Optimization of CCS-Enabled Coal-Gas-Solar Power Generation

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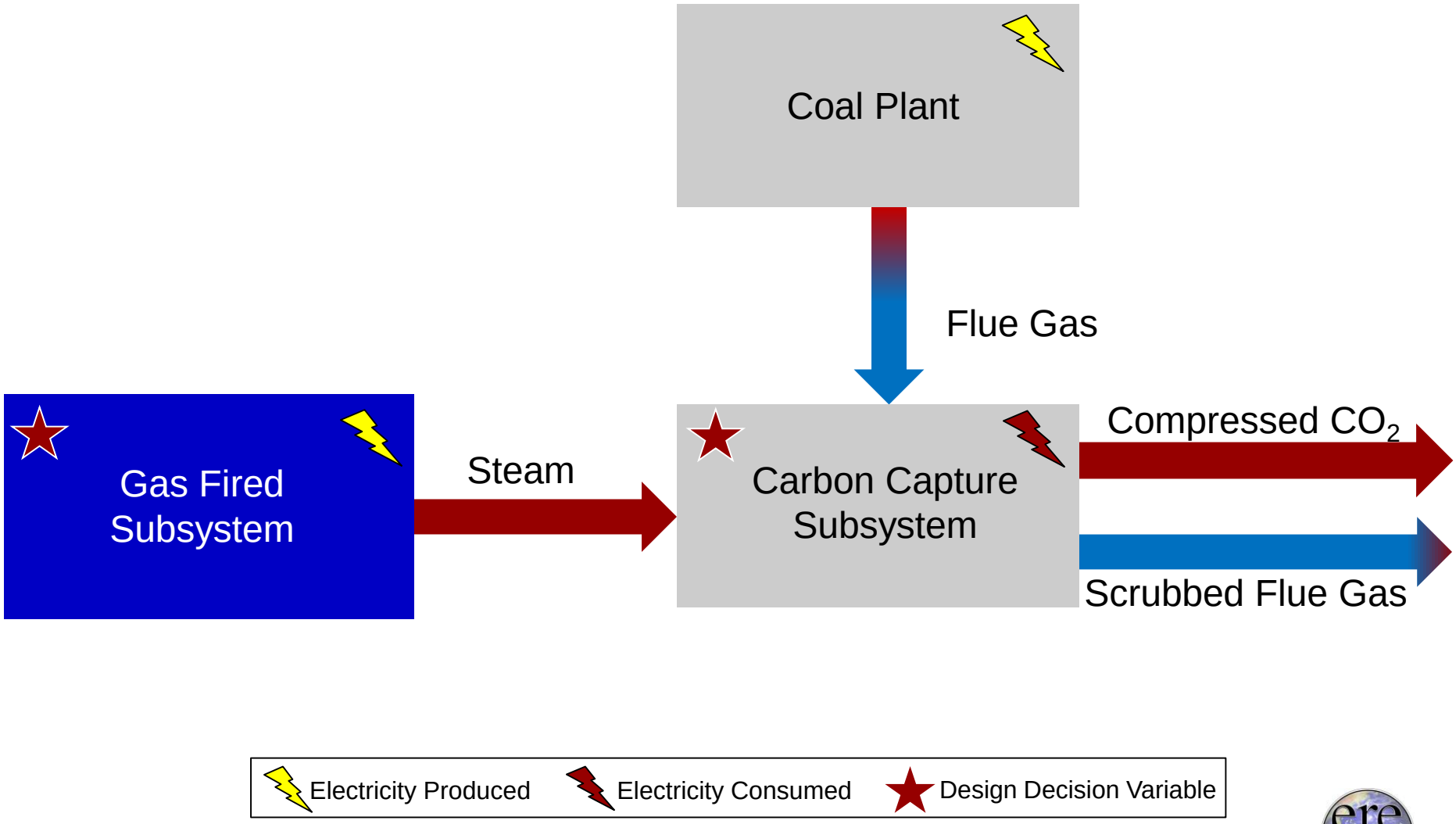
Outline

- Problem Design
- System Model
- Optimization Methodology
- Input Data
- Optimization Results

Auxiliary Heat Source



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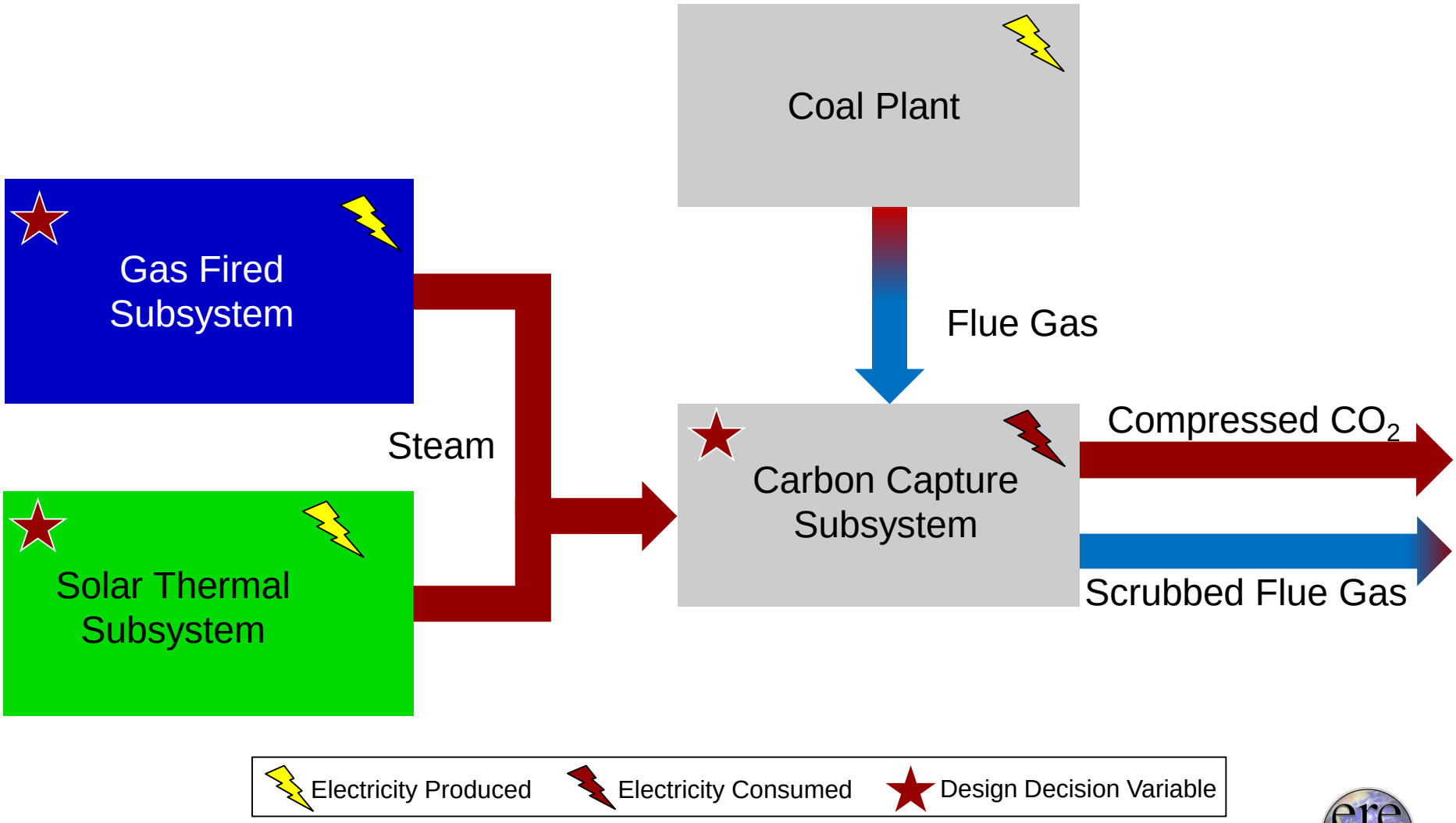

