *Characterization and testing of integrated SOEC+DRI system*

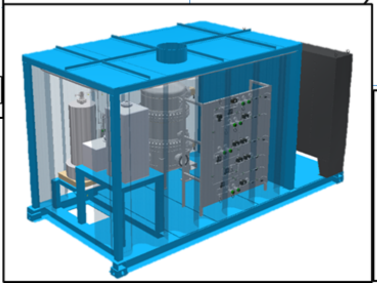
**WP5: Techno-economic optimization of full scale SOEC+DRI layouts**

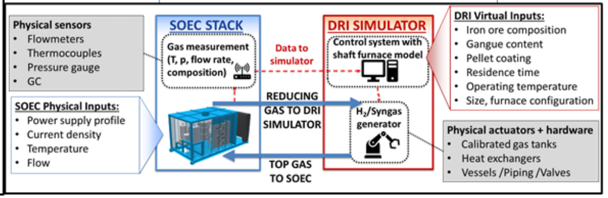
- *Economic and market background build-up*
- *Design and Techno-economic assessment of full-scale system*
- *Comparative assessment with state-of-the-art*
- *Sector coupling assessment*

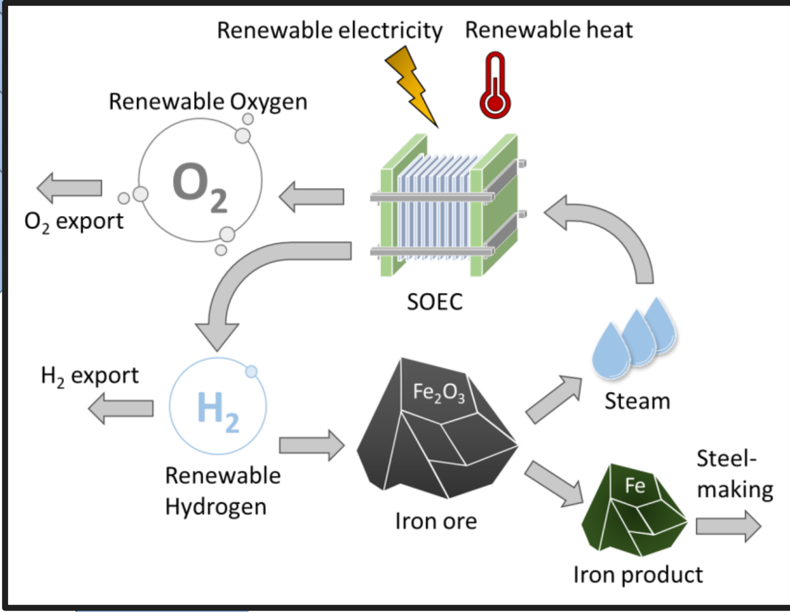


Mastropasqua et al., 2020, Applied Energy 261, 114392





# Hydrogen Direct Reduction (HDR) concept

Voltage = 1.206 V

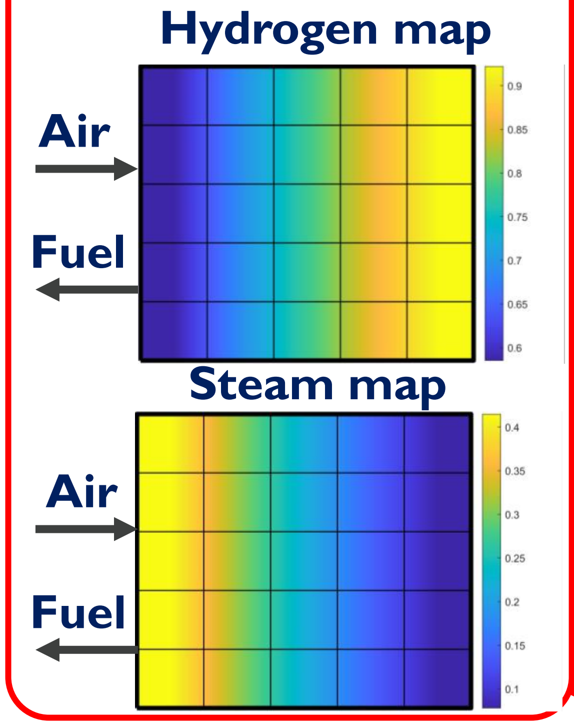
Current Density = 829 A/m2

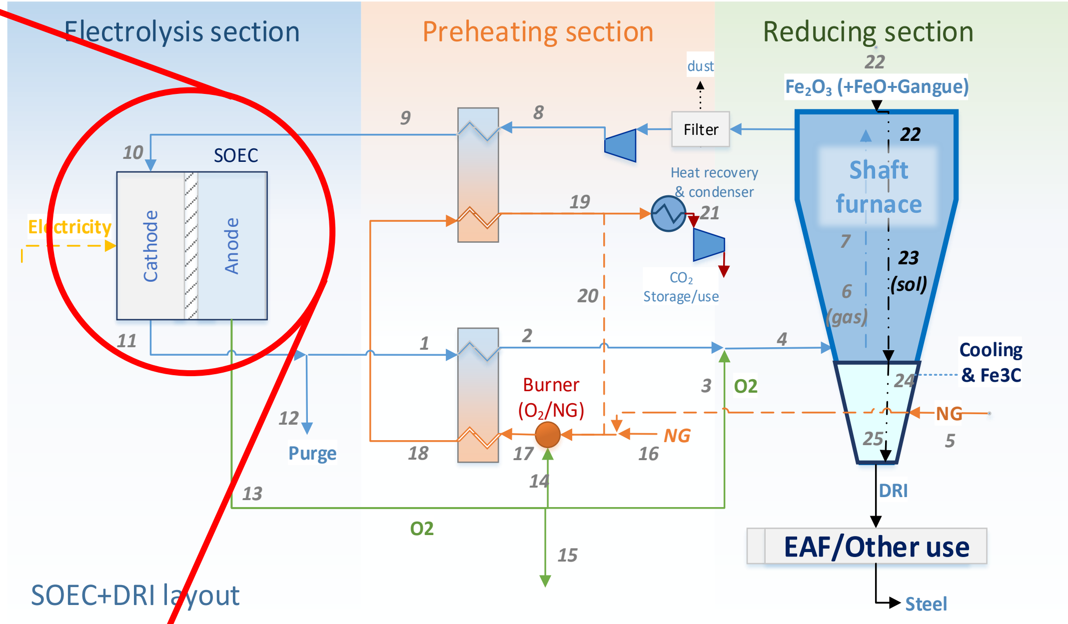
Operating Power = 495 MW

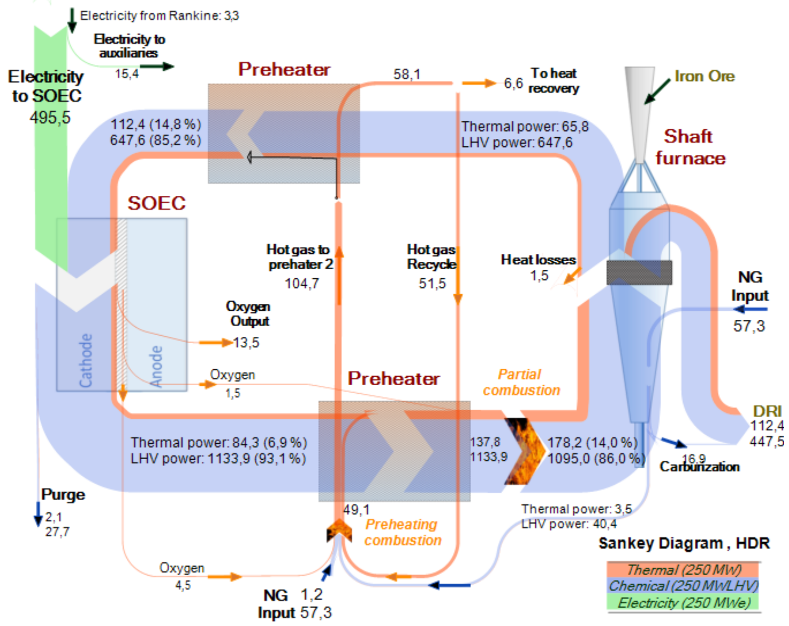
Steam Utilization = 0.8936

