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Optimal Design of Solar Systems for Decarbonizing Industrial Process Heat Applications

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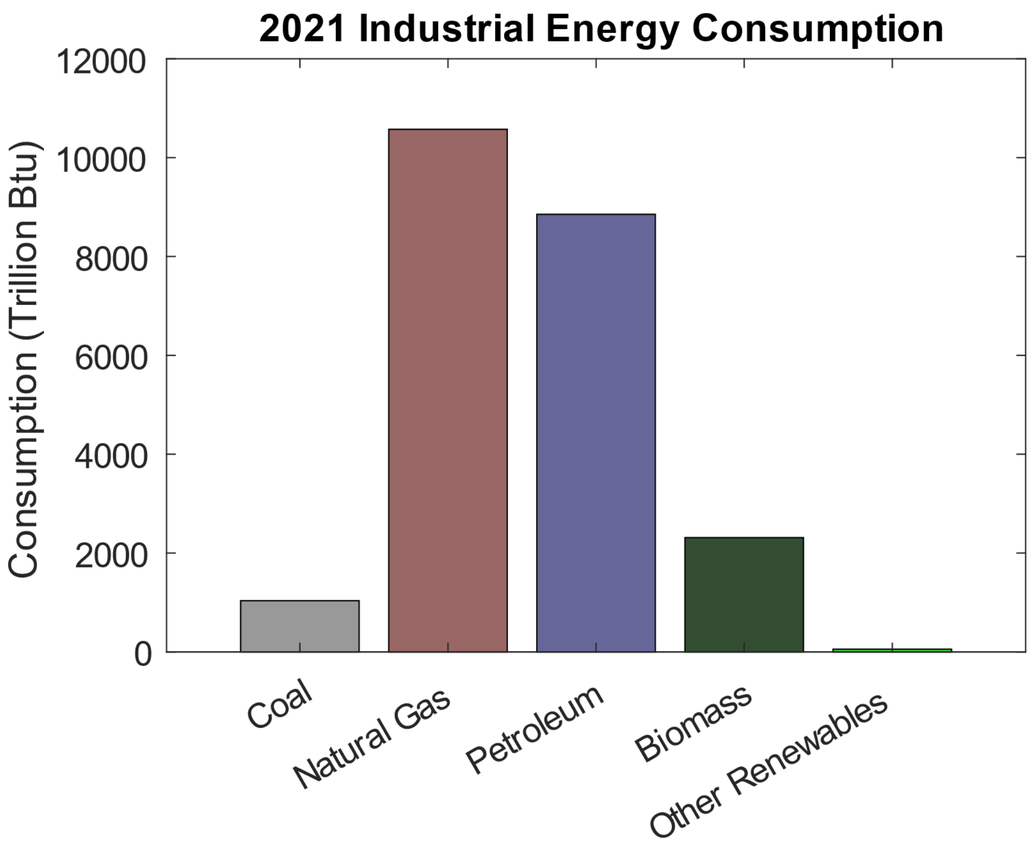
2022 AIChE ANNUAL MEETING

Process Systems and Operations Research Laboratory

Outline

1. Motivation and Background
2. Problem Formulation, Modeling, and Simulation
3. Case Studies
4. Results & Conclusions

Motivation: US industrial fossil fuel consumption



- Fossil Fuels account for almost 90% of industrial energy[1]
- Non-biomass renewables accounted for 42 trillion Btu (<0.2%)[1]
- Industrial process heat (IPH) uses 7,500 trillion Btu annually[1] (~36% of total energy consumption of mfg. sector)[2]

[1] October Monthly Energy Review, US EIA, pg.45 (2022)
[2] Renewable Heating and Cooling: Renewable IPH, US EPA (2022)

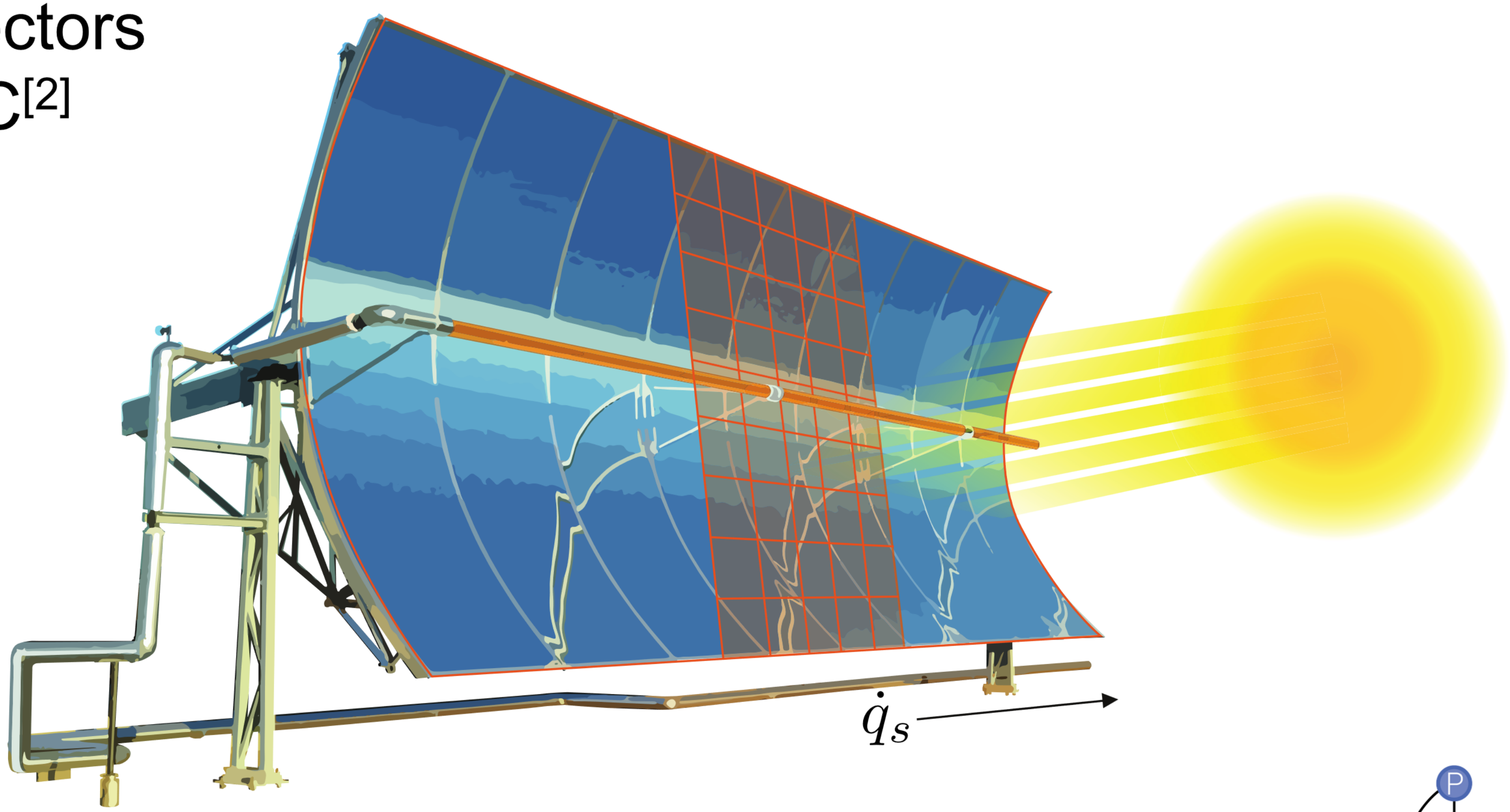
Motivation: Low Temperature IPH Hybridization

- 50% of IPH is below 300°C[2]

[3] Margolis, McMillan, Kurup. Solar for Industrial Process Heat, *EERE SETO CSP Program Summit* (2019)

Motivation: Low Temperature IPH Hybridization

- 50% of IPH is below 300°C[2]
- Parabolic Trough Collectors (PTC) can reach 550°C[2]



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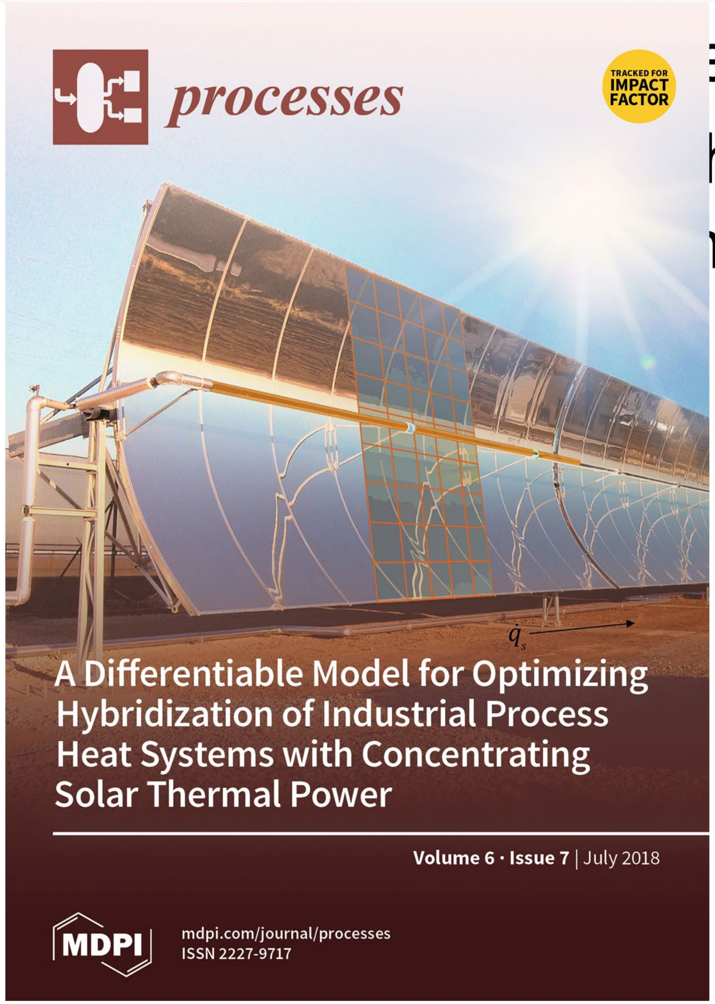
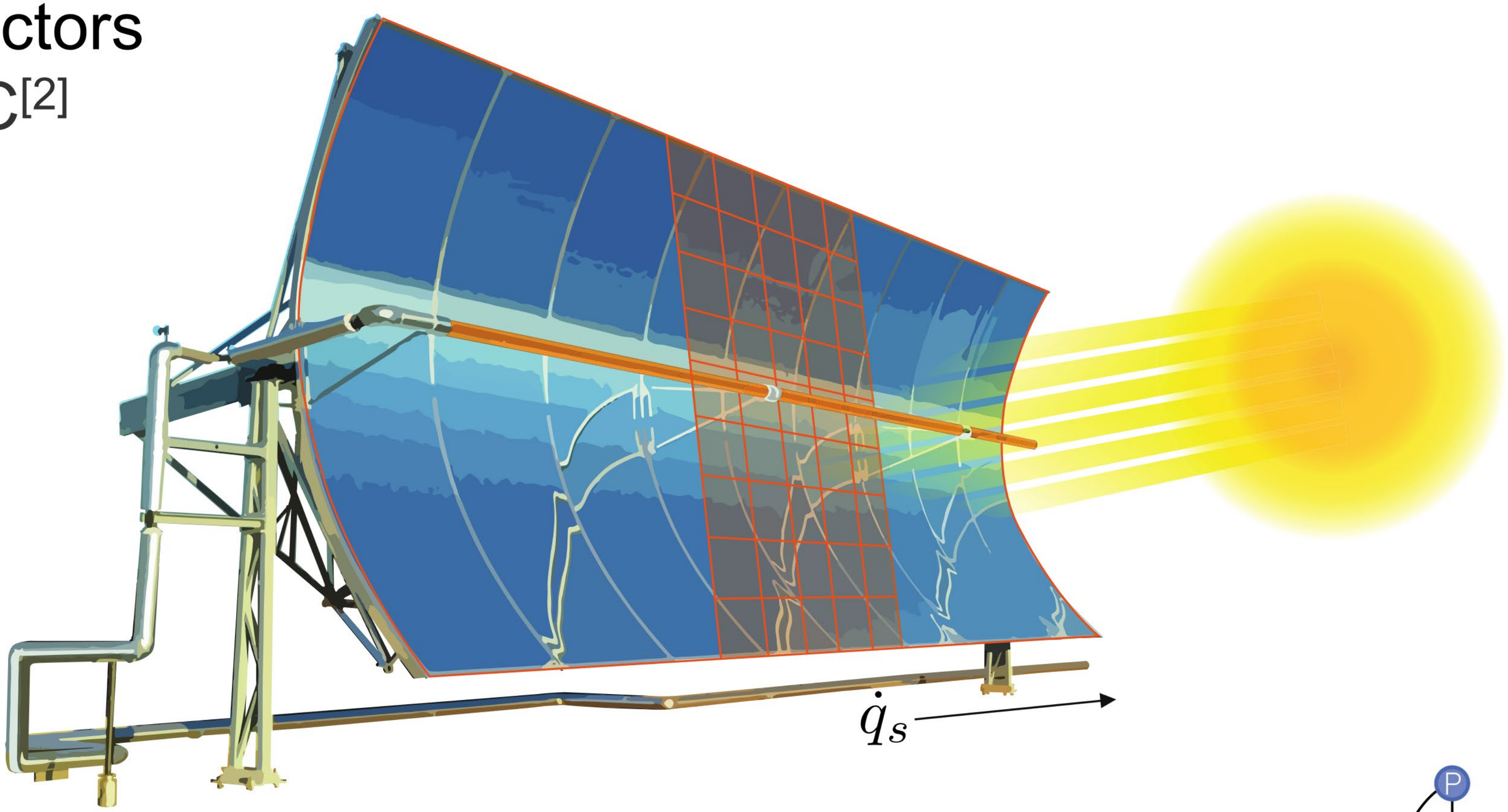
Motivation: Low Temperature IPH Hybridization