Problem Setup

- Coal plant in New Mexico, exporting power to Southern California
- System and component emissions cap at 500 kg / MWh, based on California Law SB 1368

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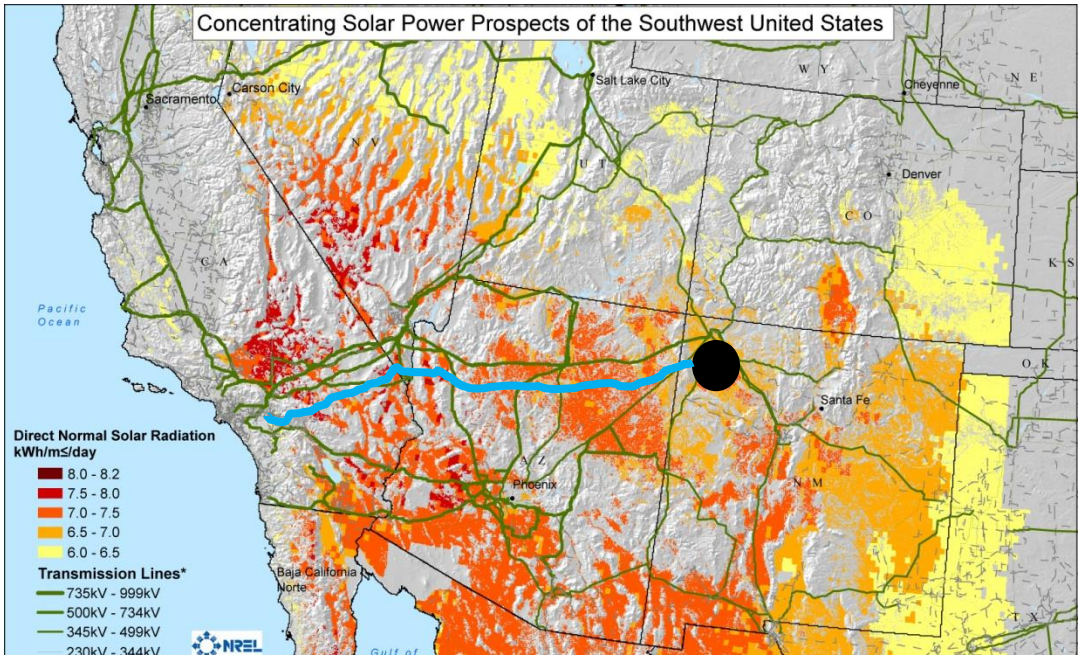
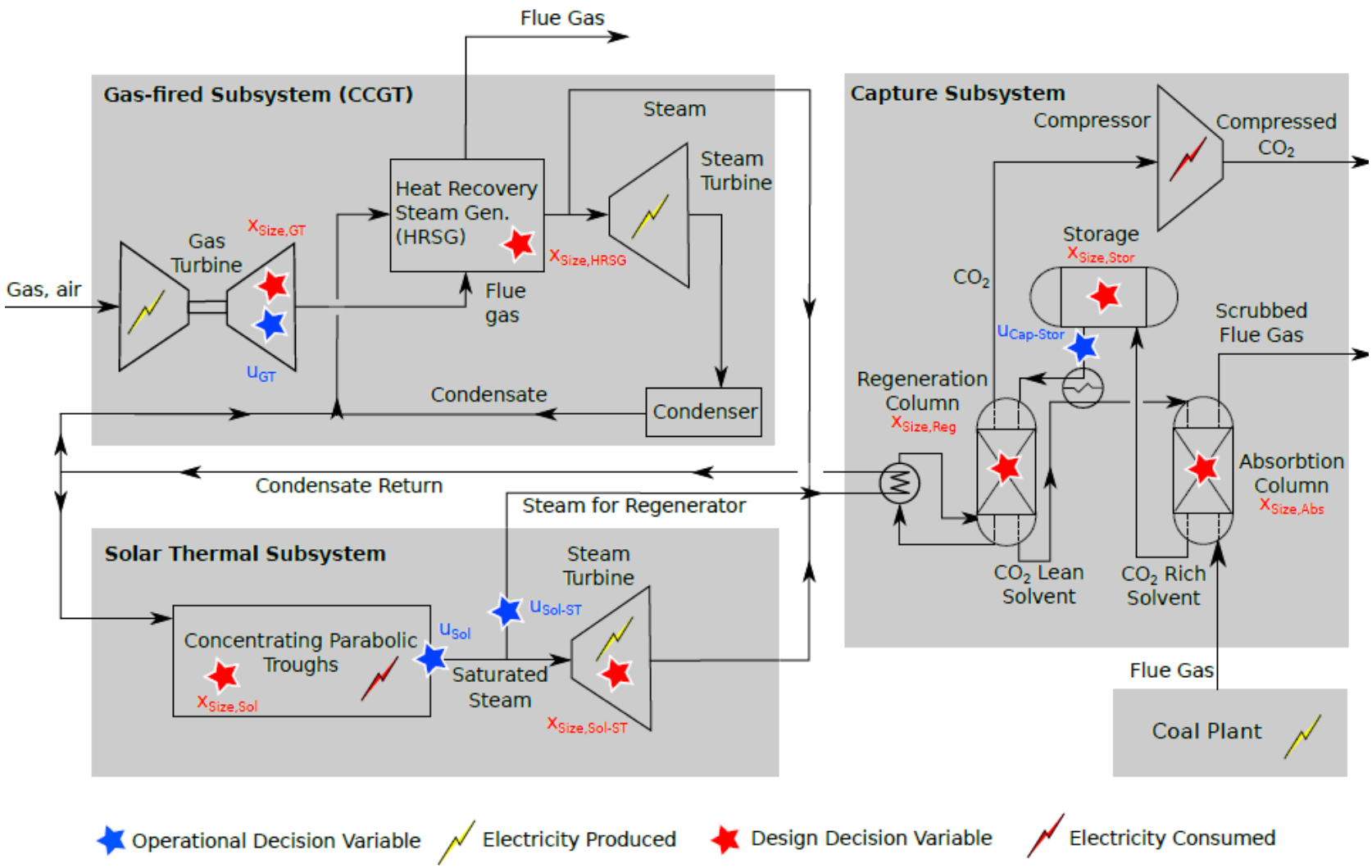