Pressure = 7 bar

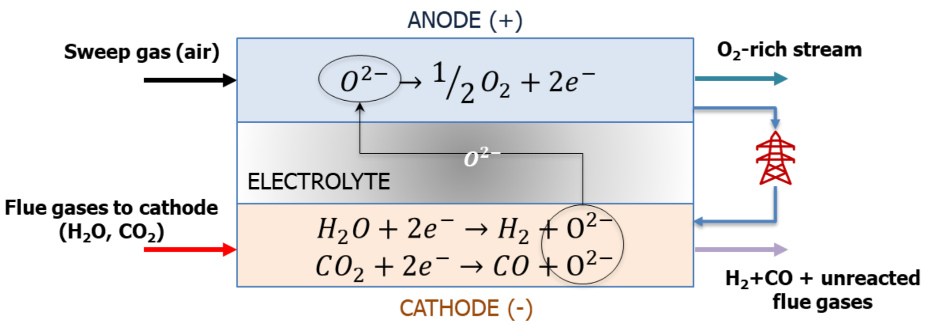
Efficiency = 95%

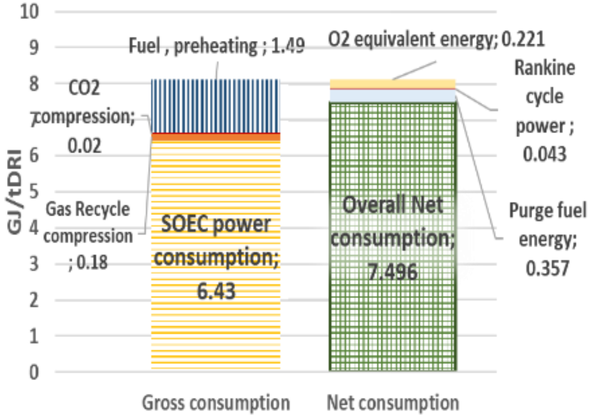


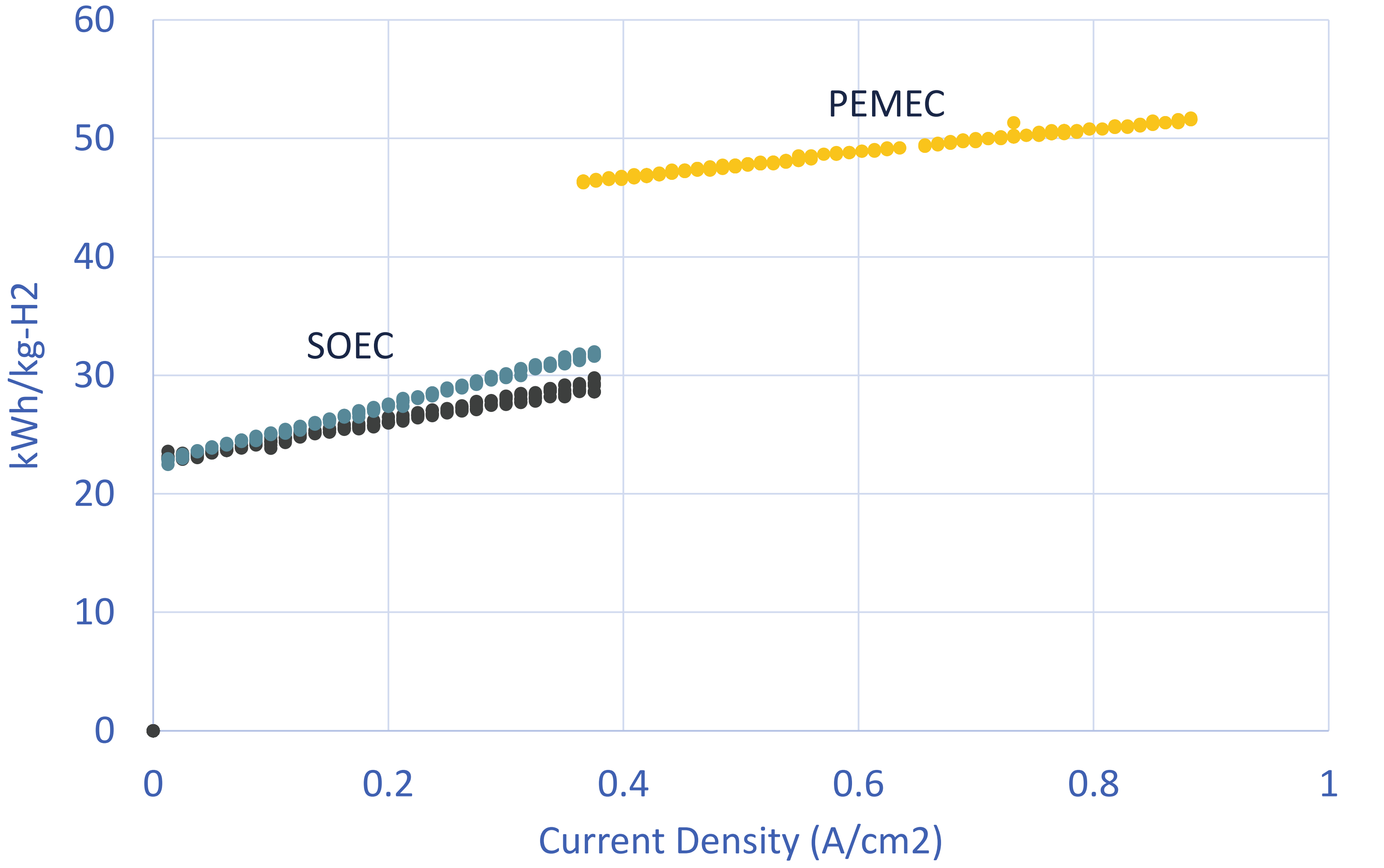

## Steam and co-electrolysis



# Solid Oxide Electrolyzers & Fuel Cells

- Can achieve much higher round-trip efficiency

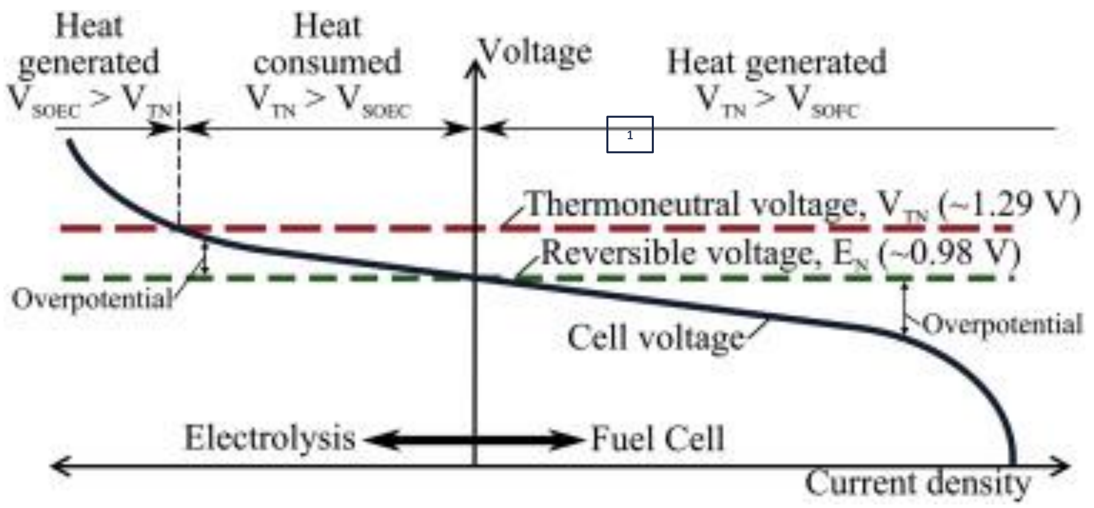


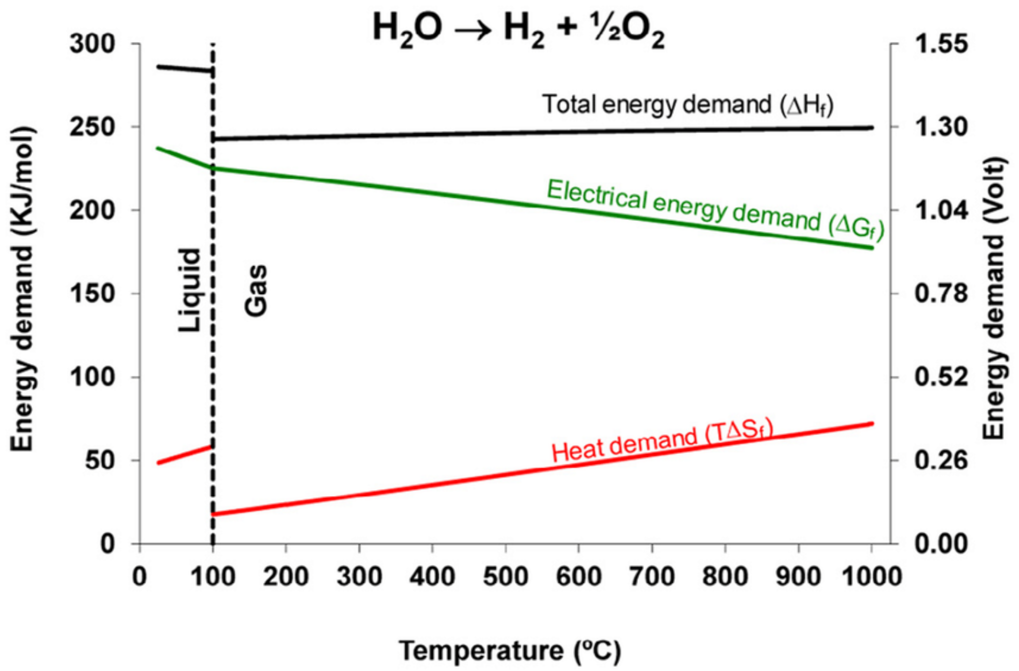

- **SOFC & SOEC systems not known for highly dynamic operation**

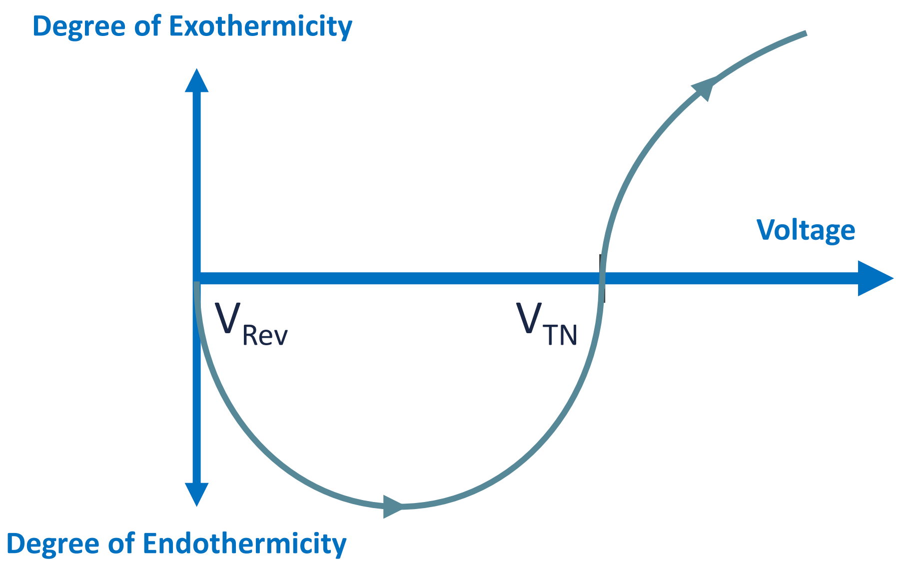
# Solid Oxide Electrolysis Cell/Stack Model

## High Temperature Electrolysis Thermodynamics

- Three possible operating conditions:
  - 1- Thermoneutral (V = VTN) → No heating or cooling
  - 2- Exothermic (V > VTN) → Cooling is required
  - 3- Endothermic (V < VTN) → Heating is required