elow 300°C[2]

h Collectors

550°C[2]

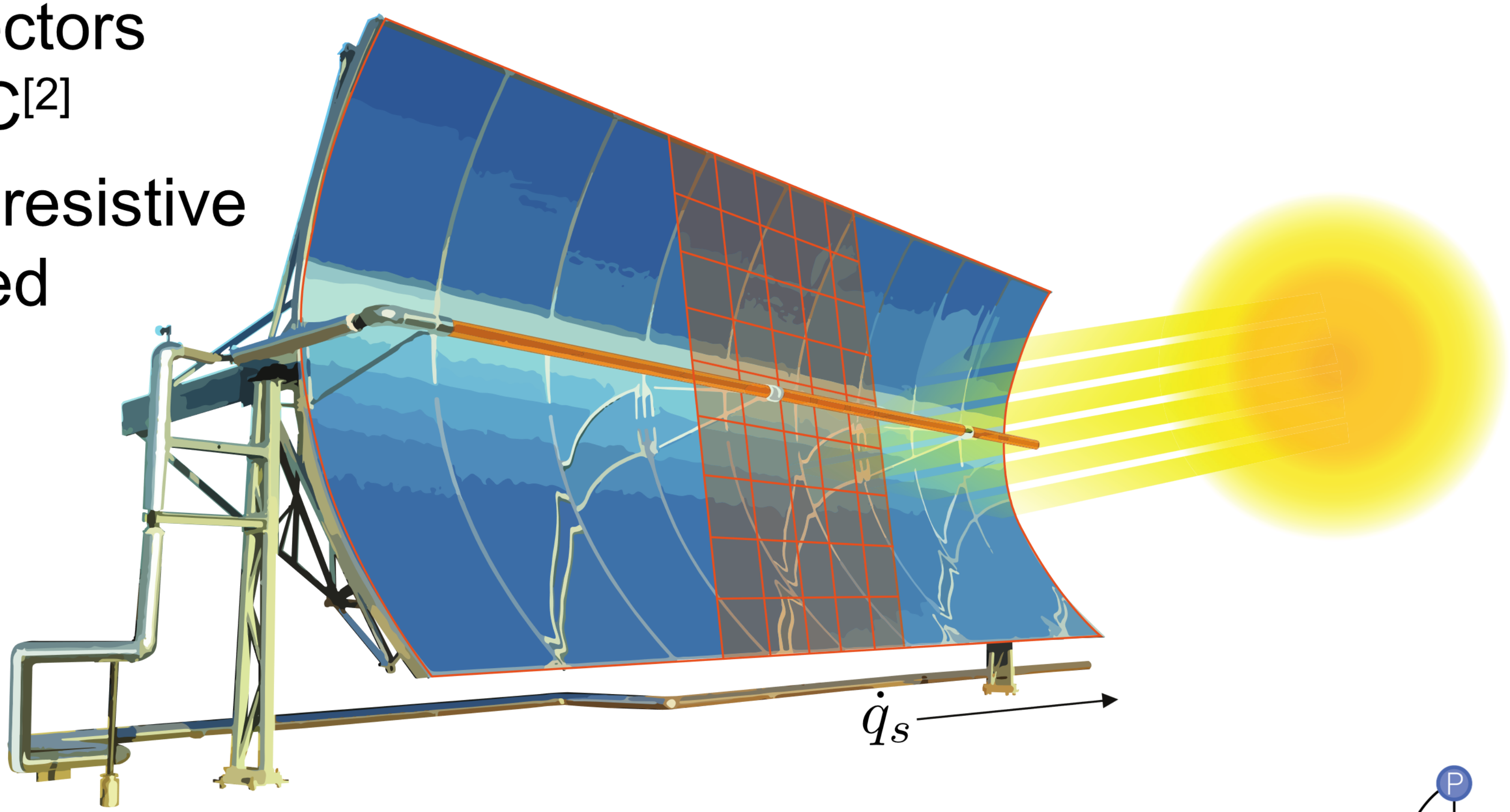




Stuber, MD. *Processes*, 6,7 (2018)

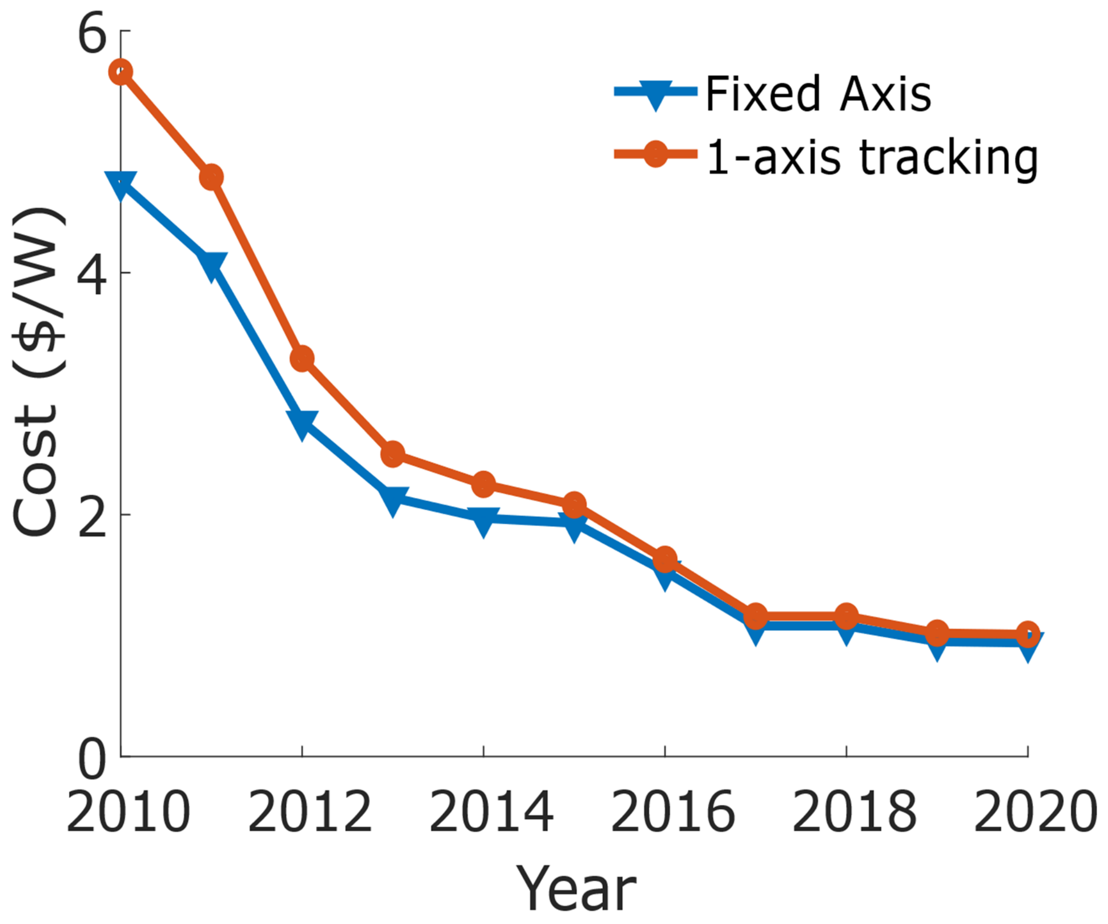
Motivation: Low Temperature IPH Hybridization