Source: Visualizing the US Electricity Grid, by NPR

Process Flow Model

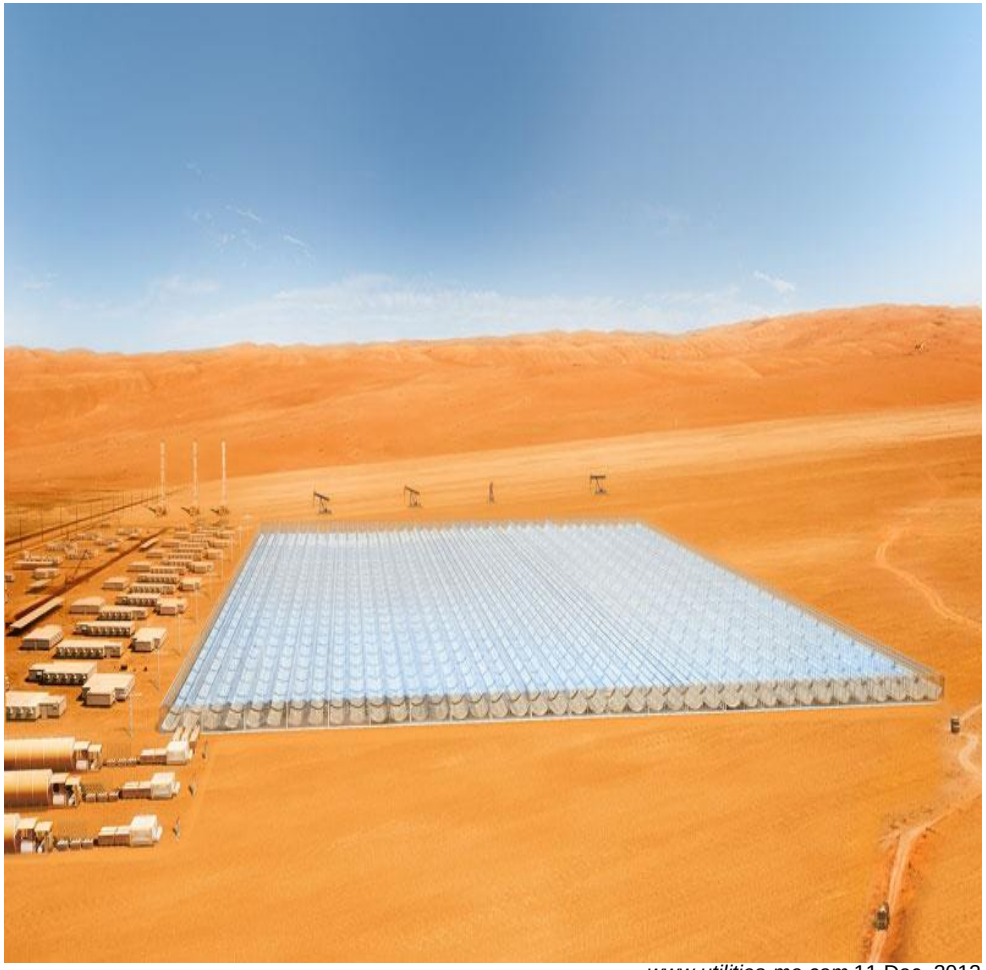


Solar Thermal Subsystem

- Based on the GlassPoint system
- Designed to produce process heat for enhanced oil recovery
- Relatively low capital cost
- Mid-level temperature

www.glasspoint.com. 2013.

GlassPoint Troughs



www.utilities-me.com 11 Dec. 2012.

GlassPoint Installation, Oman – 7 MW

Solar Thermal Subsystem

Design Decision Variables

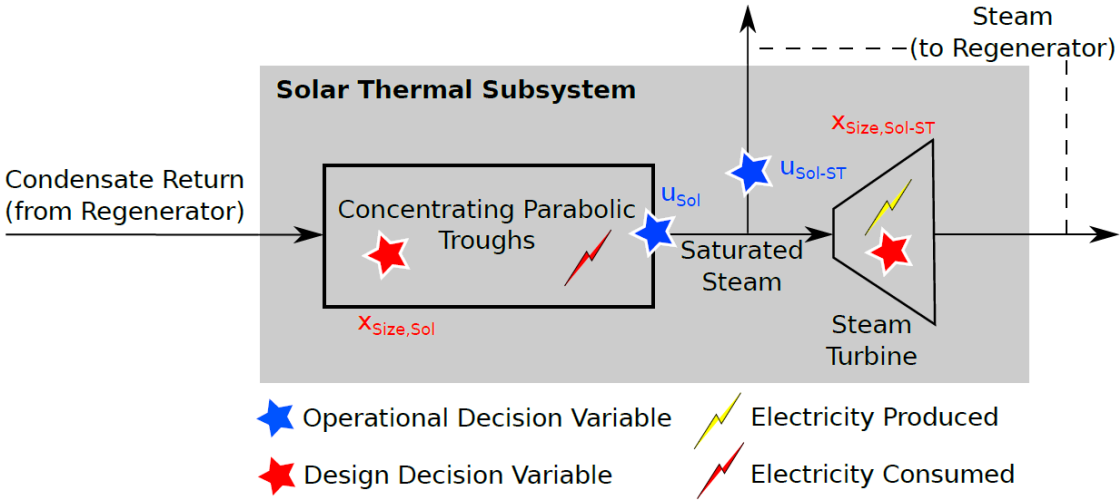
($x_{Size,Sol}$) Size of concentrating parabolic troughs

($x_{Size,Sol-ST}$) Size of steam turbine

Operational Decision Variables

(u_{Sol}) Percent of steam output to utilize

(u_{Sol-ST}) Percent of steam to run through steam turbine



Capture Subsystem

- Amine-based temperature swing absorption system
- Thermodynamic and cost data comes from Carnegie Mellon's Integrated Environmental Control Model (IECM) for a default amine CO_2 capture design
- Includes storage of CO_2 rich solvent to allow for regeneration when steam is available