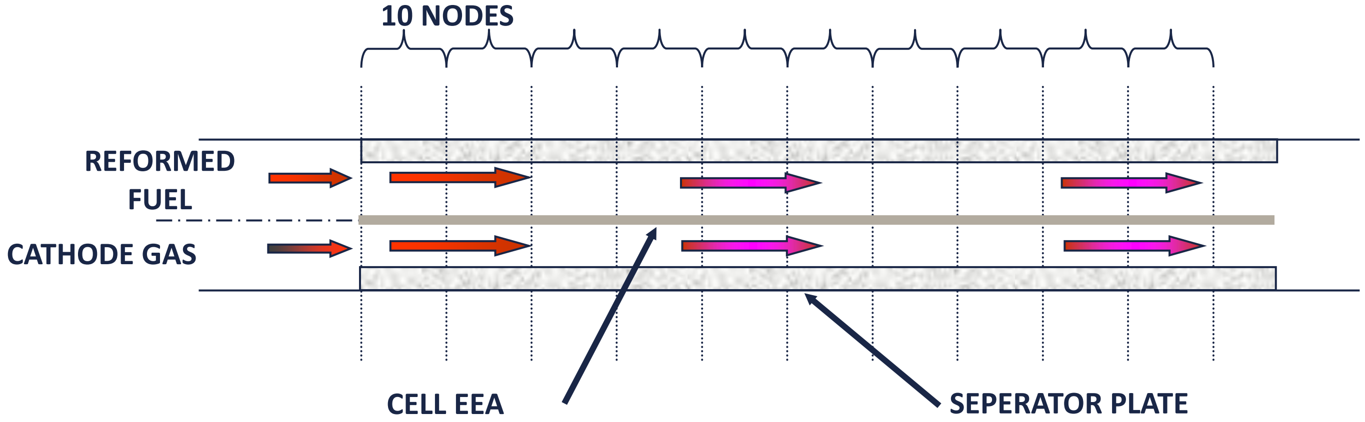



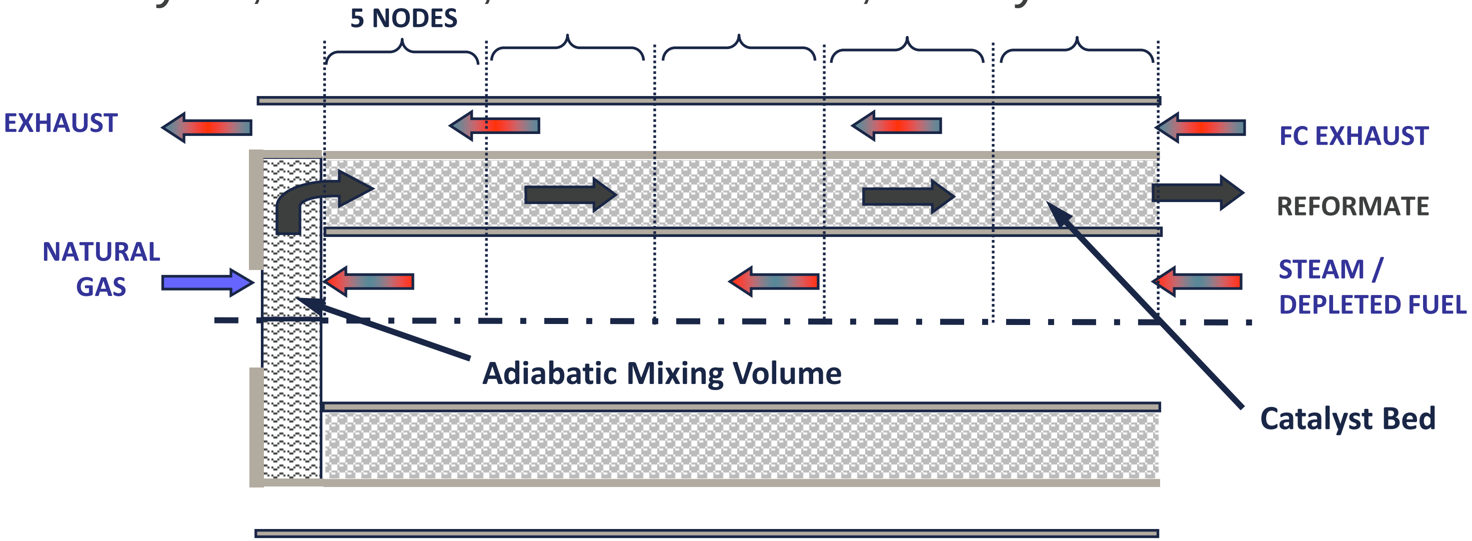

Wendel, C.H., Kazempoor, P. and Braun, R.J.,. Journal of Power Sources, 2016.

# Key Simplification: Limited Geometric Resolution

- Planar SOFC with 10 Discrete Computational Nodes
  - Anode Gas, Cathode Gas, Cell EEA, Separator Plates




- Reformer Module with 5 Discrete Computational Nodes
  - Anode Off-Gas Recycle, Fuel Mix, Combustor HX, Catalyst Bed

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# Sample Dynamic Conservation Equations

## Species Conservation

$$V\frac{dC_i}{dt} = N_{i_{inlet}} - N_{i_{outlet}} + R_i$$

## Momentum Conservation

$$V\frac{d(\rho\bar{v})}{dt} = P_{inlet}A_{inlet} - P_{outlet}A_{outlet} - F_s$$

## Nernst Equation

$$E = E^{\circ} + \frac{R_u T}{nF}\ln\left[\frac{[y_{H2}][y_{O2}]^{1/2}[y_{CO2,c}]P^{1/2}}{[y_{H2O}][y_{CO2,a}]}\right], P_c = P_a = P$$

## Electrochemical Losses

$$L_R = R_{cell}\, i$$

$$L_A = \frac{R_u T}{n\alpha F}\ln(i/i_o)$$

$$L_C = -\frac{R_u T}{nF}\ln(1 - i/i_L)$$

## Cell Voltage

$$Vcell = E - L_R - L_C - L_A$$

## Sample Mass Conservation Equations

$$\begin{cases} C_{out} = \dfrac{P_{out}}{RT_{out}} \\[2ex] N_{out} = N_{in} + N_R - \dfrac{d(C_{out}V)}{dt} \\[2ex] (X_{H2})_{out} = \dfrac{N_{in}(X_{H2})_{in} + R_{H2} - \dfrac{d(C_{H2}V)}{dt}}{N_{out}} \\[2ex] (X_{CO2})_{out} = \dfrac{N_{in}(X_{CO2})_{in} + R_{CO2} - \dfrac{d(C_{CO2}V)}{dt}}{N_{out}} \\[2ex] (X_{H2O})_{out} = \dfrac{N_{in}(X_{H2O})_{in} + R_{H2O} - \dfrac{d(C_{H2O}V)}{dt}}{N_{out}} \\[2ex] (X_{N2})_{out} = \dfrac{N_{in}(X_{N2})_{in} - \dfrac{d(C_{N2}V)}{dt}}{N_{out}} \end{cases}$$

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Roberts, R., Mason, J., Jabbari, F., Brouwer, J., Samuelsen, S., Liese, E. and Gemmen, R., ASME Paper Number 2003-GT-38774, 2003.

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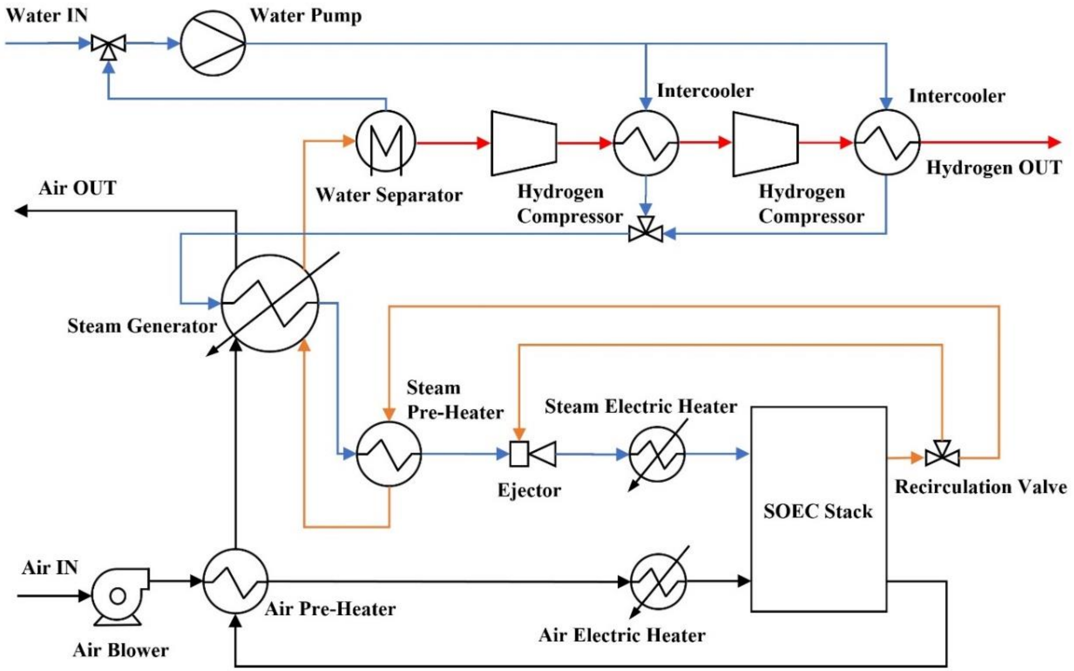
# SOEC System Model & Control Strategies