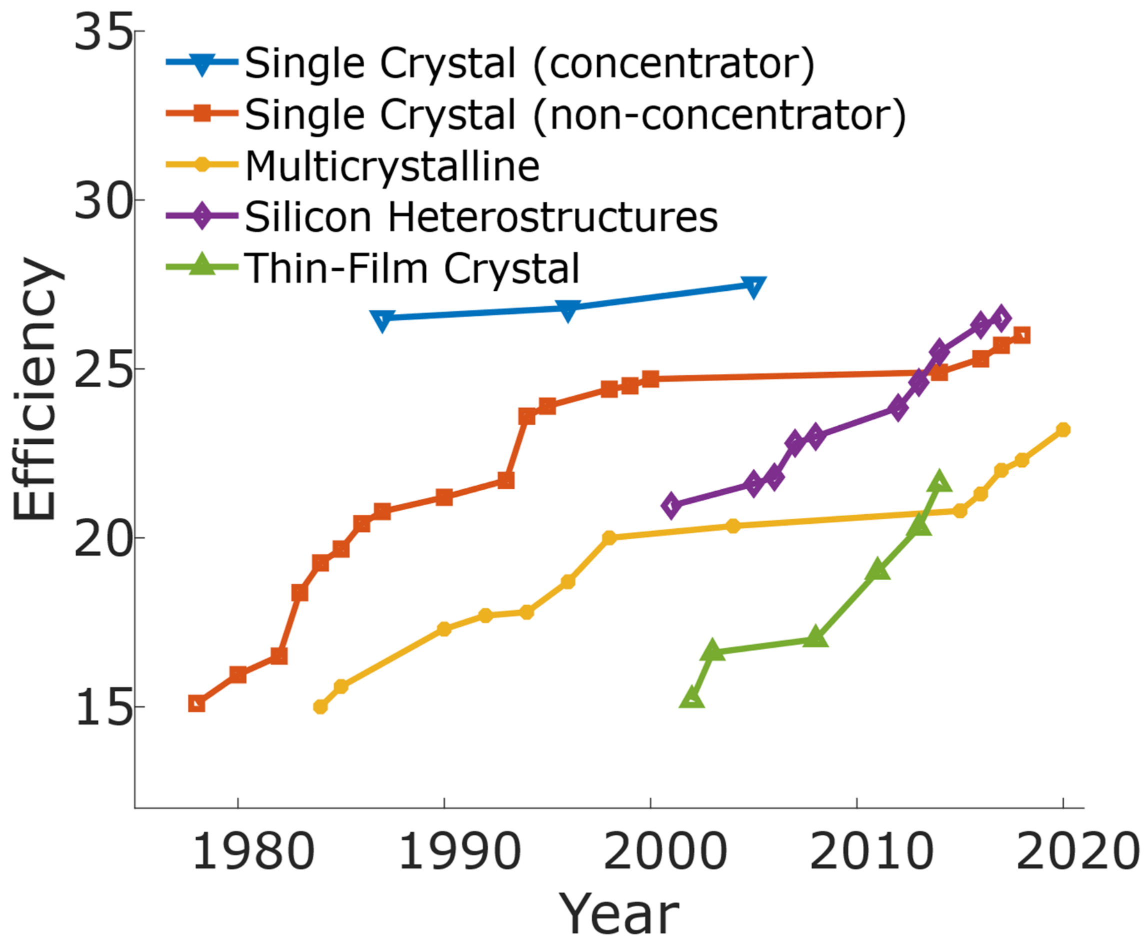
- 50% of IPH is below 300°C[2]
- Parabolic Trough Collectors (PTC) can reach 550°C[2]
- Photovoltaics can use resistive heating to reach desired temperatures



[3] Margolis, McMillan, Kurup. Solar for Industrial Process Heat, *EERE SETO CSP Program Summit* (2019)

Background: PVs Cost Reductions

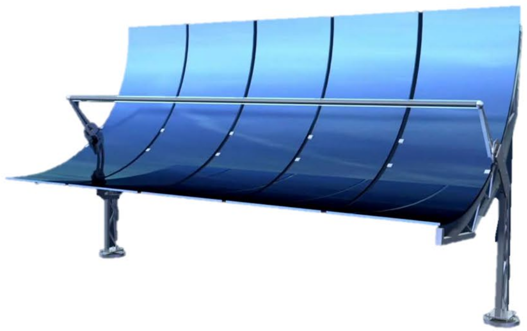




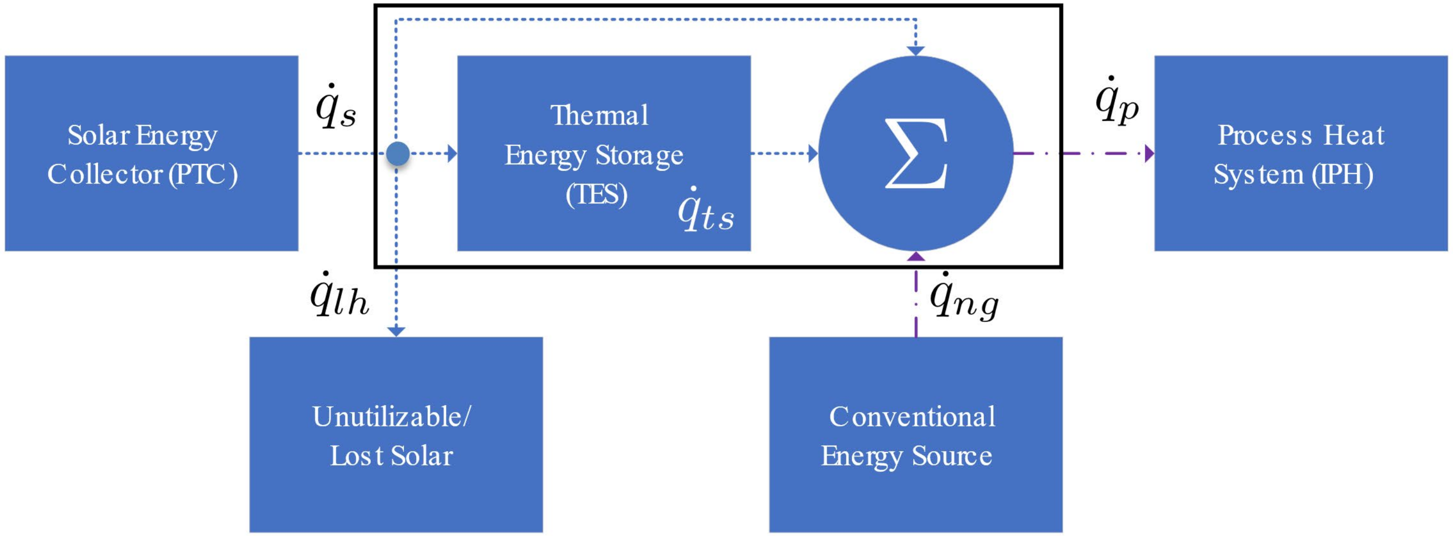
Feldman, Ramasamy, Fu, Ramdas, Desai, Margolis, US Solar Photovoltaic System, NREL (2021)

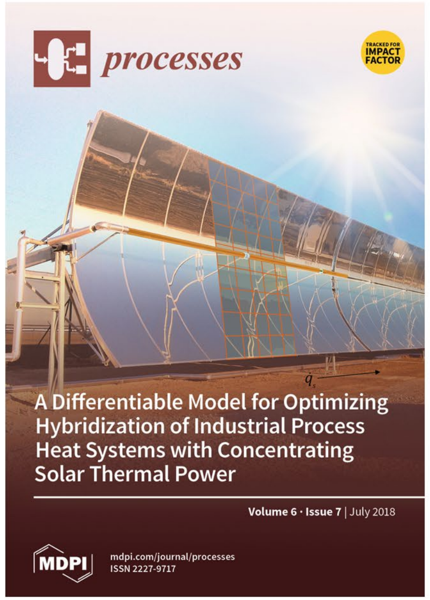
Modeling: Solar Technologies for IPH Hybridization

1. Parabolic trough collectors using thermal energy storage



Modeling: Energy Systems





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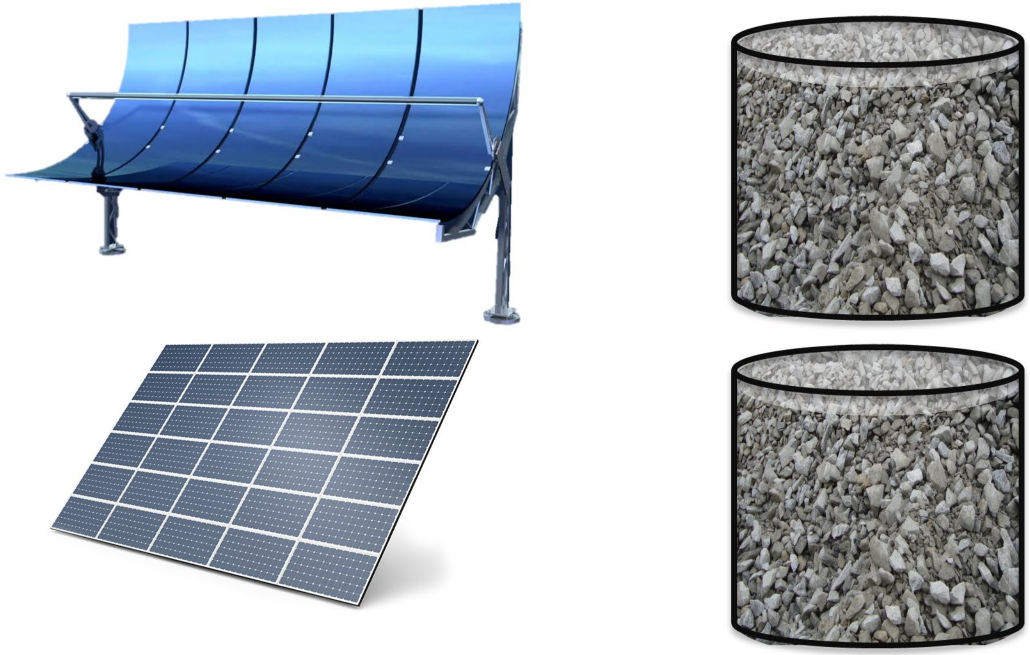
Modeling: Solar Technologies for IPH Hybridization

1. Parabolic trough collectors using thermal energy storage

2. Photovoltaic cells using thermal energy storage



Modeling: Solar Technologies for IPH Hybridization

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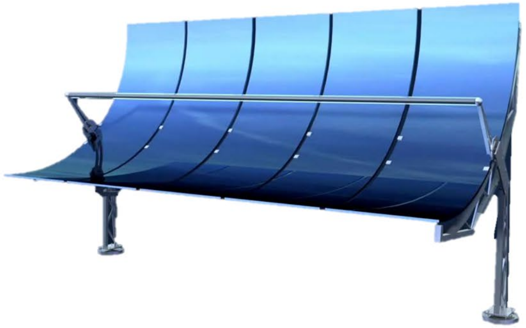
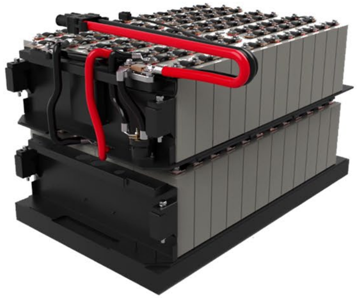
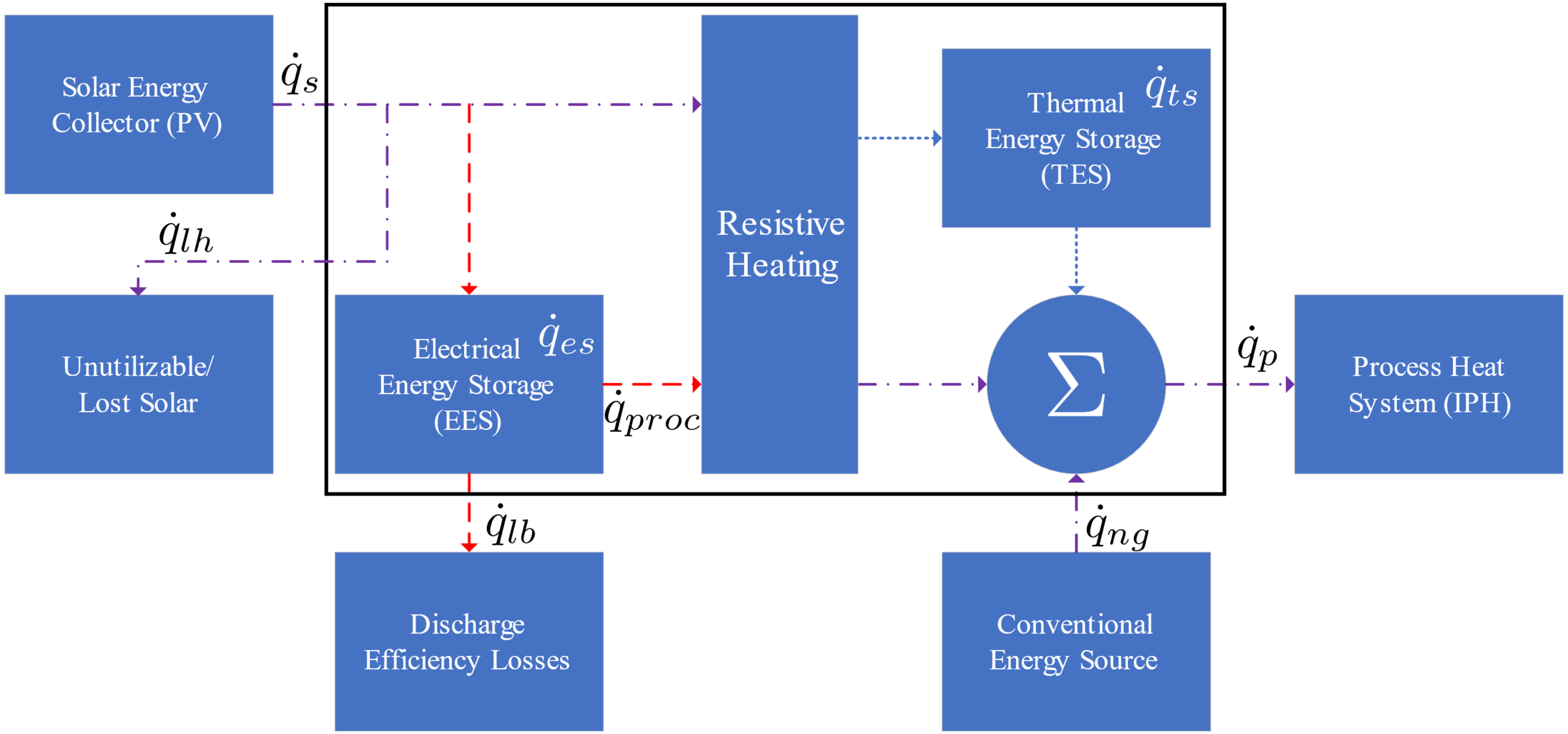