Capture Subsystem

Design Decision Variables

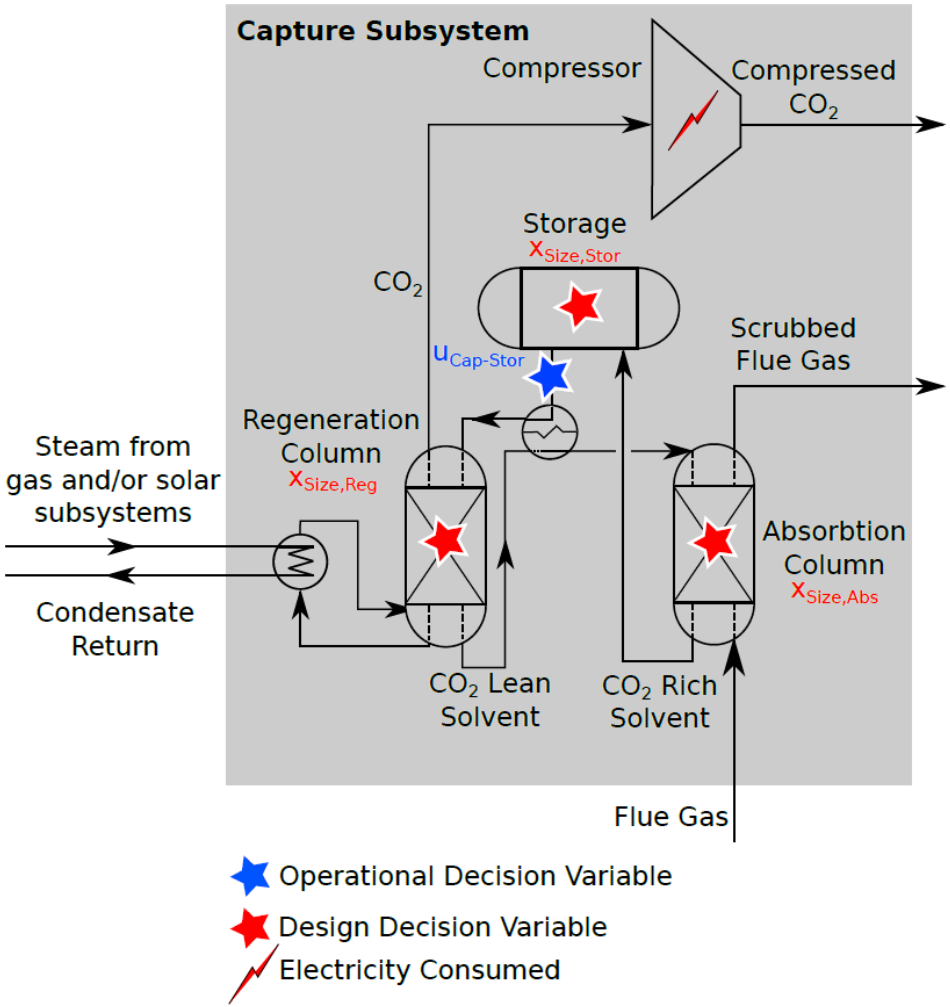
($x_{Size,Abs}$) Size of absorber

($x_{Size,Reg}$) Size of regenerator

($x_{Size,Stor}$) Size of amine storage system

Operational Decision Variables

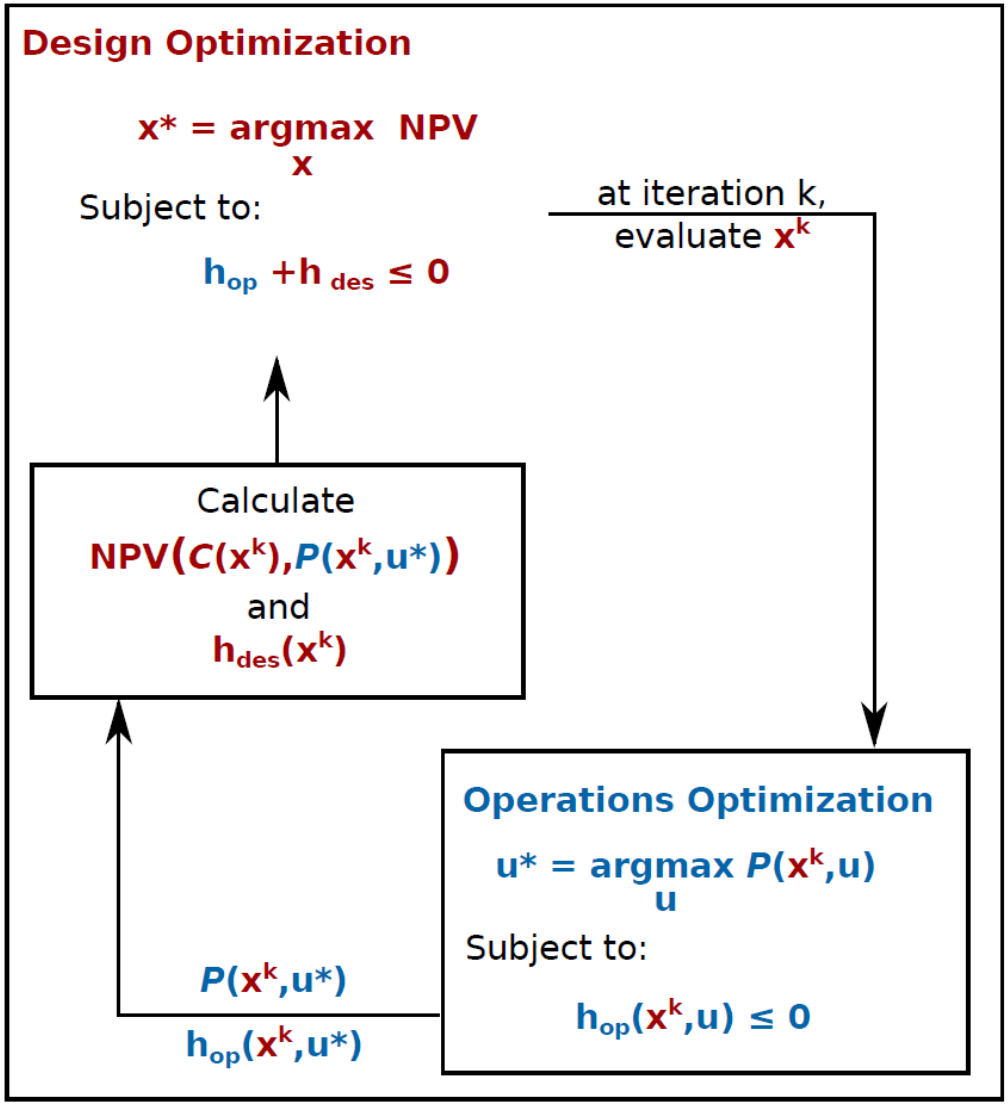
($u_{Cap\text{-}Stor}$) Percent of absorbed CO_2 to be stored



Optimization Methodology

- Mixed integer nonlinear optimization problem
- Two-level optimization – design and operations are optimized iteratively with joint optimization upon convergence
- Constrained by CO_2 emissions, and by mass and energy balances