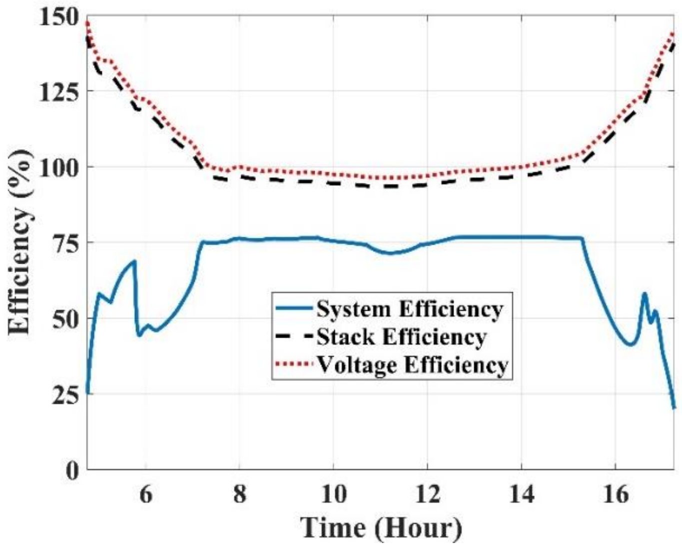


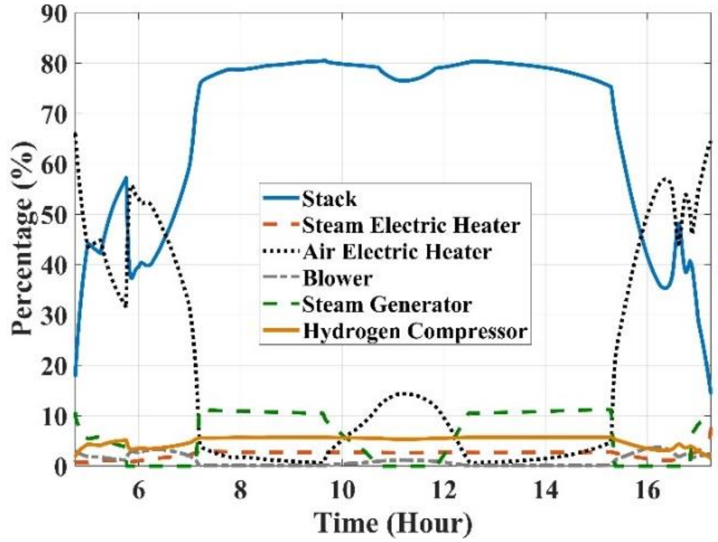

| Controlled Parameter | Manipulated Variable | Controller Type |
|---|---|---|
| Stack Average Temperature | Air Electric Heater Power | PI Feedback Loop Controller |
| Stack Temperature Gradient | Blower Power | PI Feedback Loop Controller |
| $H_2$ at Cathode Inlet | Valve Position | PI Feedback Loop Controller |
| Steam Utilization | Water Pump power | Feedforward Controller |
| Power Demand | Current | Feedforward Controller |

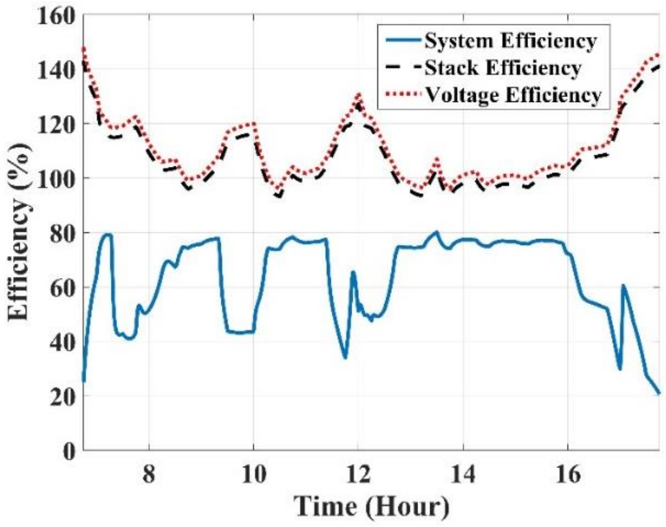


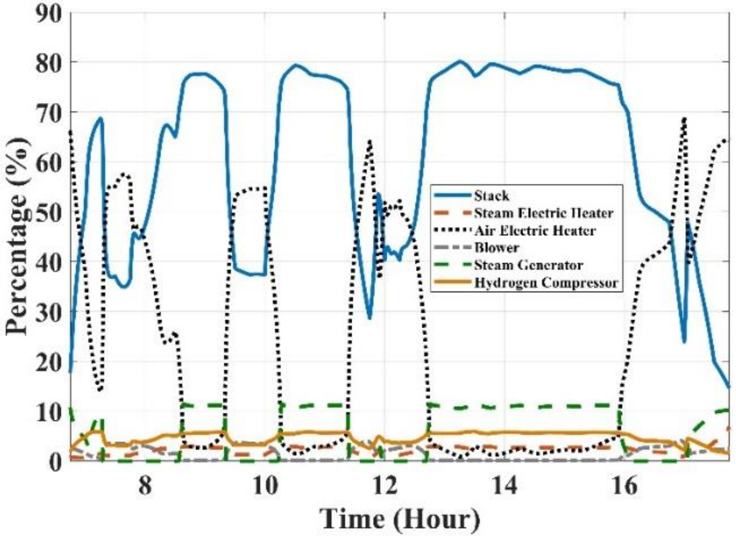
Saeedmanesh, A., Colombo, P., McLarty, D. and Brouwer, J., Journal of Electrochemical Energy Conversion and Storage, 2019.

# Dynamic Operation of SOEC System

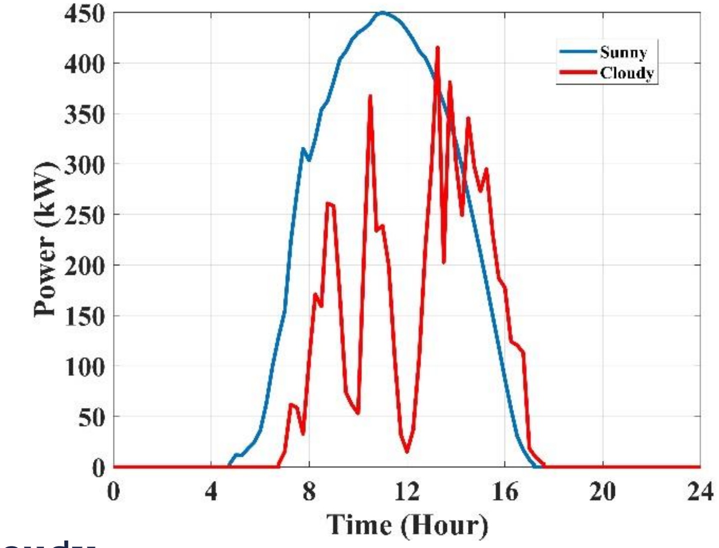


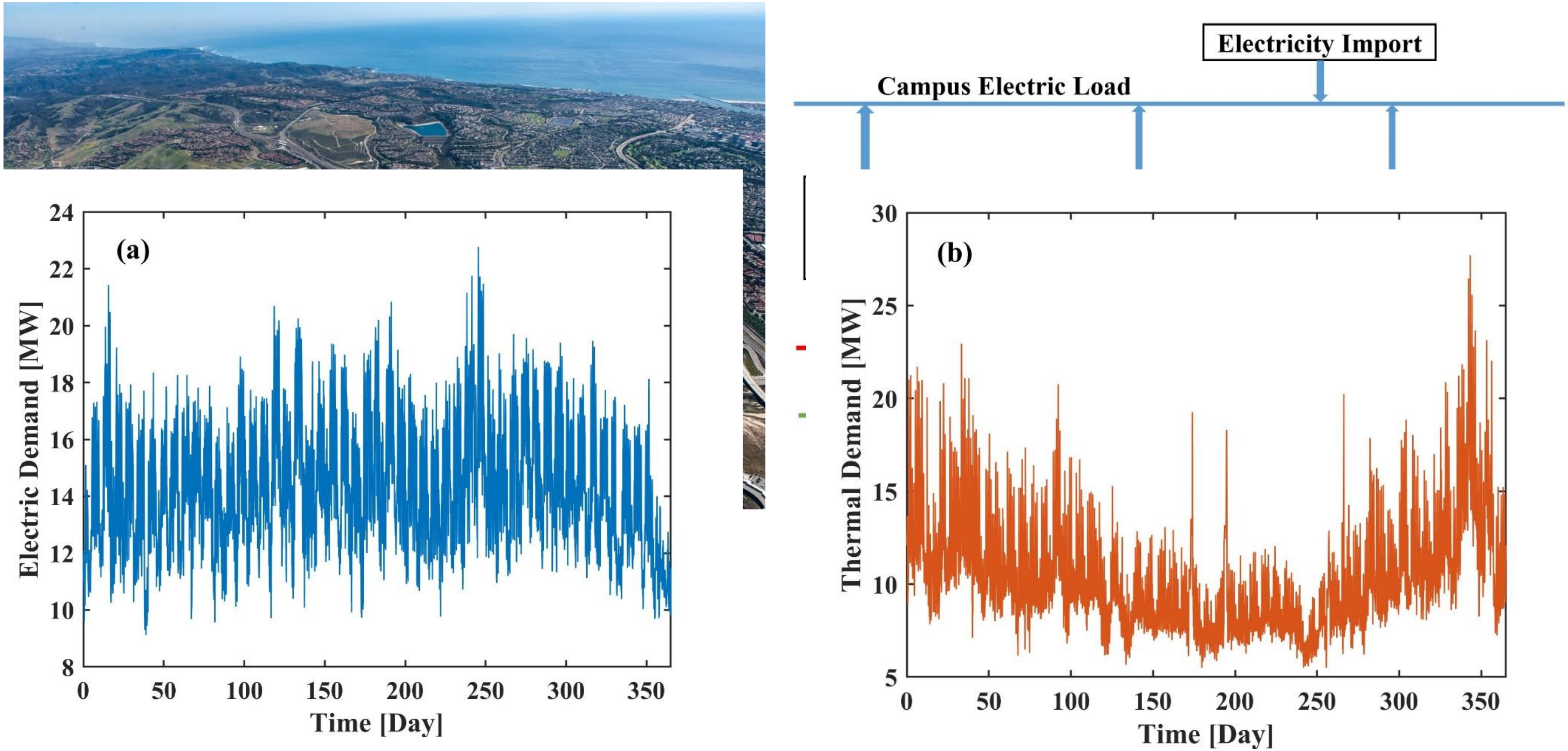

Sunny




Cloudy

Saeedmanesh, A., Colombo, P., McLarty, D. and Brouwer, J., Journal of Electrochemical Energy Conversion and Storage, 2019.