2. Photovoltaic cells using thermal energy storage

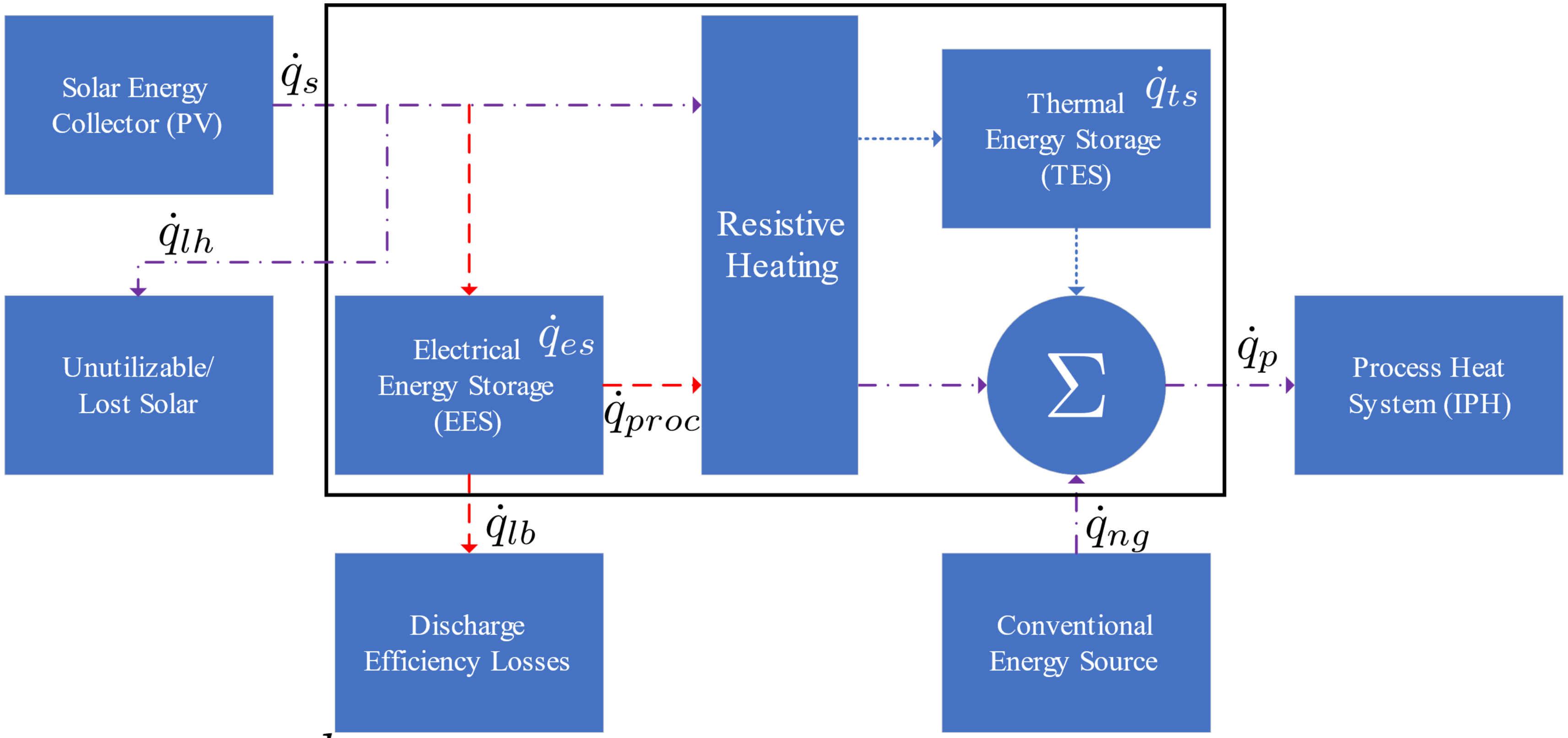
3. Photovoltaic cells using electrical energy storage