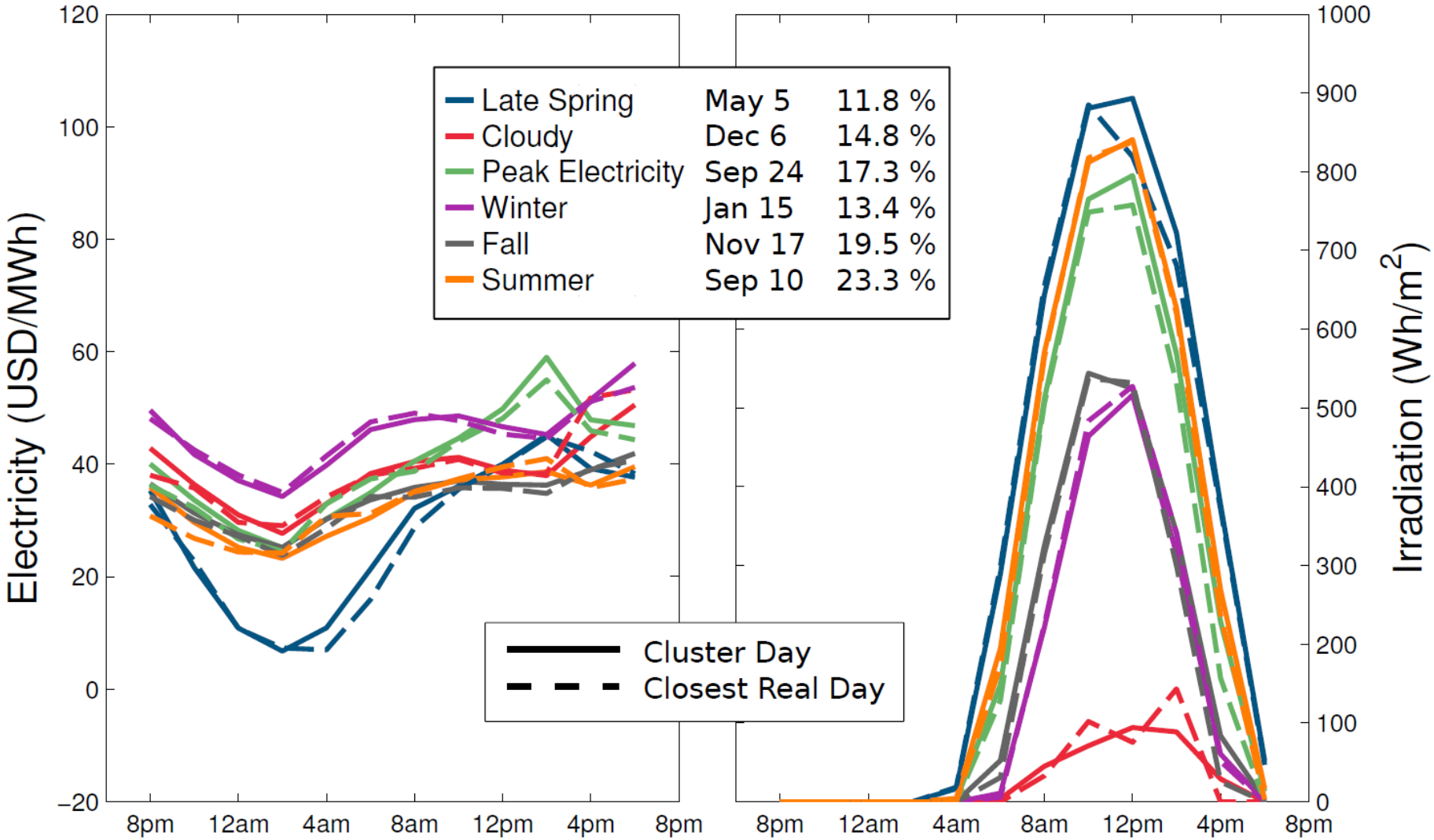
Optimization Overview



Data

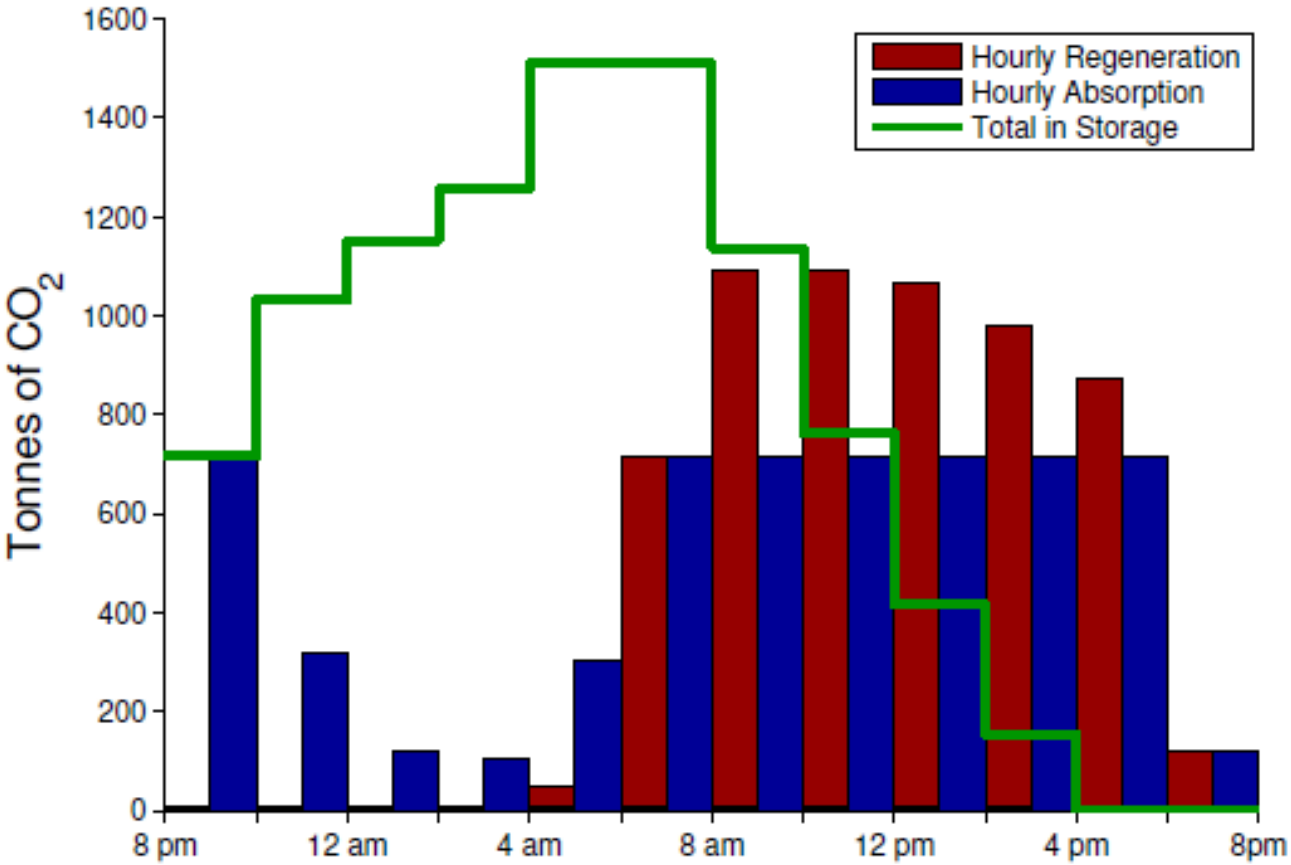
- Solar irradiation and electricity prices on an hourly basis are needed
- Hourly optimization is expensive, so there is a need to use a limited number of representative days
- k-means clustering is used to cluster data based on centroid values
- Clusters are based on a 24 element day vector – (12 irradiation, 12 electricity price)

Paired Electricity and Irradiation Data

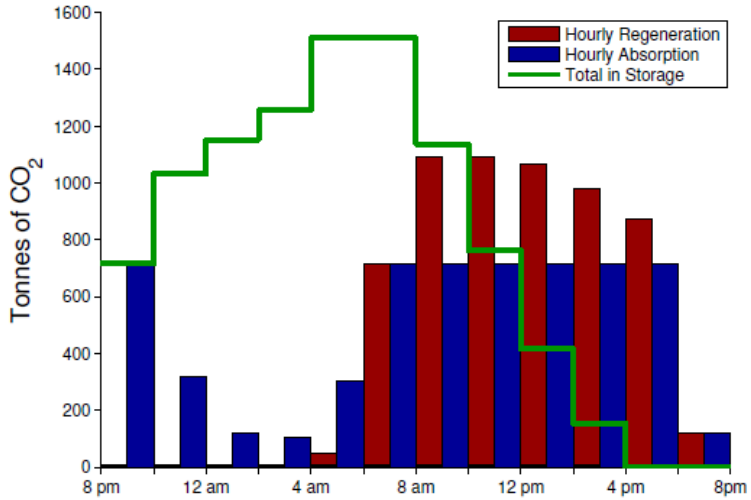


Capture System Operations in Solar Design

54.5 USD/MWh, 30% Investment Tax Credit



Late Spring Cluster



Late Spring Cluster

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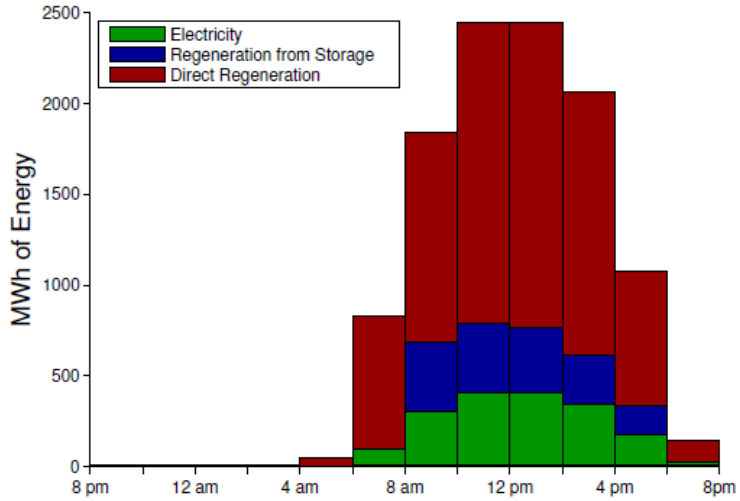
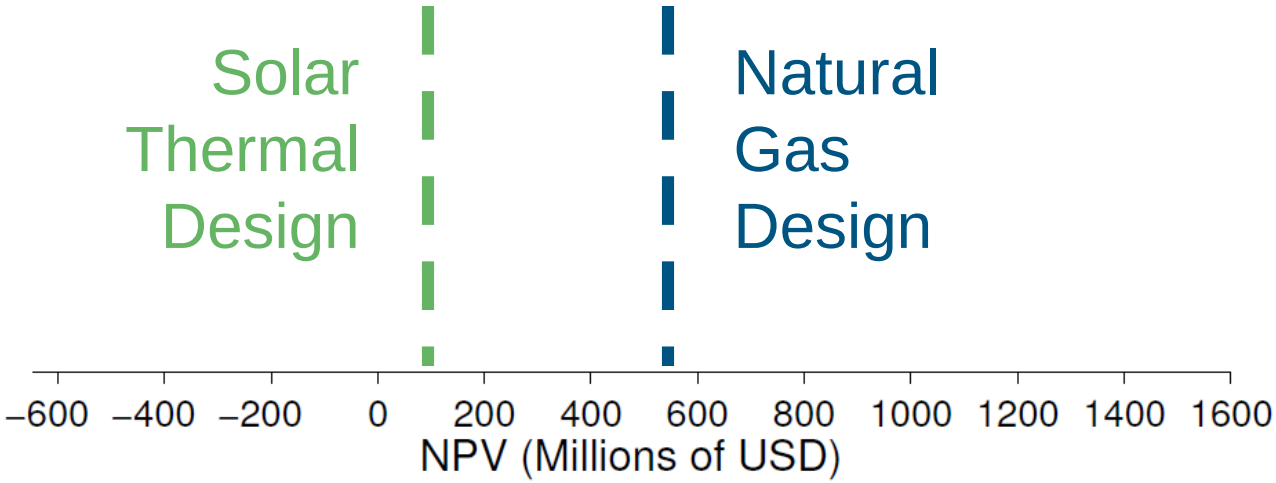