# UCI Microgrid Simulation

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Colombo, P., Saeedmanesh, A., Santarelli, M. and Brouwer, J., Energy Conversion and Management, 2019.

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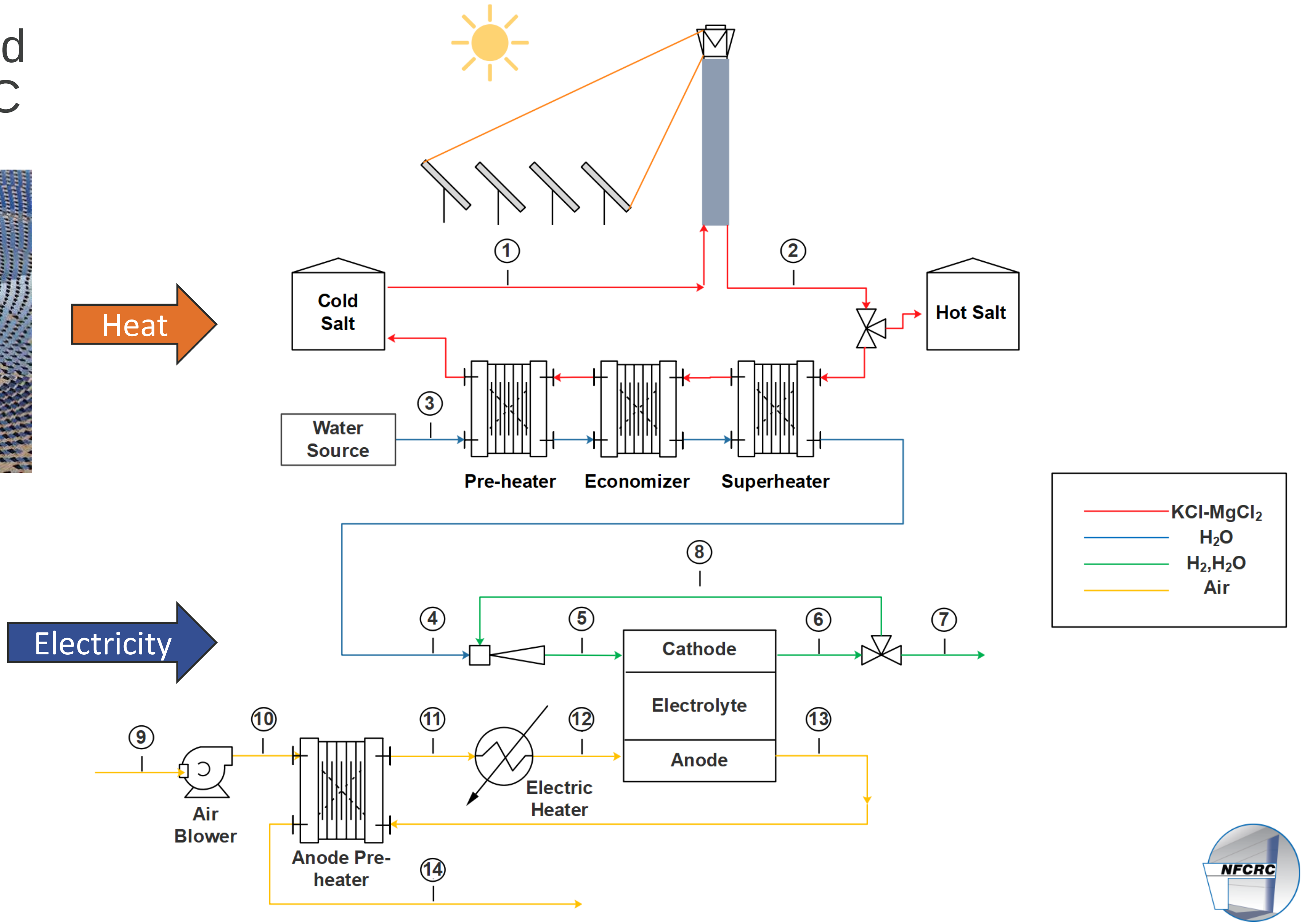
# Concentrated Solar + Solid Oxide Electrolysis

- Integrating concentrated solar energy with SOEC

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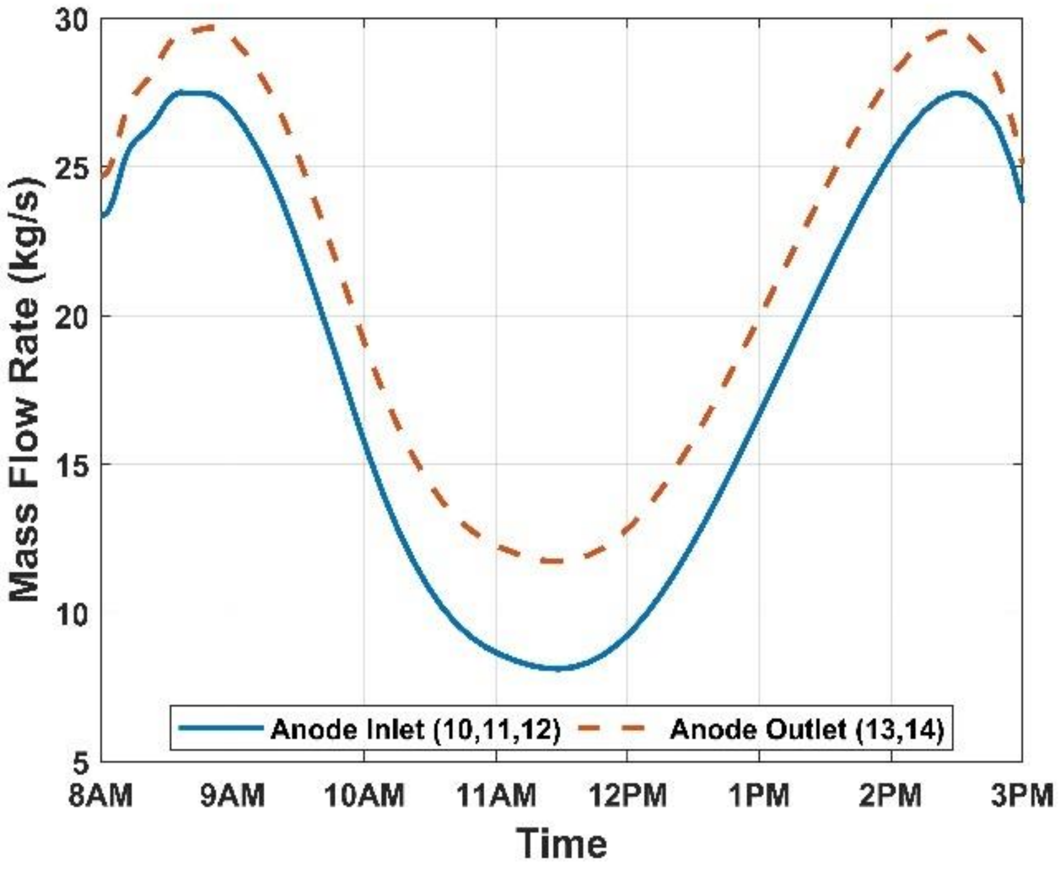
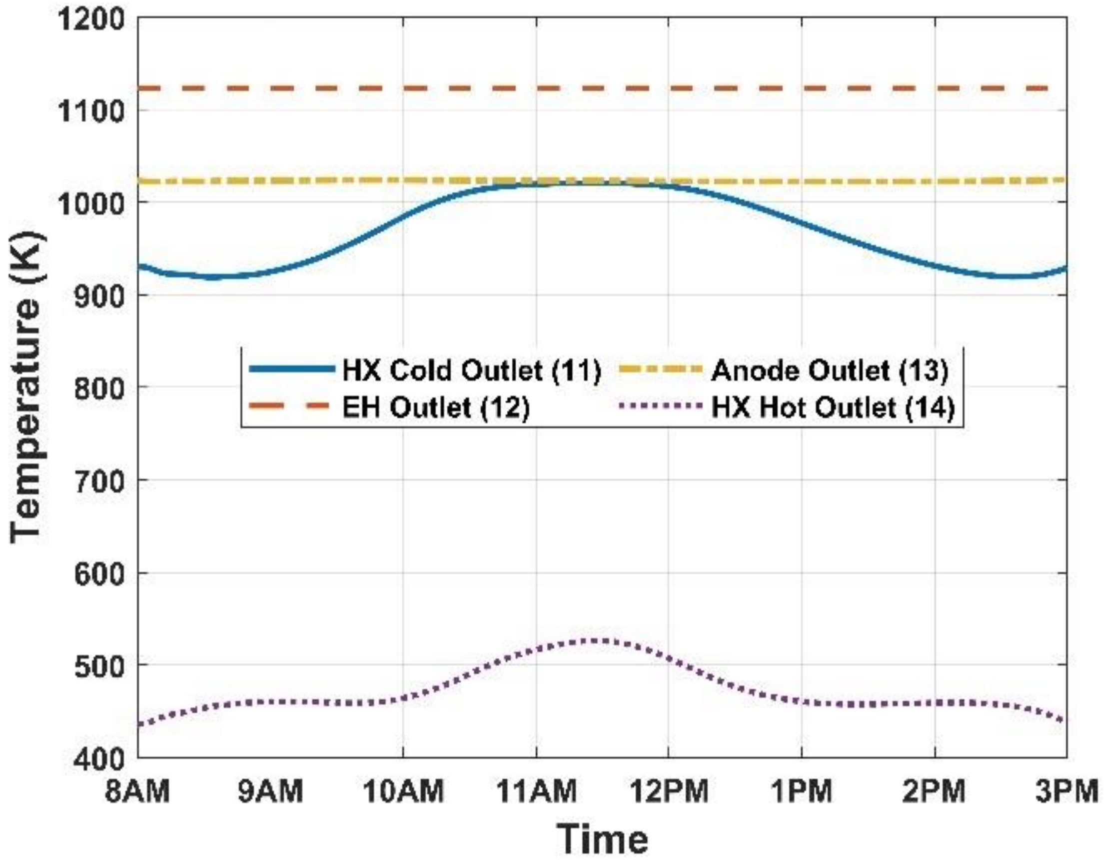
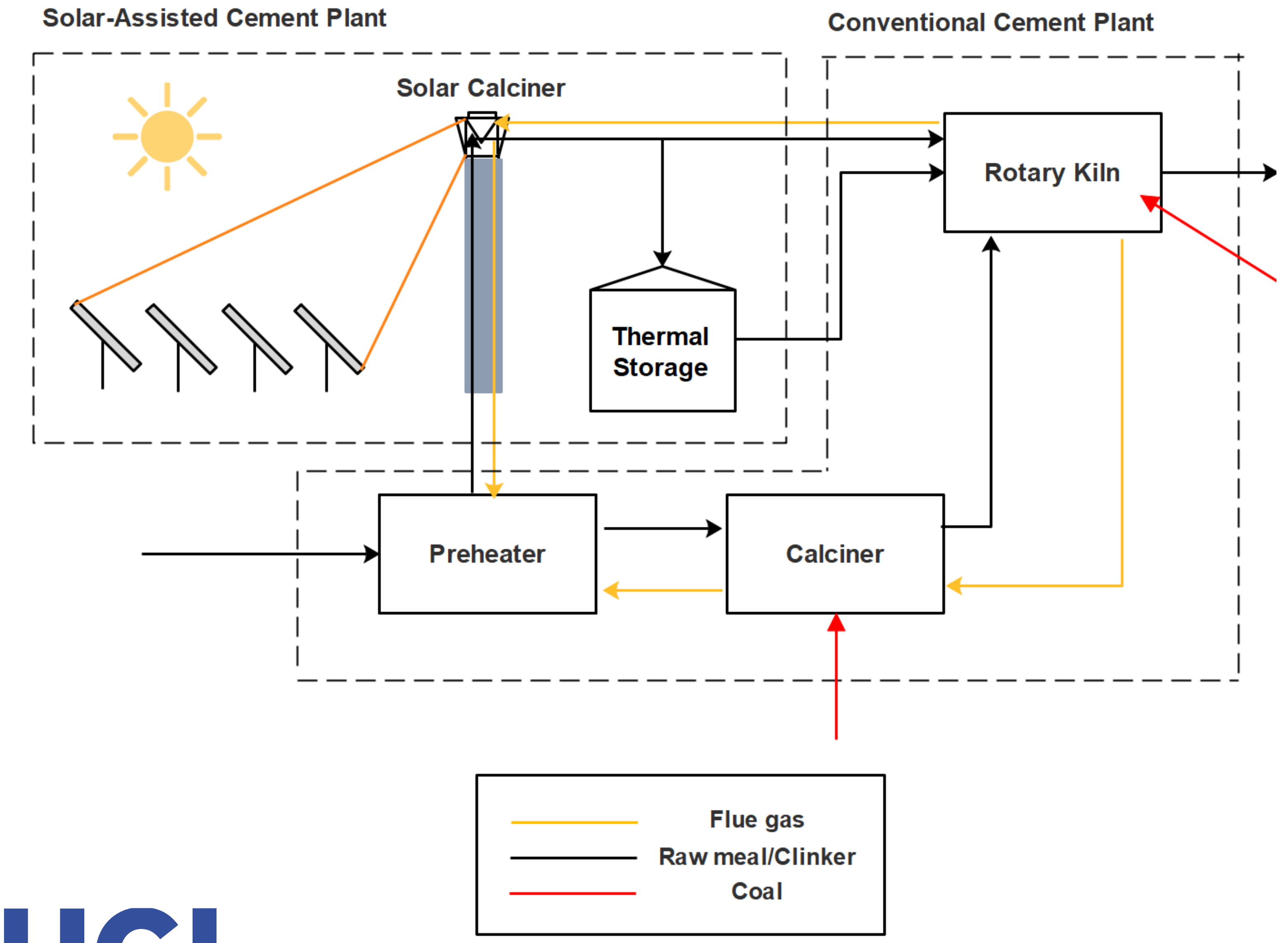
# Concentrated Solar + Solid Oxide Electrolysis