Modeling: Energy Systems



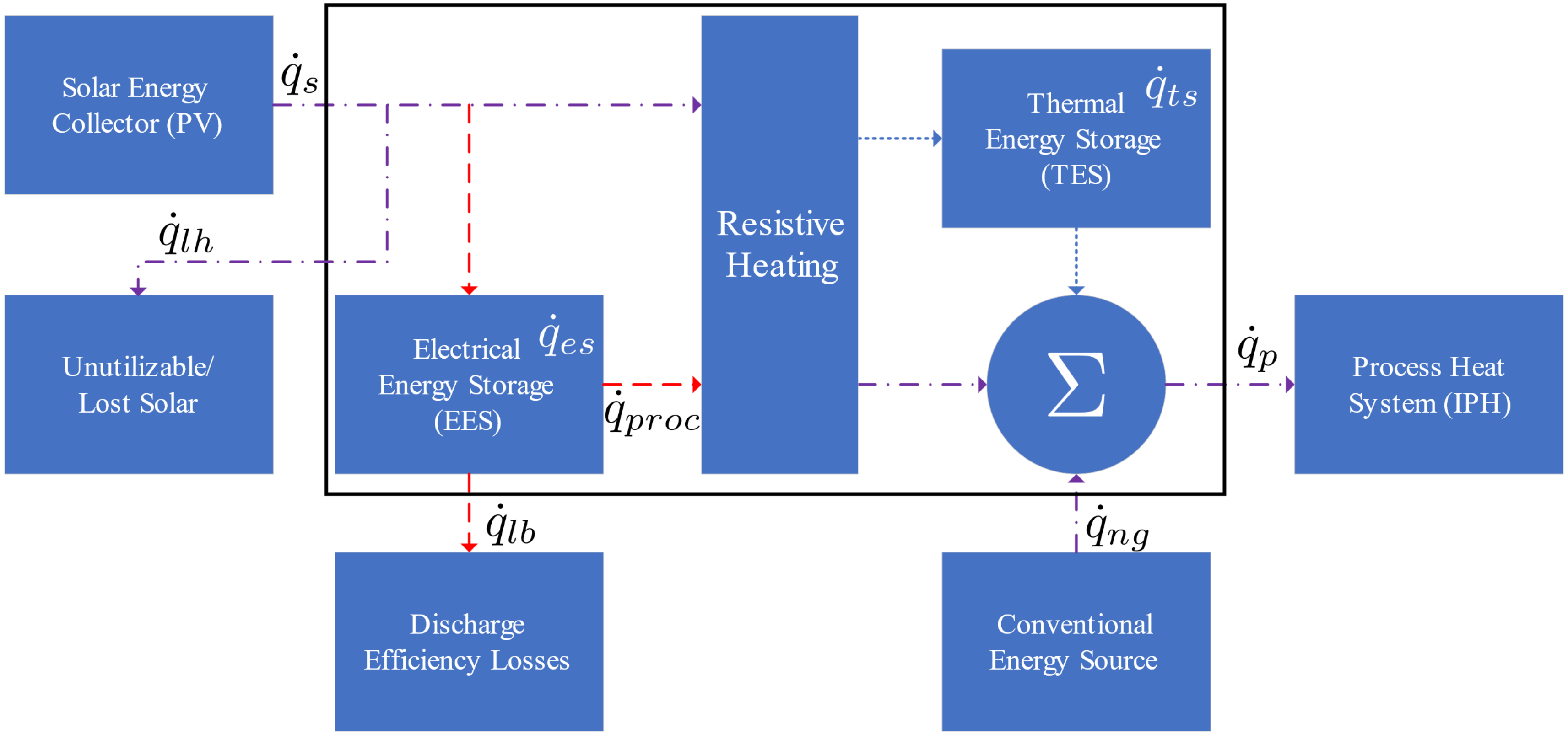
Modeling: Energy Systems



Overall Energy Balance

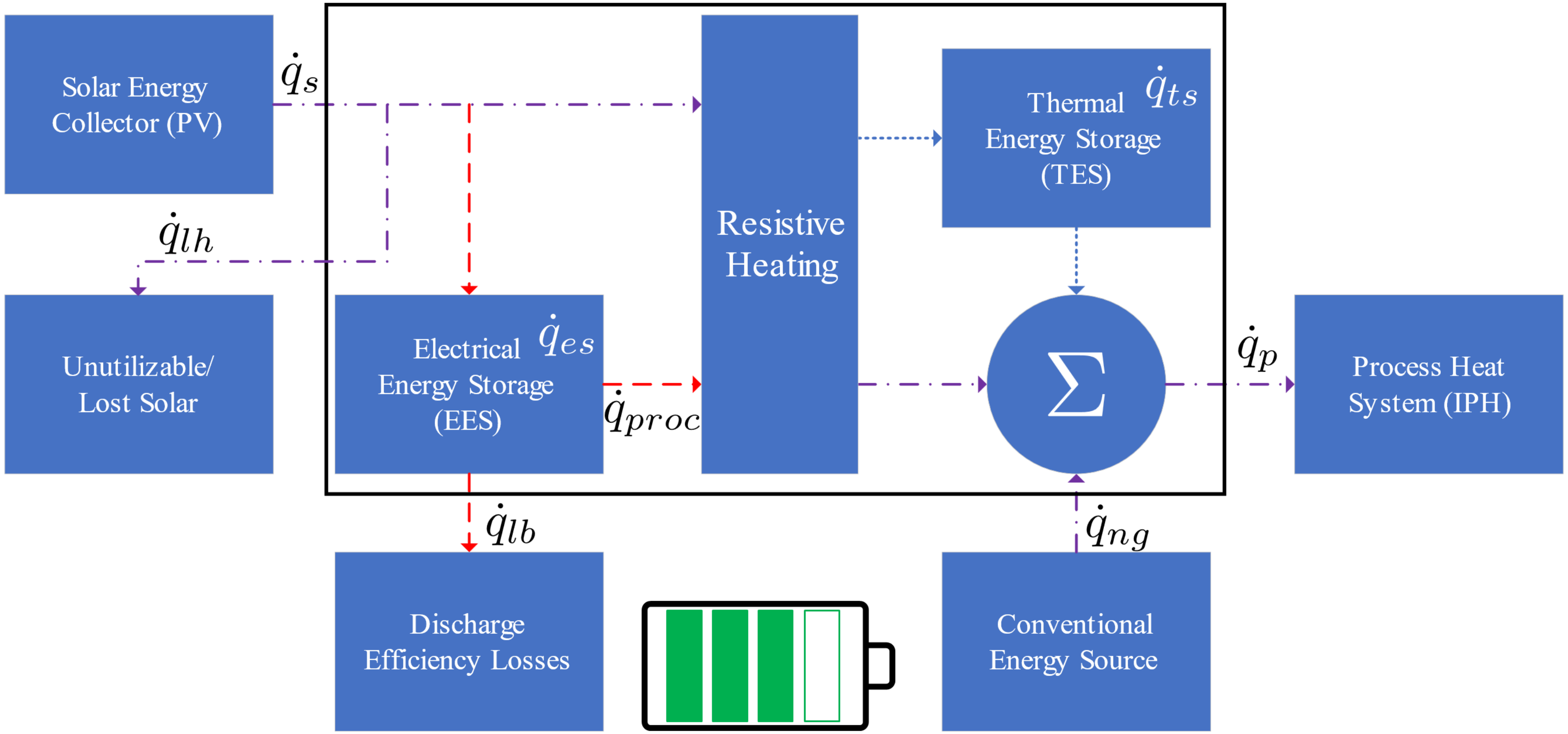
$$\frac{dq_k}{dt} = \dot{q}_s + \dot{q}_{ng} - \dot{q}_{lb} - \dot{q}_{lh} - \dot{q}_p, \;\; k \in \{es, ts\}$$

Modeling: Energy Systems



Overall Energy Balance $$q_k^{j+1} = q_k^j + h(\dot{q}_s + \dot{q}_{ng} - \dot{q}_{lb} - \dot{q}_{lh} - \dot{q}_p), \;\; k \in \{es, ts\}$$

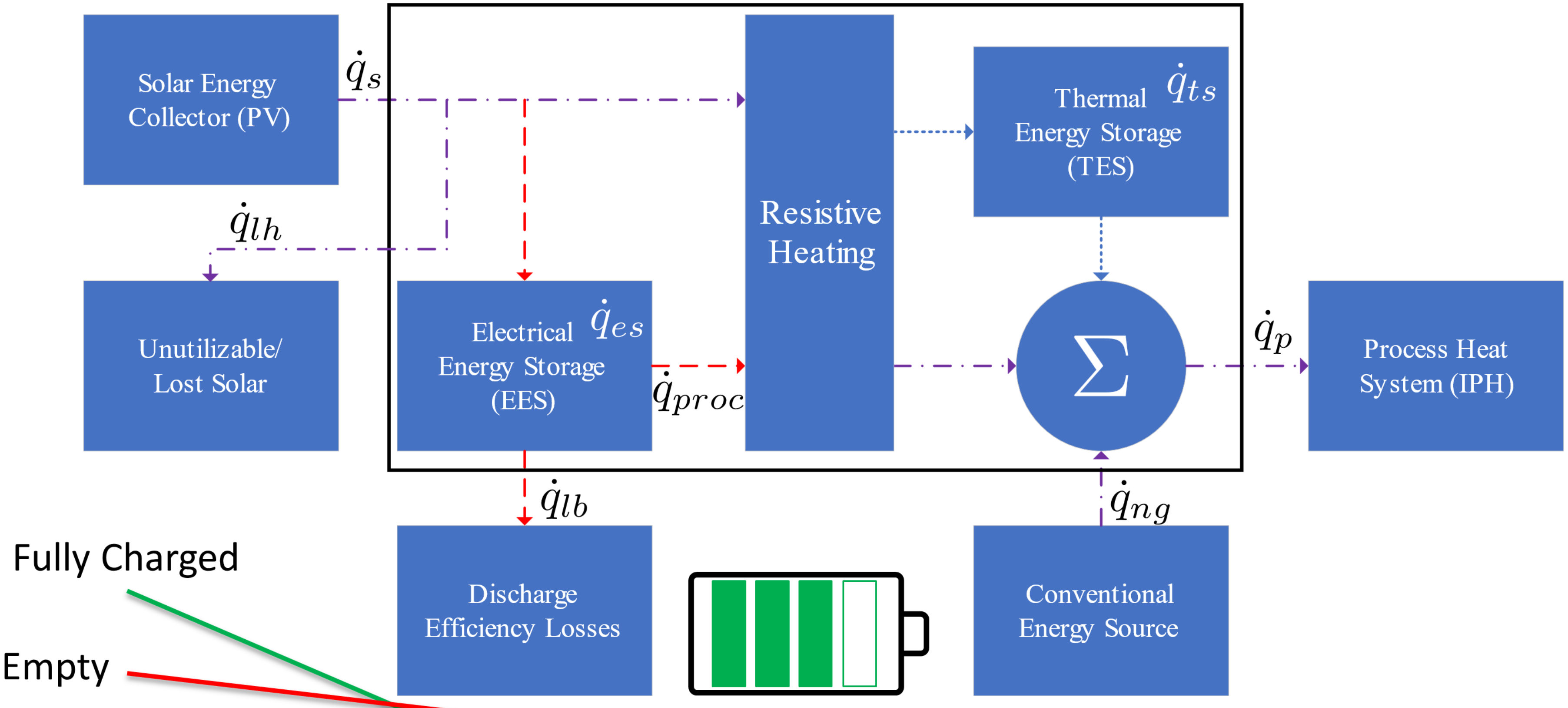
Modeling: Energy Systems



Storage Balance

$$q_k^{j+1} = \mathrm{mid}\{\dot{q}_p^{peak} x_k,\ 0,\ q_k^j + h(\dot{q}_s^j - \dot{q}_p^j - \dot{q}_{lb}^j)\},\ k \in \{es, ts\}$$

Modeling: Energy Systems



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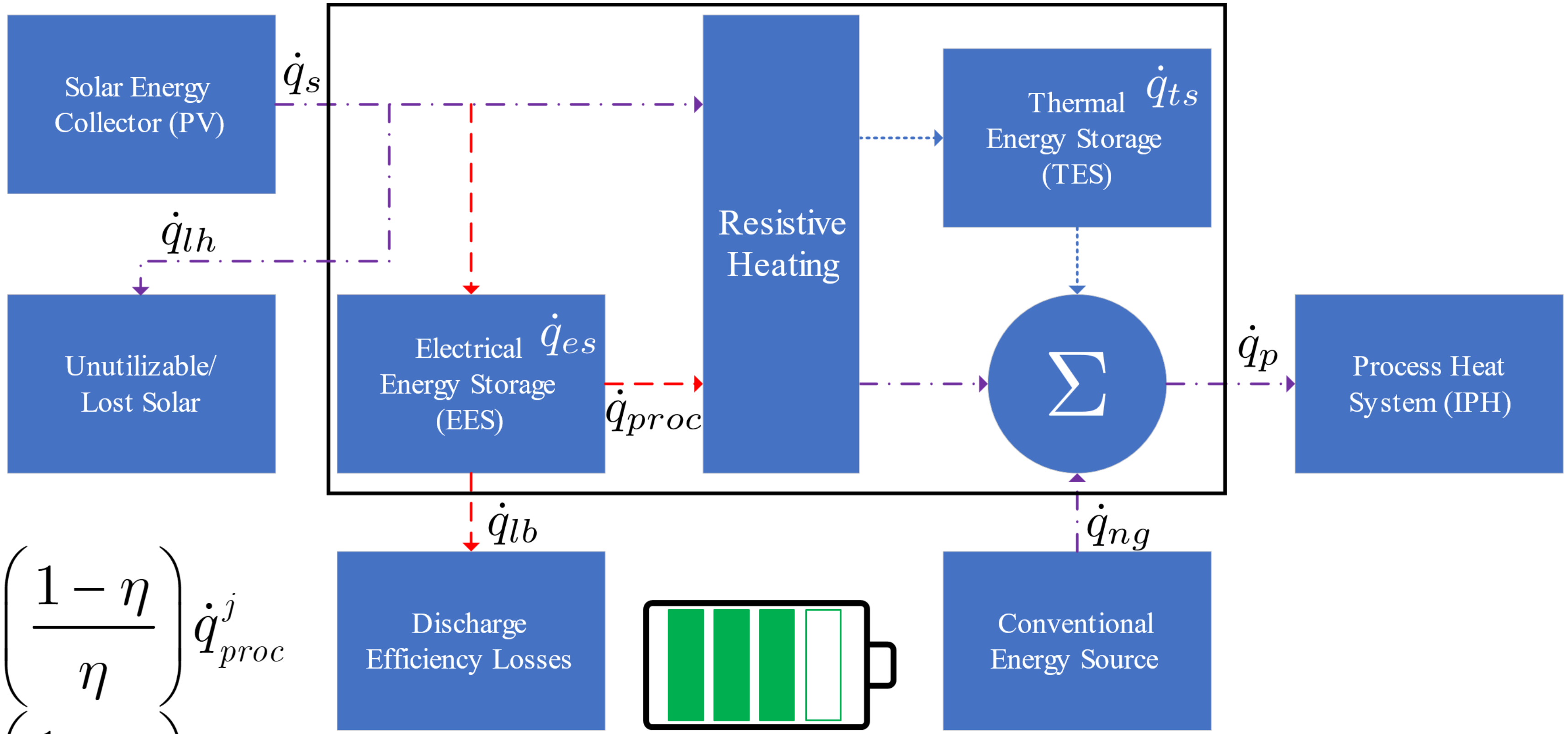
Modeling: Energy Systems