Late Spring Cluster

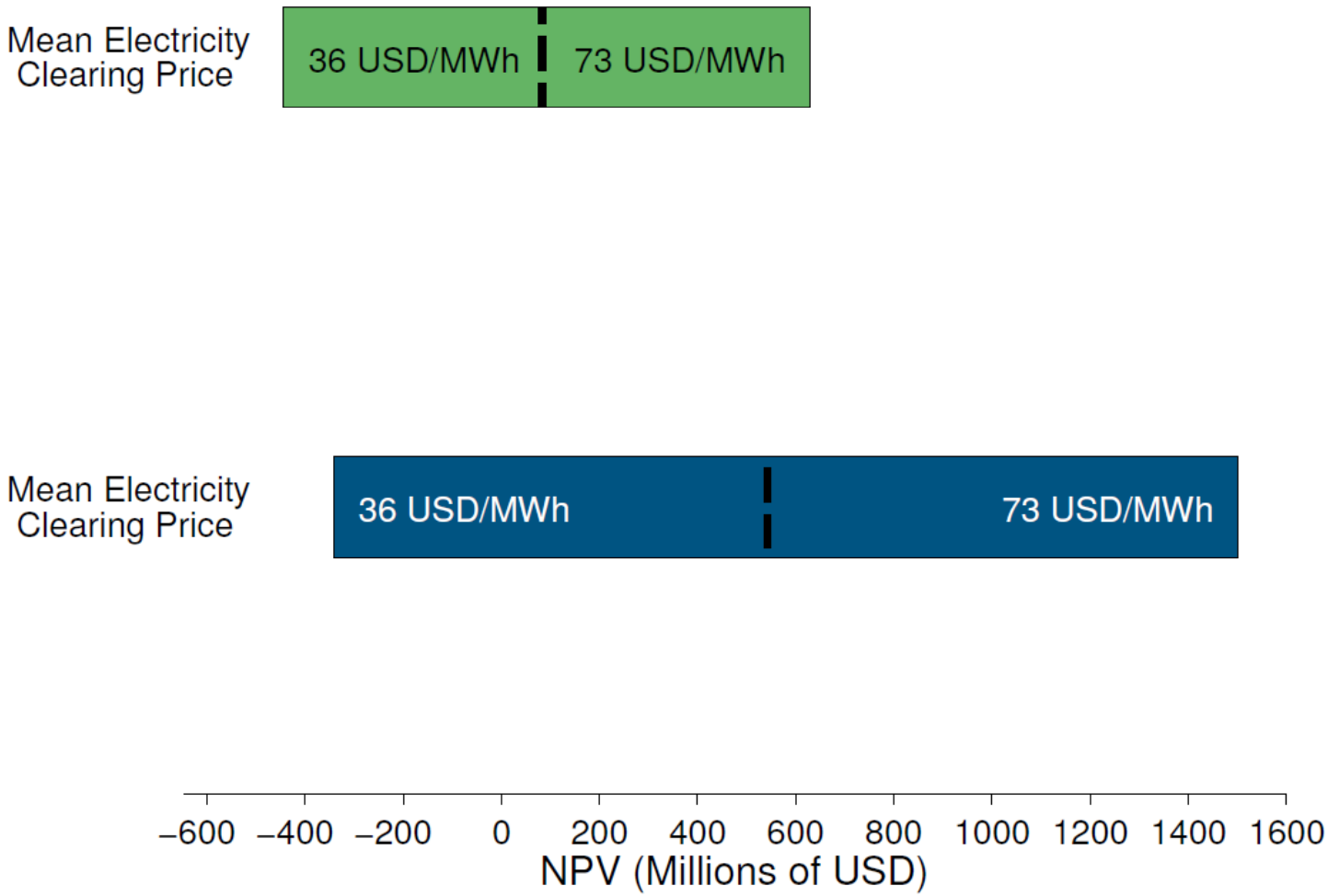
Solar Thermal System Operations

Base Case

Average Electricity Price: 54.5 USD/MWh
Natural Gas Price: 6.5 USD/GJ
Investment Tax Credit: 30%
Discount Rate: 8%



Parametric Study



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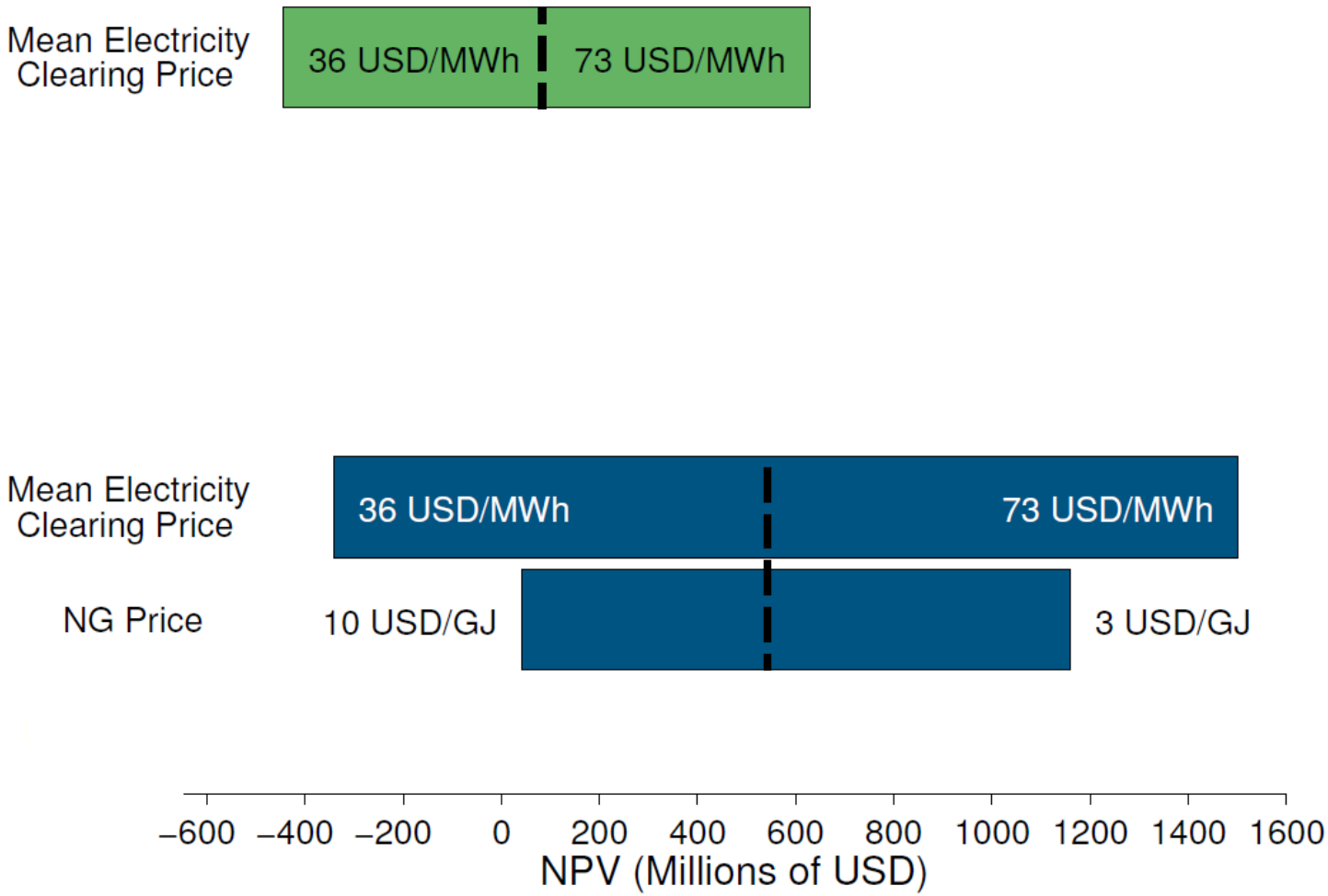