- Integrating concentrated solar energy with solid oxide electrolysis



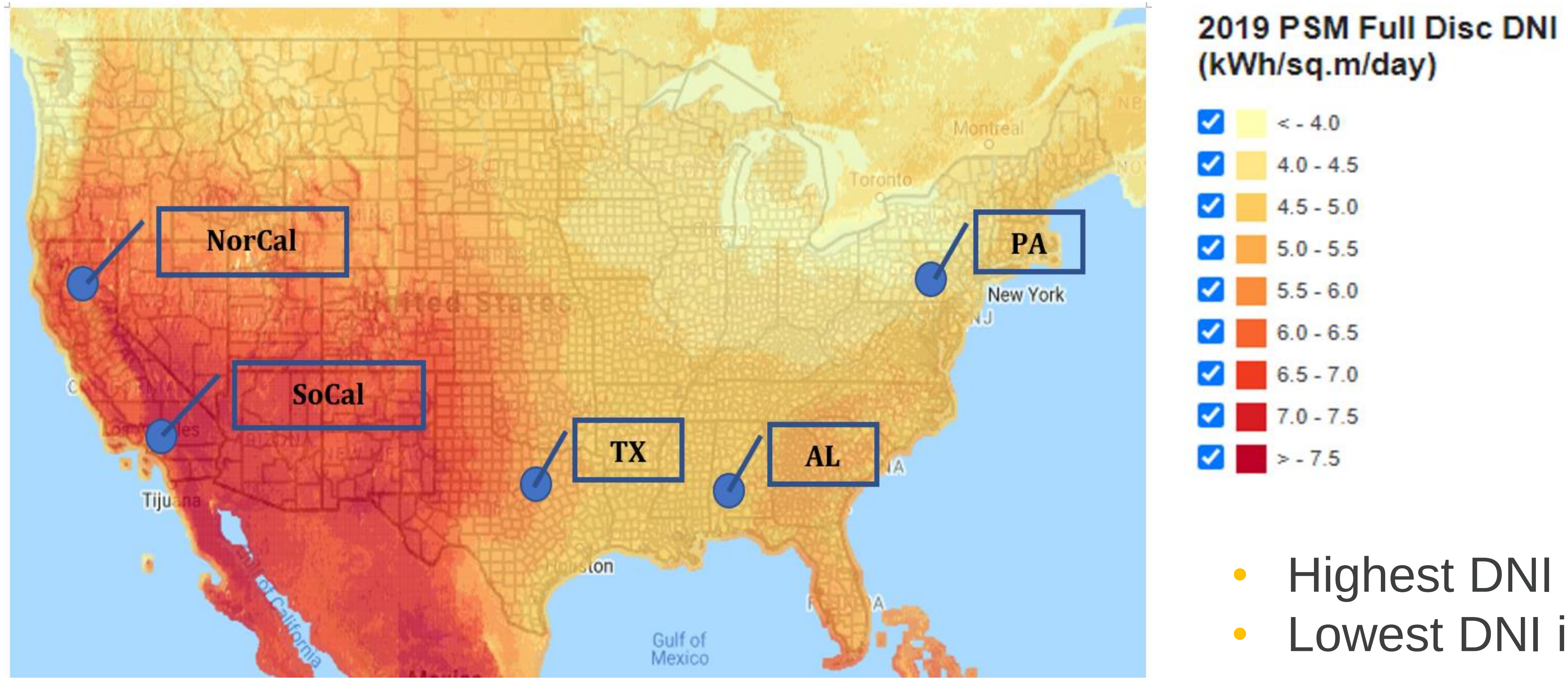
# Integrated CSP + Cement – Plant Layout




**Design conditions:**

- **Design point DNI : 950 W/m2**
- **Steady-state thermal power: 58MW**
- **Solar multiple: 3**
- **Storage capacity: 870 MWh**

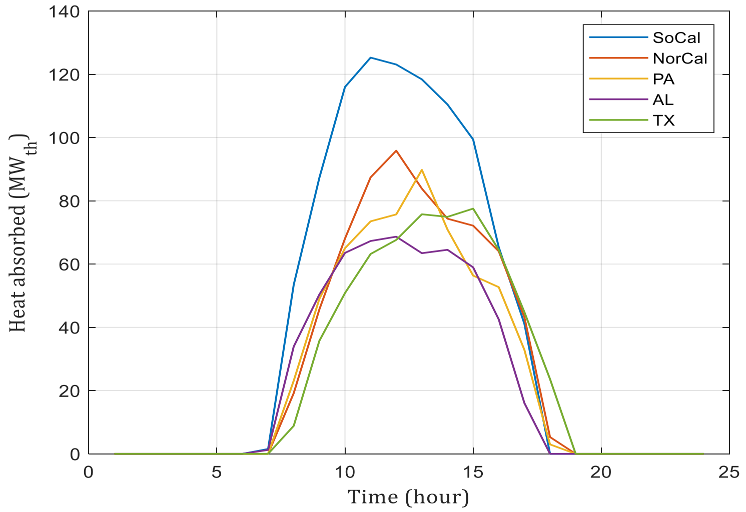
# CSP-Integrated Cement Plant Locations



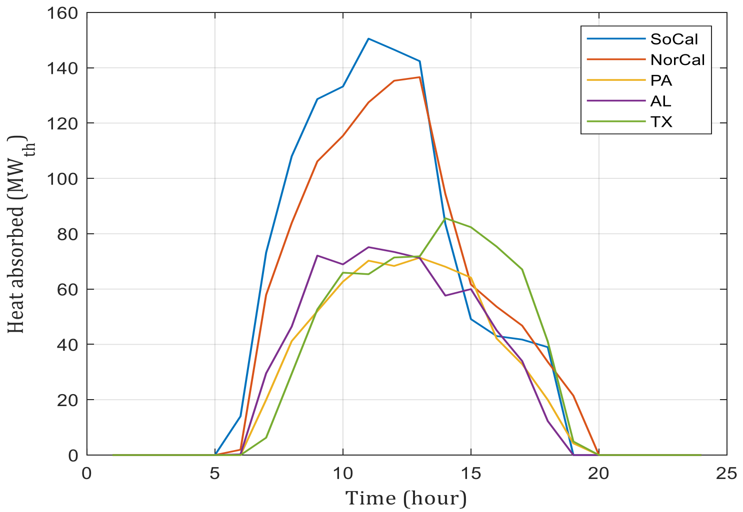

- Highest DNI in California
- Lowest DNI in Pennsylvania

- Five sites investigated
  - Two in California
  - One in Texas
  - One in Alabama
  - One in Pennsylvania