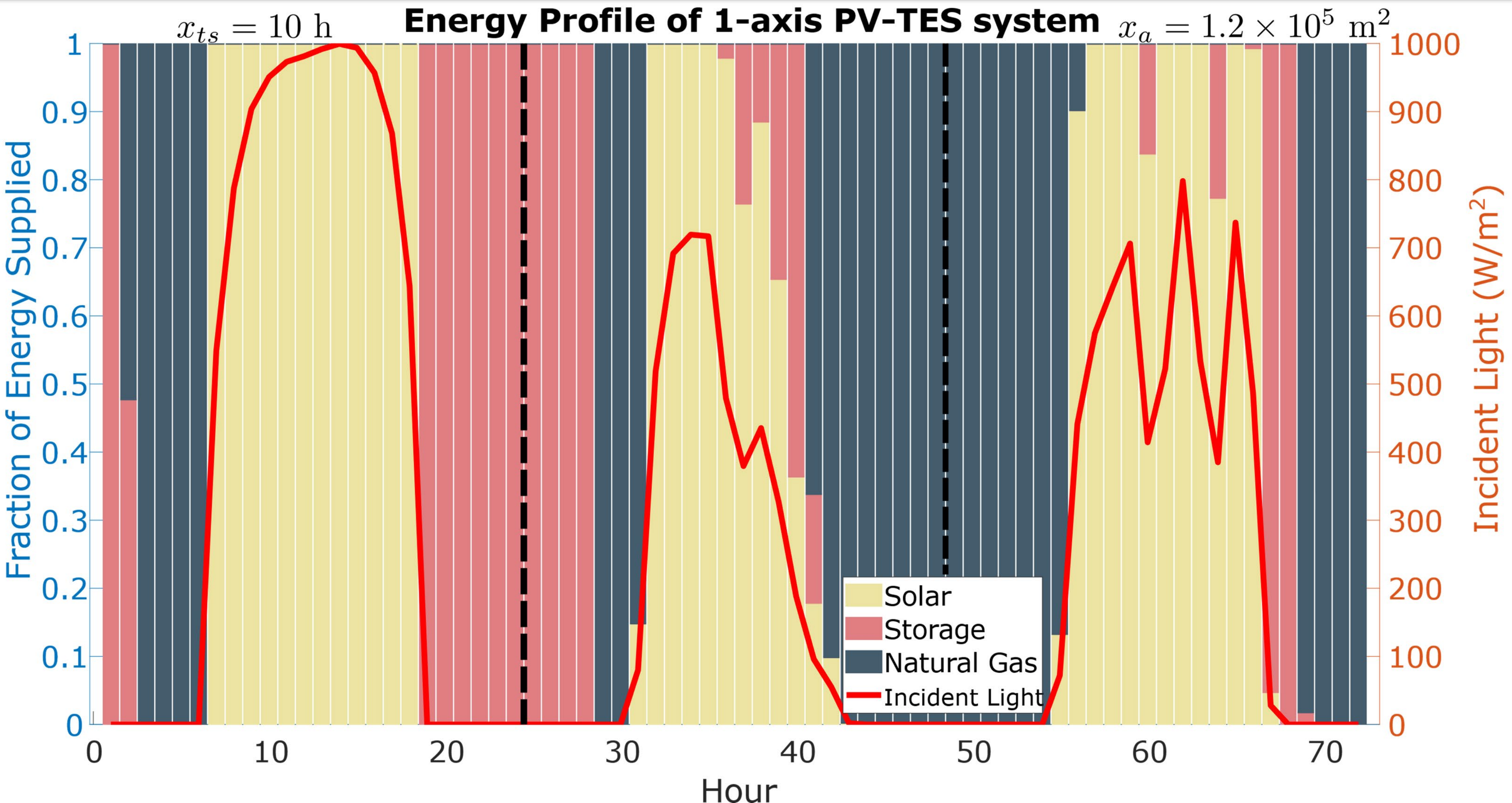


Discharge Losses

$$\dot{q}_{lb}^{j} = \left(\frac{1-\eta}{\eta}\right)\dot{q}_{proc}^{j}$$

$$h\dot{q}_{lb}^{j} = \left(\frac{1-\eta}{\eta}\right)\mathrm{mid}\{\eta\dot{q}_{es}^{j},\ 0,\ h(\dot{q}_{p}^{j} - \dot{q}_{s}^{j})\}$$

Modeling: Energy Systems



Modeling: Global Dynamic Optimization

We want to maximize the life cycle savings of the hybridization strategy:

$$\max_{\mathbf{x}\in X} \sum_{i=1}^{t_{life}} \frac{\left[\int \frac{\dot{q}_s(\mathbf{x},t) - \dot{q}_{lh}(\mathbf{x},t) - \dot{q}_{lb}(\mathbf{x},t)}{\dot{q}_p(t)}\,dt\right] C_{ng,i} - C_{cap,i}(\mathbf{x})}{(1+r)^i}$$

$$\begin{aligned}
\text{s.t. } & \frac{dq_k}{dt}(\mathbf{x},t) = f(\mathbf{x},t),\ t \in I \\
& q_k(\mathbf{x},0) = 0 \\
& \xi - \int \frac{\dot{q}_s(\mathbf{x},t) - \dot{q}_{lh}(\mathbf{x},t) - \dot{q}_{lb}(\mathbf{x},t)}{\dot{q}_p(t)}\,dt \le 0
\end{aligned}$$

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$$\mathbf{x} = (x_k, x_a)$$

$$\begin{aligned} \text{s.t. } & \frac{dq_k}{dt}(\mathbf{x},t) = f(\mathbf{x},t),\ t \in I \\ & q_k(\mathbf{x},0) = 0 \\ & \xi - \int \frac{\dot{q}_s(\mathbf{x},t) - \dot{q}_{lh}(\mathbf{x},t) - \dot{q}_{lb}(\mathbf{x},t)}{\dot{q}_p(t)}\,dt \le 0 \end{aligned}$$

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“Solar Fraction”

$$\text{s.t.}\quad \frac{dq_k}{dt}(\mathbf{x},t) = f(\mathbf{x},t),\ t \in I$$

$$q_k(\mathbf{x},0) = 0$$

$$\xi - \boxed{\int \frac{\dot{q}_s(\mathbf{x},t) - \dot{q}_{lh}(\mathbf{x},t) - \dot{q}_{lb}(\mathbf{x},t)}{\dot{q}_p(t)}\,dt} \le 0$$

Modeling: Global Dynamic Optimization

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$$\max_{\mathbf{x}\in X} \sum_{i=1}^{t_{life}} \frac{\left[\int \frac{\dot{q}_s(\mathbf{x},t) - \dot{q}_{lh}(\mathbf{x},t) - \dot{q}_{lb}(\mathbf{x},t)}{\dot{q}_p(t)} dt\right] C_{ng,i} - C_{cap,i}(\mathbf{x})}{(1+r)^i}$$

$$\text{s.t.} \quad \boxed{\begin{aligned} &\frac{dq_k}{dt}(\mathbf{x},t) = f(\mathbf{x},t),\, t \in I \\ &q_k(\mathbf{x},0) = 0 \end{aligned}}$$

Continuous-time energy balance

$$\xi - \int \frac{\dot{q}_s(\mathbf{x},t) - \dot{q}_{lh}(\mathbf{x},t) - \dot{q}_{lb}(\mathbf{x},t)}{\dot{q}_p(t)} dt \leq 0$$

Modeling: Global Dynamic Optimization

We want to maximize the life cycle savings of the hybridization strategy:

$$
\max_{\mathbf{x}\in X} \boxed{\sum_{i=1}^{t_{life}} \frac{\left[\int \frac{\dot{q}_s(\mathbf{x},t) - \dot{q}_{lh}(\mathbf{x},t) - \dot{q}_{lb}(\mathbf{x},t)}{\dot{q}_p(t)}\,dt\right] C_{ng,i} - C_{cap,i}(\mathbf{x})}{(1+r)^i}}
$$

Net-present value of savings

$$
\begin{aligned}
\text{s.t. } & \frac{dq_k}{dt}(\mathbf{x},t) = f(\mathbf{x},t),\ t \in I \\
& q_k(\mathbf{x},0) = 0 \\
& \xi - \int \frac{\dot{q}_s(\mathbf{x},t) - \dot{q}_{lh}(\mathbf{x},t) - \dot{q}_{lb}(\mathbf{x},t)}{\dot{q}_p(t)}\,dt \le 0
\end{aligned}
$$

Modeling: Global Dynamic Optimization

Utilize the discrete-time energy balance introduced earlier and reformulate:

$$\max_{\mathbf{x}\in X} \sum_{i=1}^{t_{life}} \frac{\left[\sum_j \frac{h(\dot{q}_s^j(\mathbf{x}) - \dot{q}_{lh}^j(\mathbf{x}) - \dot{q}_{lb}^j(\mathbf{x}))}{\dot{q}_p^j}\right] C_{ng,i} - C_{cap,i}(\mathbf{x})}{(1+r)^i}$$

$$\text{s.t. } \xi - \sum_j \frac{h(\dot{q}_s^j(\mathbf{x}) - \dot{q}_{lh}^j(\mathbf{x}) - \dot{q}_{lb}^j(\mathbf{x}))}{\dot{q}_p^j} \leq 0$$

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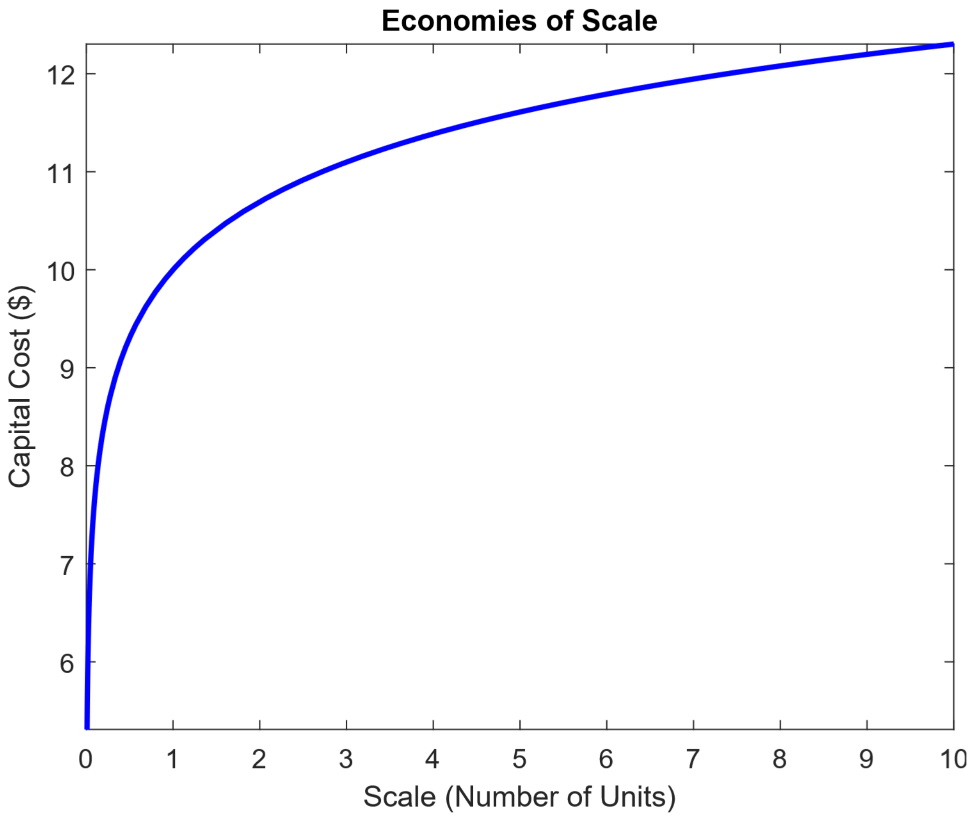
$$\text{s.t. } \xi - \sum_j \frac{\boxed{h(\dot{q}_s^j(\mathbf{x}) - \dot{q}_{lh}^j(\mathbf{x}) - \dot{q}_{lb}^j(\mathbf{x}))}}{\dot{q}_p^j} \leq 0$$

Discrete-time energy balance equations are embedded here

$$q_k^{j+1} = \mathrm{mid}\{\dot{q}_p^{peak} x_k,\ 0,\ q_k^j + h(\dot{q}_s^j - \dot{q}_p^j - \dot{q}_{lb}^j)\},$$
$$j = 0, \ldots, 8759$$