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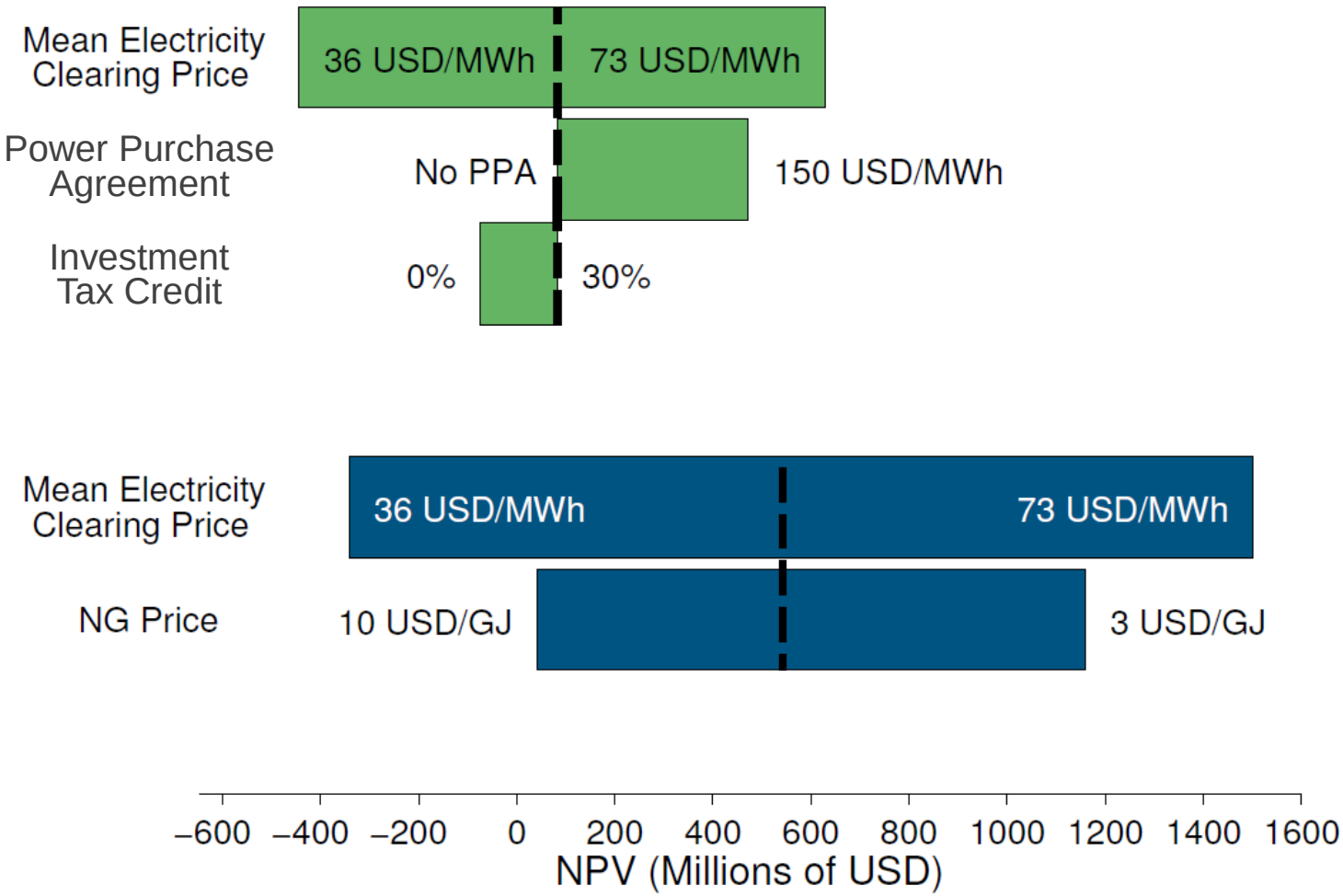

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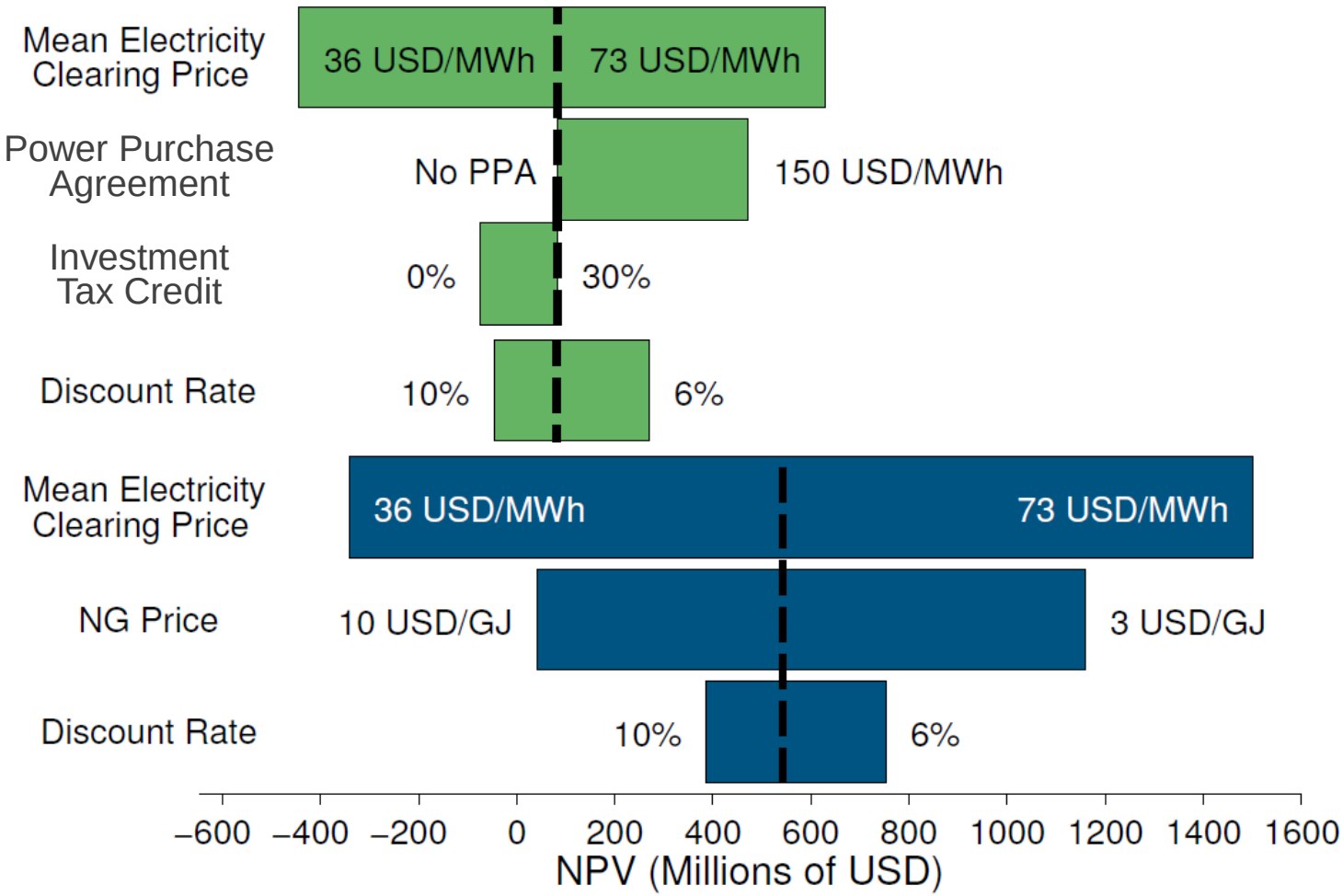
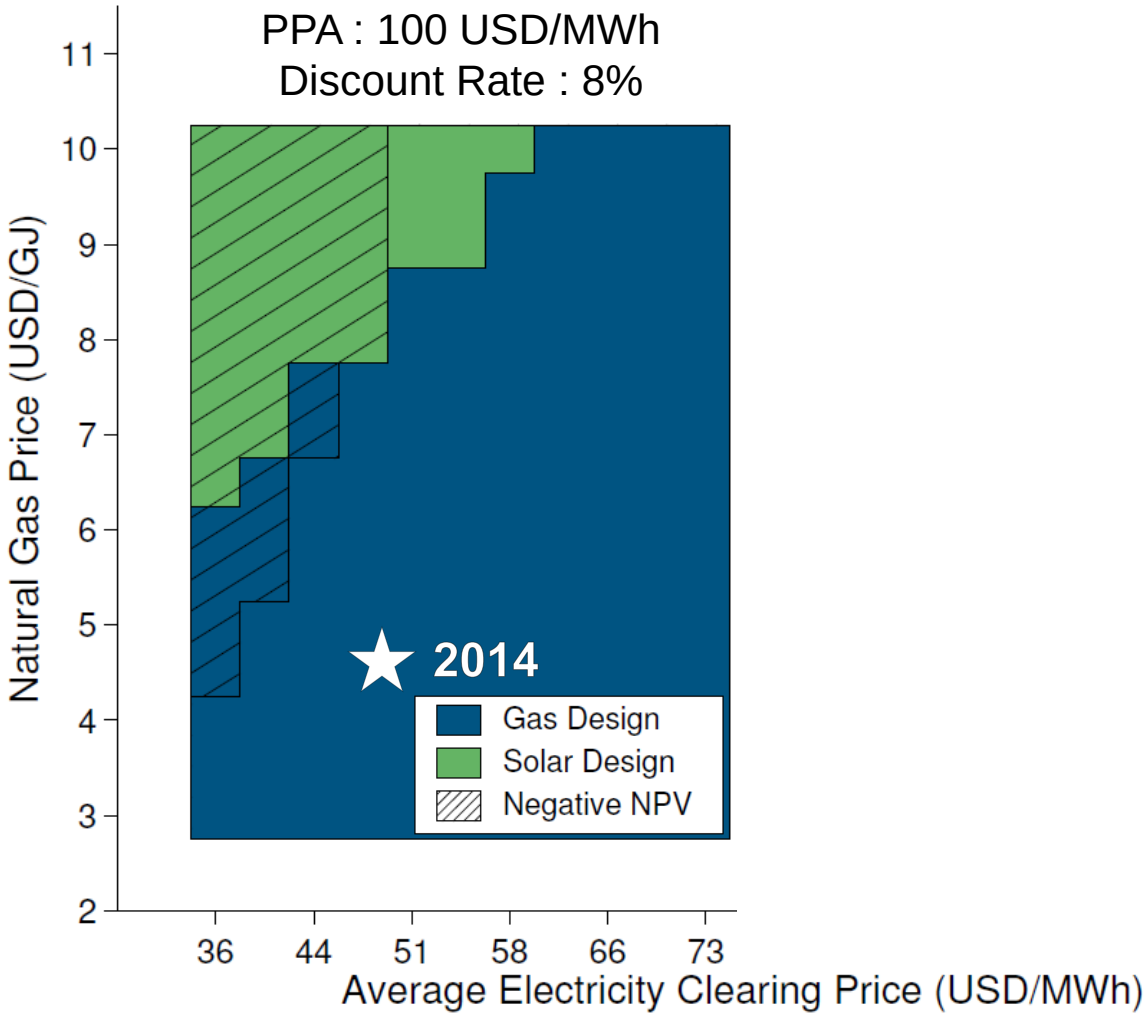