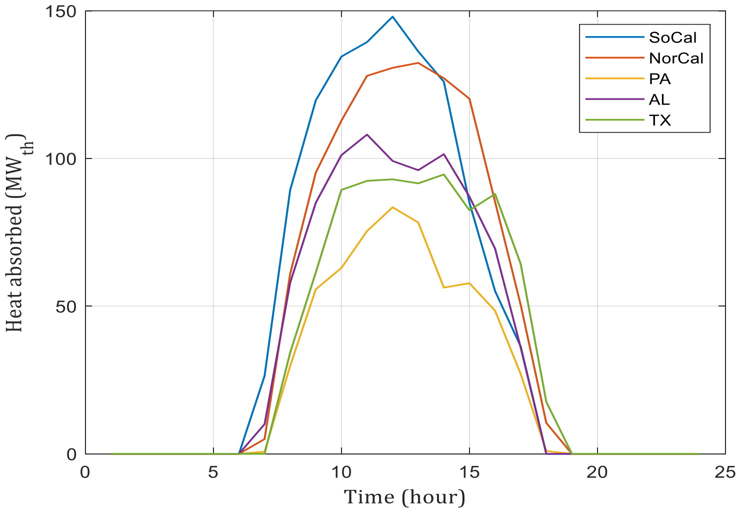
# Average Monthly Solar Profiles in Locations



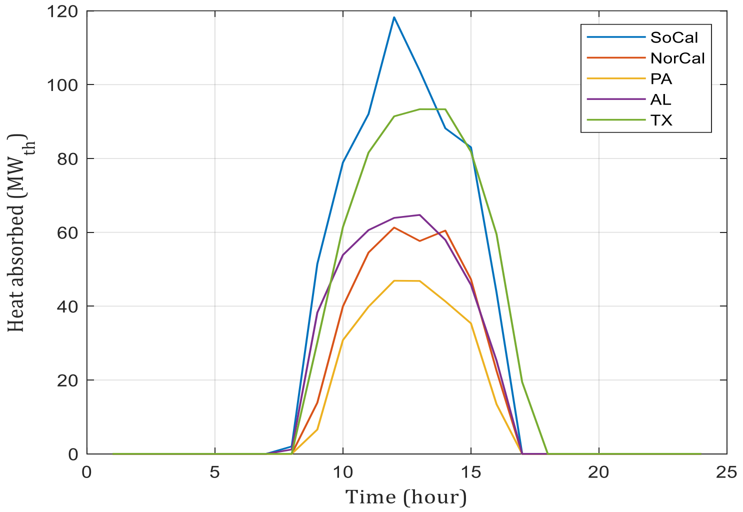

**March**




**June**




**September**

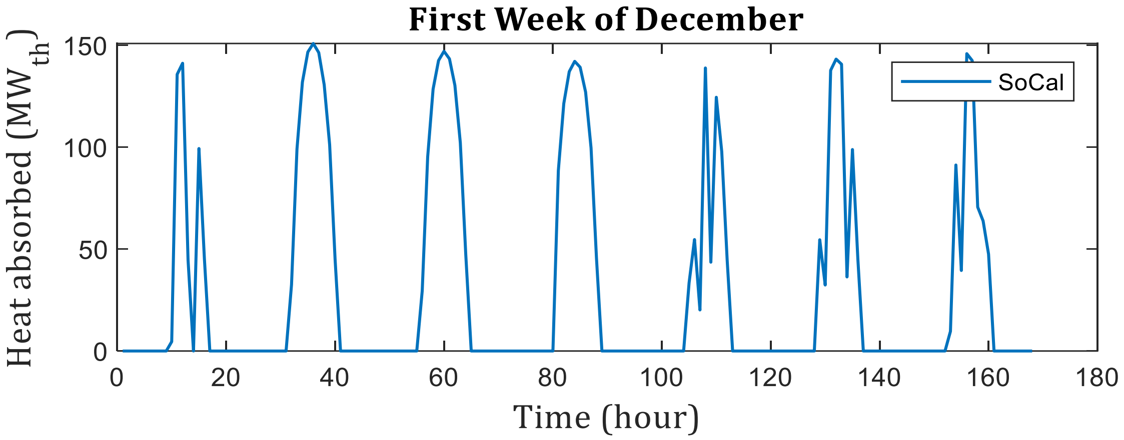


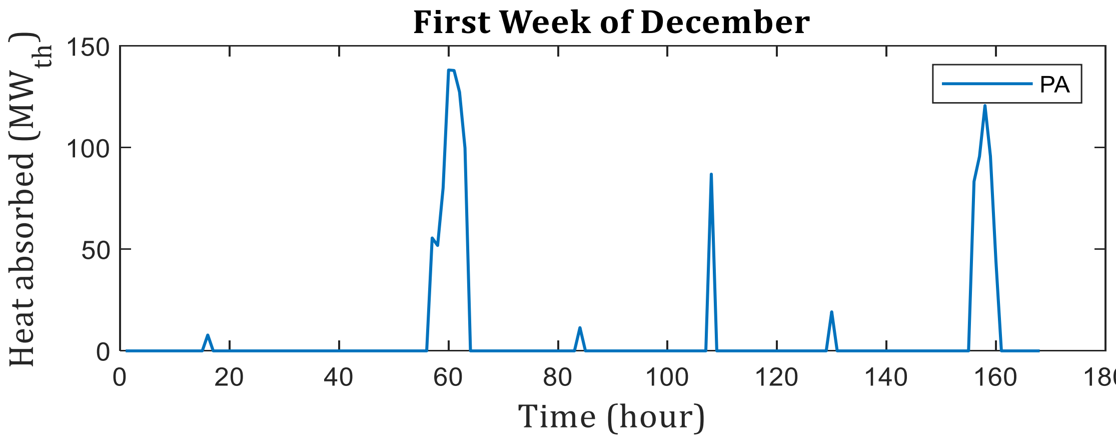

**December**

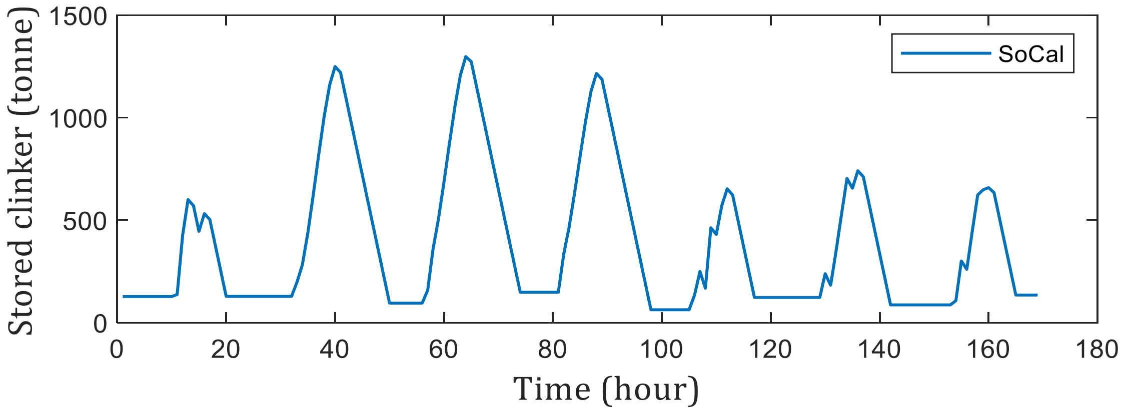
- Heat absorbed profiles for March, June, Sept., Dec.
  - Proportional to DNI profile
- Sudden decrease in afternoon of June for CA plants
  - Due to low heliostat field optical efficiency
- Amount of calcined clinker is proportional to heat absorbed
  - Highest solar-calcined clinker production in the SoCal plant
  - Lowest solar-calcined clinker production in the PA plant.

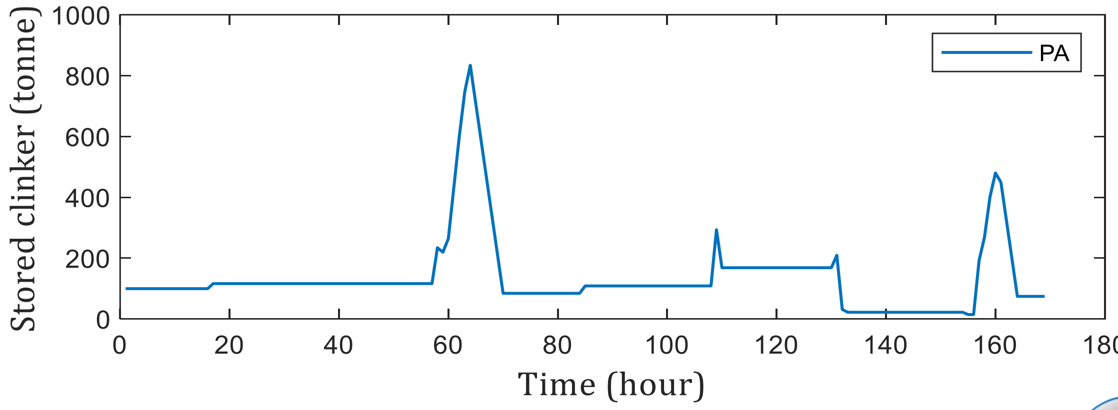
# CSP + Calciner/Clinker Storage – Dynamic Operation

- Solar calciner and storage operation
  - SoCal plant vs. Pennsylvania plant
  - More $CO_2$ reduction for the plant in SoCal.