Modeling: Capital Cost Models



PTC-TES:

$$C_{cap,0}^{PTC}\left(x_{ts},x_{a}\right)=425x_{a}^{0.92}+45.14\left(\dot{q}_{p}^{peak}x_{ts}\right)^{0.91}$$

PV0-TES:

$$C_{cap,0}^{PV0T}\left(x_{ts},x_{a}\right)=200.18x_{a}^{0.96}+45.14\left(\dot{q}_{p}^{peak}x_{ts}\right)^{0.91}$$

PV0-EES:

$$C_{cap,0}^{PV0E}\left(x_{es},x_{a}\right)=200.18x_{a}^{0.96}+736.38\left(\dot{q}_{p}^{peak}\frac{x_{es}}{DoD}\right)^{0.94}$$

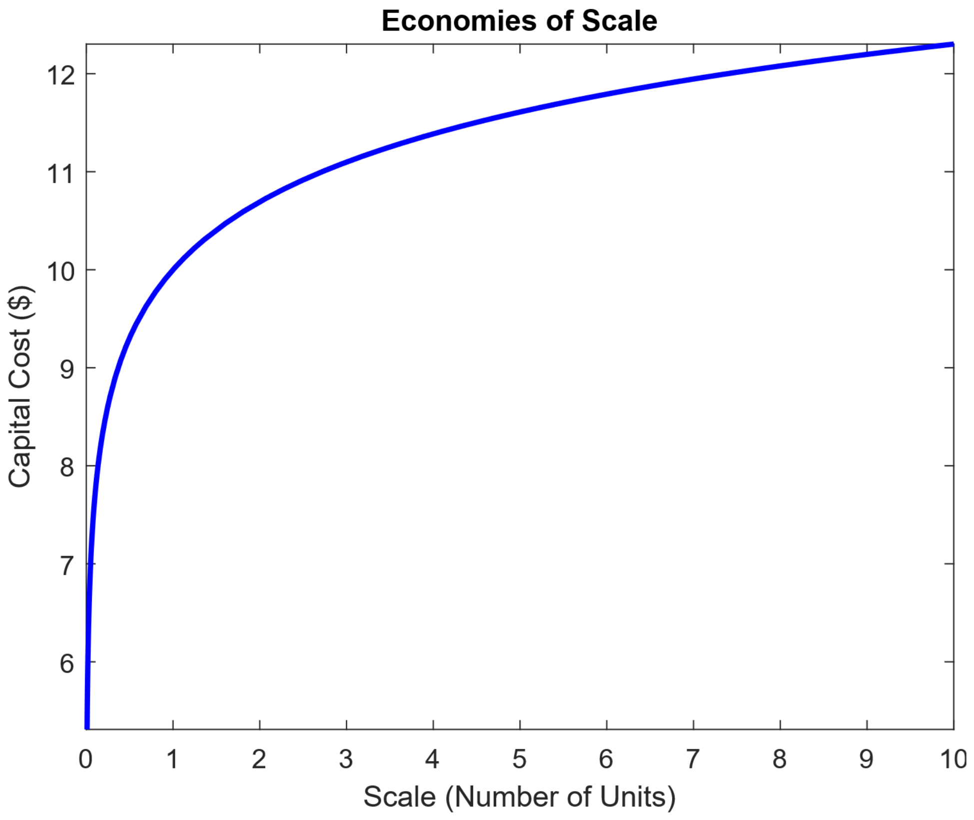
PV1-TES:

$$C_{cap,0}^{PV1T}\left(x_{ts},x_{a}\right)=233.49x_{a}^{0.959}+45.14\left(\dot{q}_{p}^{peak}x_{ts}\right)^{0.91}$$

PV1-EES:

$$C_{cap,0}^{PV1E}\left(x_{es},x_{a}\right)=223.49x_{a}^{0.959}+736.38\left(\dot{q}_{p}^{peak}\frac{x_{es}}{DoD}\right)^{0.94}$$

Modeling: Capital Cost Models



PTC-TES:

$$C_{cap,0}^{PTC}\left(x_{ts},x_a\right) = 425x_a^{0.92} + 45.14\left(\dot{q}_p^{peak}x_{ts}\right)^{0.91}$$

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Modeling: Global Dynamic Optimization

$$\max_{\mathbf{x}\in X} \sum_{i=1}^{t_{life}} \frac{\left[\sum_j \frac{h(\dot{q}_s^j(\mathbf{x}) - \dot{q}_{lh}^j(\mathbf{x}) - \dot{q}_{lb}^j(\mathbf{x}))}{\dot{q}_p^j}\right] C_{ng,i} - \boxed{C_{cap,i}(\mathbf{x})}}{(1+r)^i}$$

$$\text{s.t. } \xi - \sum_j \frac{h(\dot{q}_s^j(\mathbf{x}) - \dot{q}_{lh}^j(\mathbf{x}) - \dot{q}_{lb}^j(\mathbf{x}))}{\dot{q}_p^j} \leq 0$$

PTC-TES:

$$C_{cap,0}^{PTC}(x_{ts}, x_a) = 425 x_a^{0.92} + 45.14\left(\dot{q}_p^{peak} x_{ts}\right)^{0.91}$$

PV0-TES:

$$C_{cap,0}^{PV0T}(x_{ts}, x_a) = 200.18 x_a^{0.96} + 45.14\left(\dot{q}_p^{peak} x_{ts}\right)^{0.91}$$

PV0-EES:

$$C_{cap,0}^{PV0E}(x_{es}, x_a) = 200.18 x_a^{0.96} + 736.38\left(\dot{q}_p^{peak} \frac{x_{es}}{DoD}\right)^{0.94}$$

PV1-TES:

$$C_{cap,0}^{PV1T}(x_{ts}, x_a) = 233.49 x_a^{0.959} + 45.14\left(\dot{q}_p^{peak} x_{ts}\right)^{0.91}$$

PV1-EES:

$$C_{cap,0}^{PV1E}(x_{es}, x_a) = 223.49 x_a^{0.959} + 736.38\left(\dot{q}_p^{peak} \frac{x_{es}}{DoD}\right)^{0.94}$$

Modeling: Global Dynamic Optimization

Utilize the discrete-time energy balance introduced earlier and reformulate:

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$$\text{s.t. } \xi - \sum_j \frac{h(\dot{q}_s^j(\mathbf{x}) - \dot{q}_{lh}^j(\mathbf{x}) - \dot{q}_{lb}^j(\mathbf{x}))}{\dot{q}_p^j} \leq 0$$

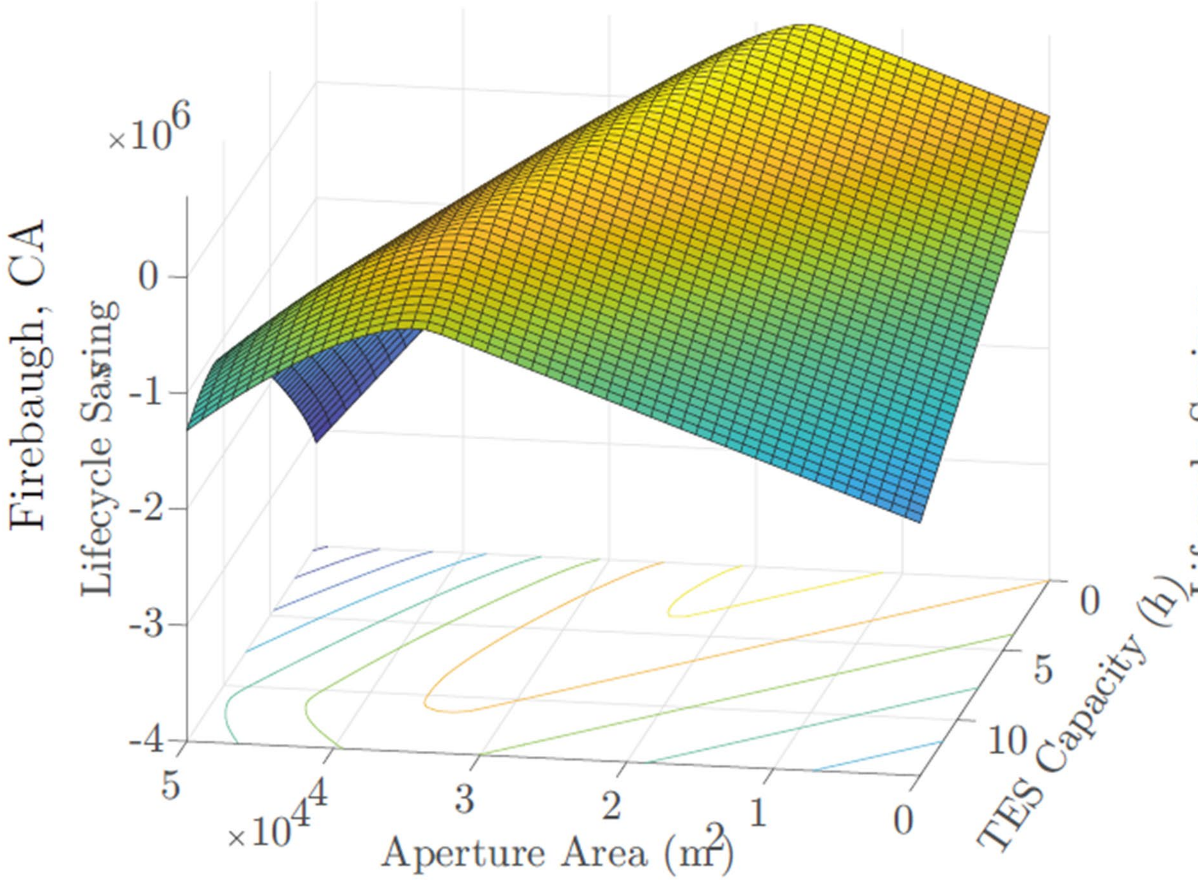
Nonconvex program because of this term (economies of scale)

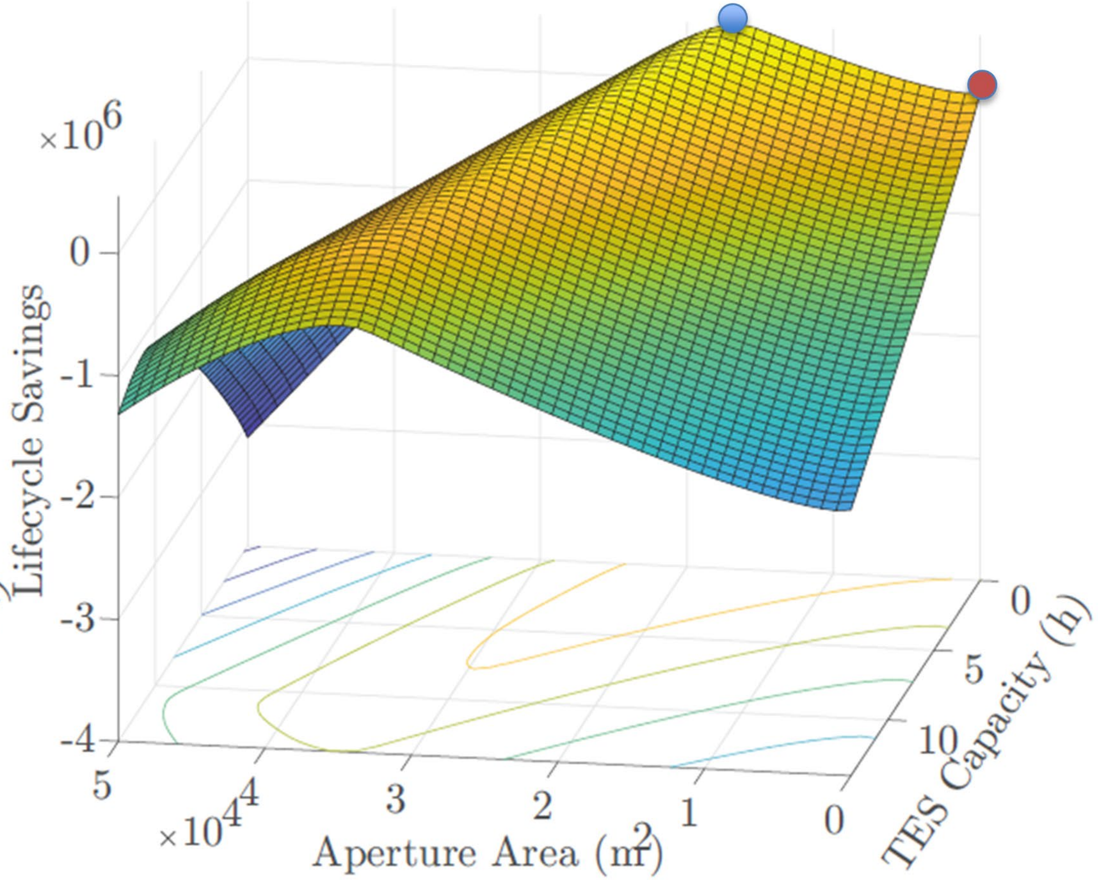
EAGO

Custom envelopes defined in Stuber (2018) used here with deterministic global optimization

Modeling: Nonconvex Optimization

Utilize the discrete-time energy balance introduced earlier and reformulate:





[3] Stuber, MD. *Processes*, 6,7 (2018)

Case Studies: Factorial Design of Test Cases

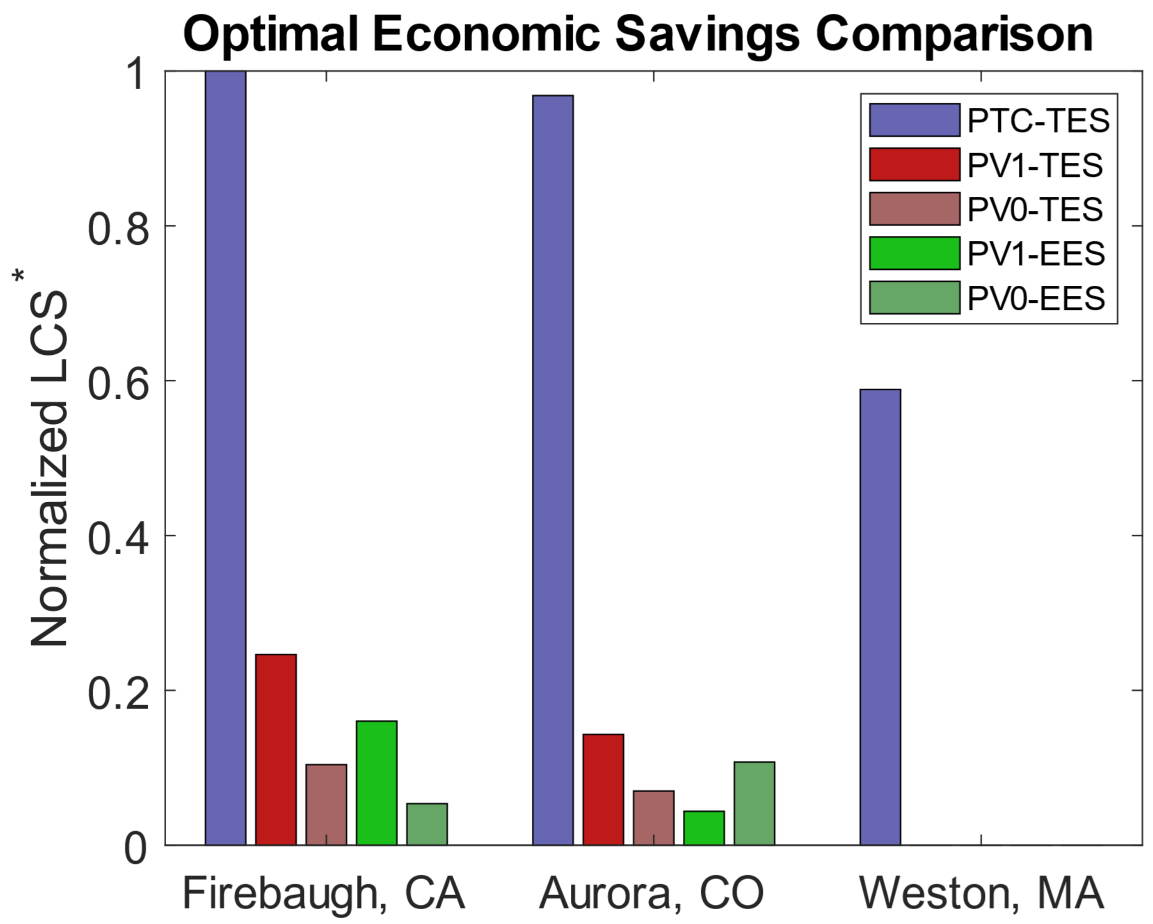
Unconstrained Case: 90 Experiments

- Solar Fraction ≥ 0

Parameters:

- Capital Cost (PTC, PV, TES, EES)
- Geographic location (Firebaugh, CA; Aurora, CO; Weston, MA)
- System size (0.1 MW, 1 MW, 10 MW)
- Natural Gas Cost ($9.52/MMBTU, $19.14/MMBTU)

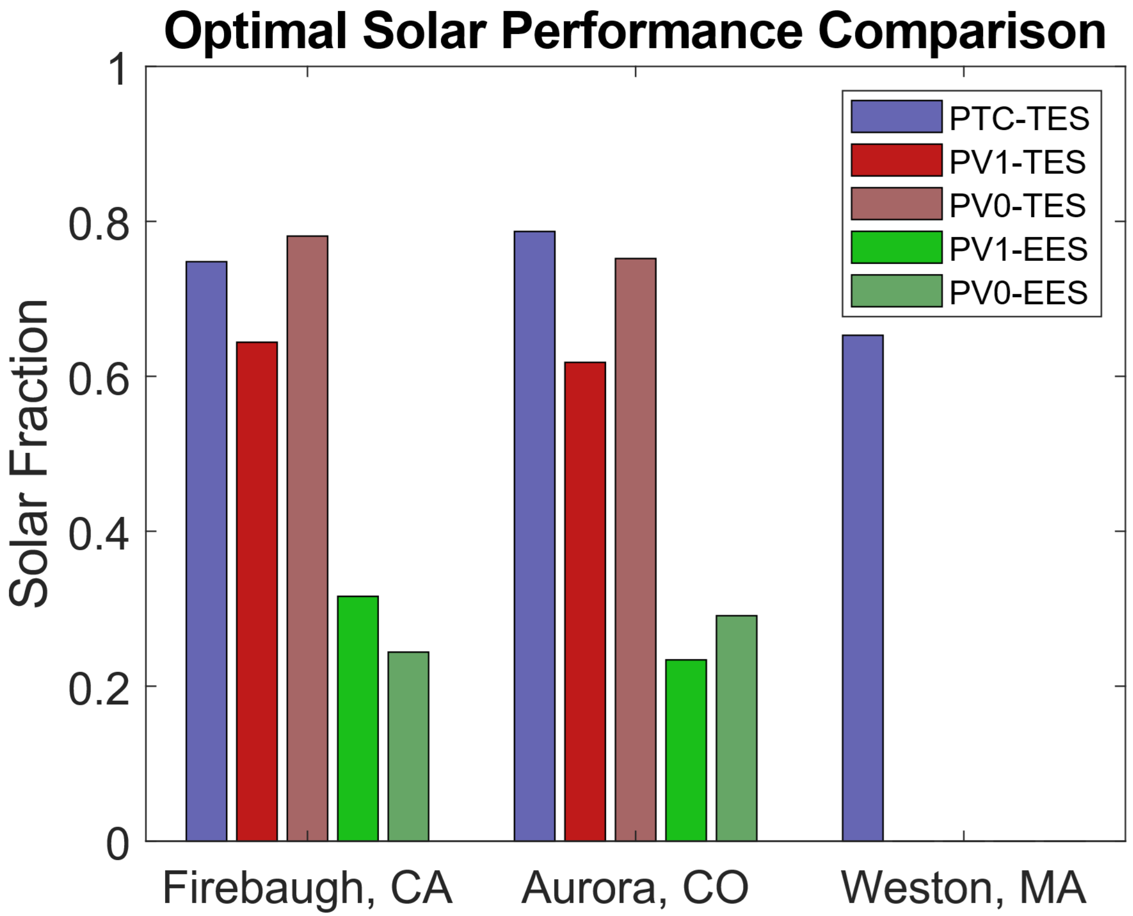
Results & Conclusions: Life cycle savings



- Optimal Lifecycle Savings normalized relative to highest result—Firebaugh PTC-TES
- Natural gas cost = $9.52/MMBTU

- Natural gas is still too cheap
- EES is too expensive
- PTCs outperform all other technologies

Results & Conclusions: Solar Fraction



- Optimal solar fractions result in significant decarbonization
- PV electrification performs about the same as solar thermal for high insolation regions

Conclusions

- We have developed an optimization-based design modeling framework for assessing the technoeconomic feasibility of hybridizing IPH systems with solar technologies
- Cost models introduce nonconvexity
  - Deterministic global optimization is needed
- Currently have a Jupyter notebook on our GitHub for a PTC-TES example

Deterministic Global Optimization for Concentrating Solar Thermal Hybridization

This example comes from M.D. Stuber. A Differentiable Model for Optimizing Hybridization of Industrial Process Heat Systems with Concentrating Solar Thermal Power. *Processes*, 6(7), 76 (2018) DOI: 10.3390/pr6070076

In this example, we seek to determine the optimal thermal energy storage capacity and parabolic trough solar array aperture area that maximizes the lifecycle savings associated with augmenting a conventional natural gas industrial process heat system. Here, we use user-defined functions, the JuMP modeling language, the EAGO spatial branch-and-bound algorithm with custom upper- and lower-bounding procedures, and the IPOPT algorithm for solving the bounding subproblems.

We will solve the optimal design problem for Firebaugh, CA with the commercial fuel rate and constant industrial process heat demand ($\xi = 0$).

Note: This example corresponds to a $\bar{q}_p = 10^4$ kW thermal demand. In the paper, it is stated that a $\bar{q}_p = 10^5$ kW thermal demand was studied. However, this is an error as all studies in the paper were conducted for a $\bar{q}_p = 10^4$ kW thermal demand.

In [1]:
```
using JuMP, EAGO, Ipopt
```

We will also use the CSV package because our solar resource data (downloaded from the NSRDB) is in a CSV file.

In [2]:
```
using CSV, DataFrames
```

Thank you! Any Questions?

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UC Berkeley

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Loureiro Engineering Assoc.

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SCHOOL OF ENGINEERING
Chemical & Biomolecular Engineering

Process Systems and Operations Research Laboratory

2022 AIChE ANNUAL MEETING