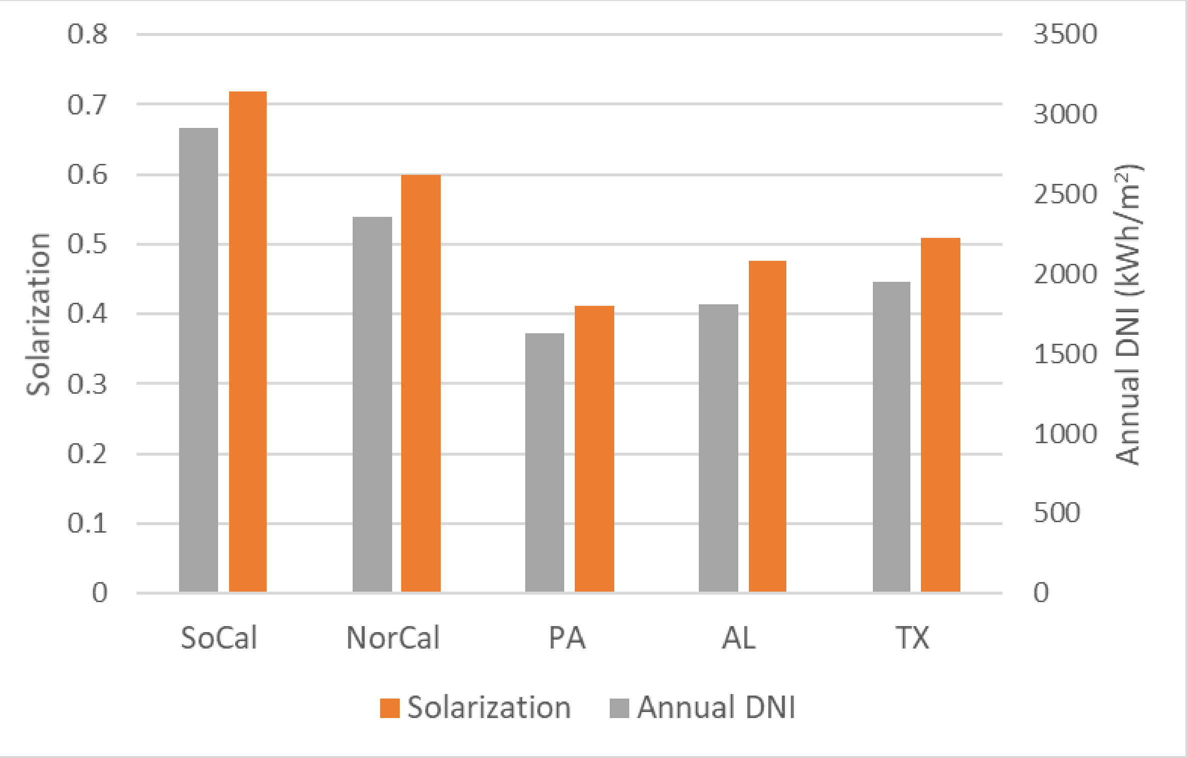



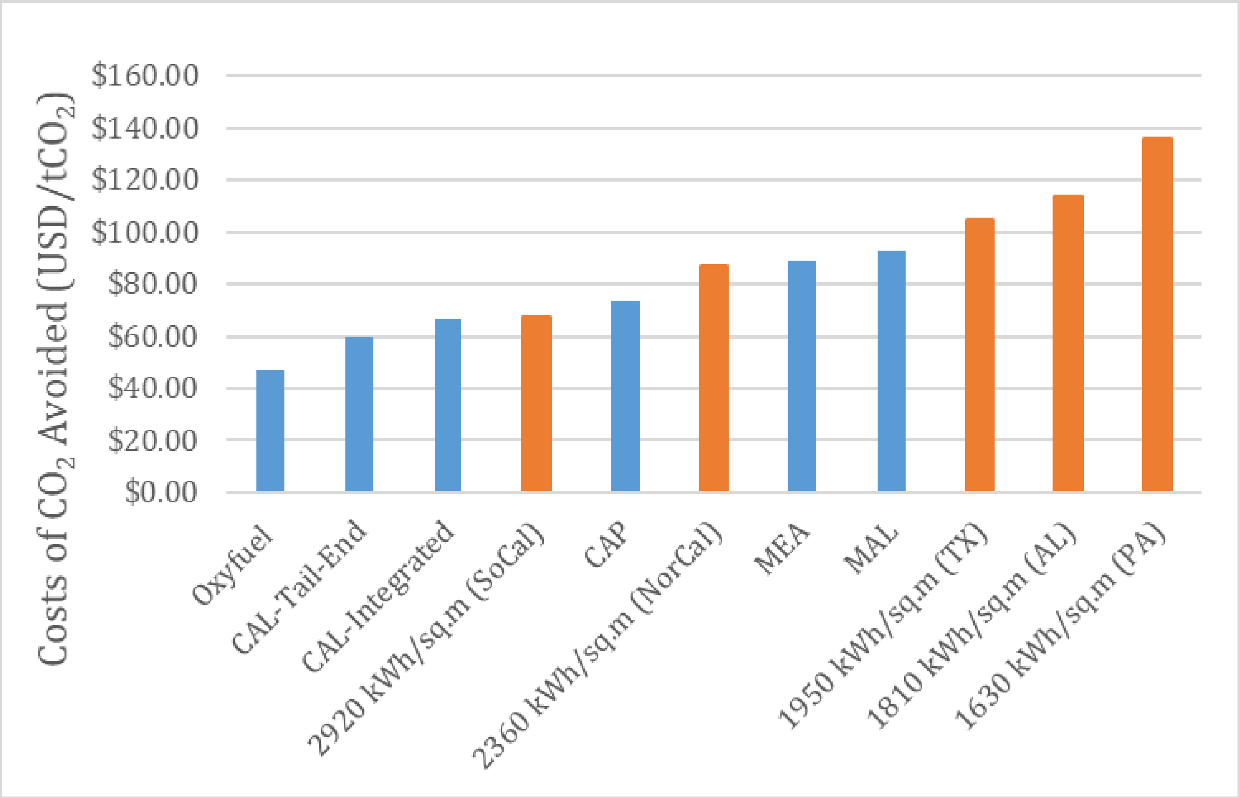
# Annual Results

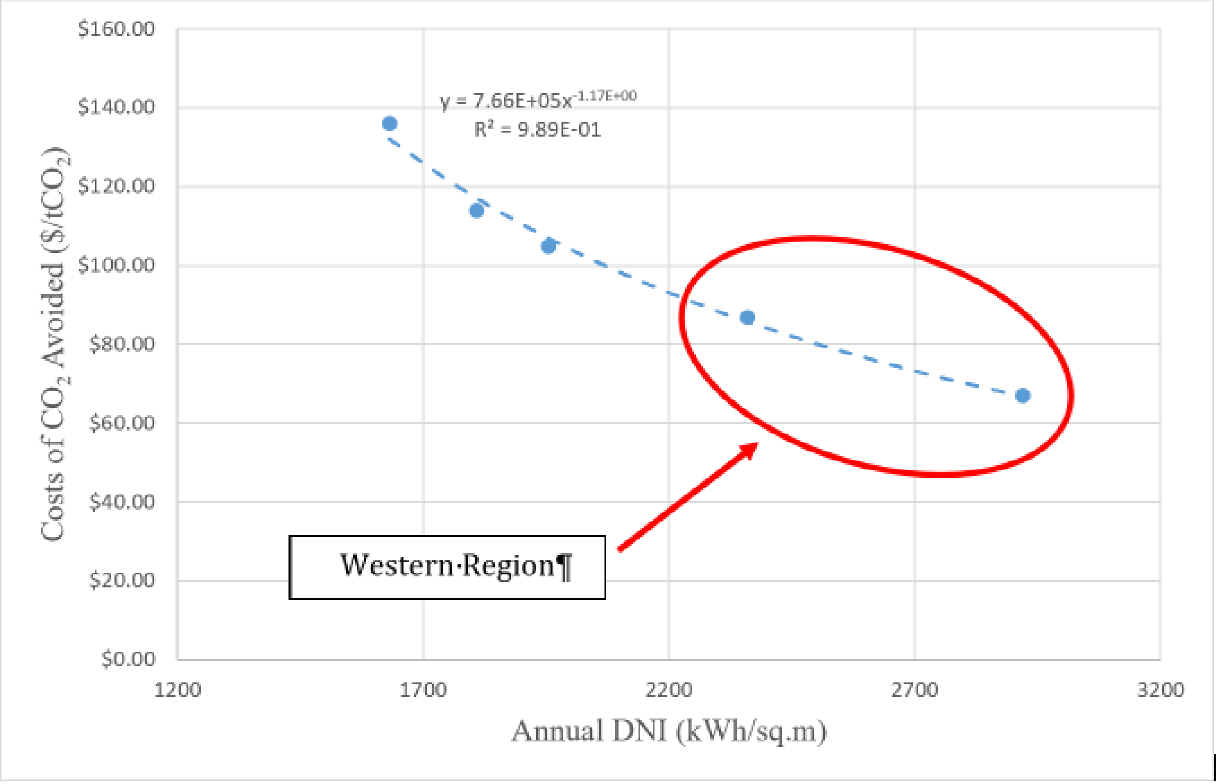
- **Percent solarization and reduction in the emissions**
  - **70% solarization for the plant in SoCal**
    - ✓ **Annual DNI = 3000 kWh/sq.m**
  - **40% solarization for the plant in PA**
    - ✓ **Annual DNI = 1500 kWh/sq.m**




| Location | Percent $CO_2$ emissions reduction (%) | Saved amount of coal (tonne) |
|---|---|---|
| SoCal | 15.1 | 54,445 |
| NorCal | 12.6 | 45,444 |
| PA | 8.63 | 31,116 |
| AL | 9.99 | 36,038 |
| TX | 10.69 | 38,542 |

# Comparison to Alternatives for Cement Decarbonization




CAL: Calcium Looping
CAP: Chilled Ammonia Process
MEA: Monoethanolamine

MAL: Membrane-assisted CO2 Liquefaction

- **CSP integration suitable in California, Arizona, Nevada, and New Mexico**
  - **Annual DNI greater than 2200 kWh/sq.m**

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*from: San Diego Union Tribune*

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