Solar / Natural Gas NPV Comparison



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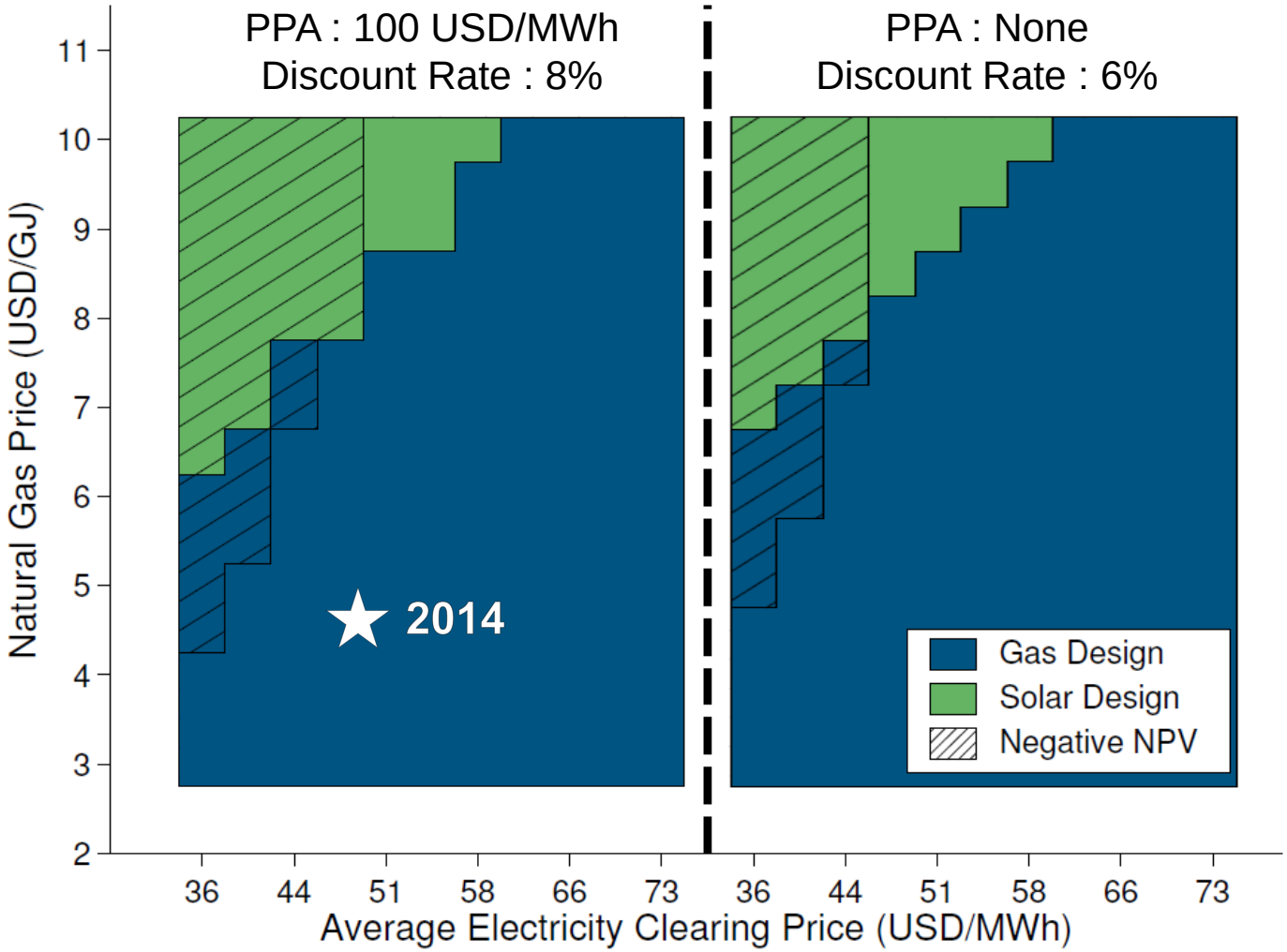


Concluding Remarks

- Developed a modeling and optimization procedure for CCS-enabled fossil fuel and solar thermal systems
- Solar thermal designs profitable with average electricity prices $\geq$ 54.5 USD/MWh and a 30% investment tax credit, though natural gas systems are generally preferable
- Future work may include more detailed system models, improved optimization procedures, the treatment of other locations, and additional carbon policies

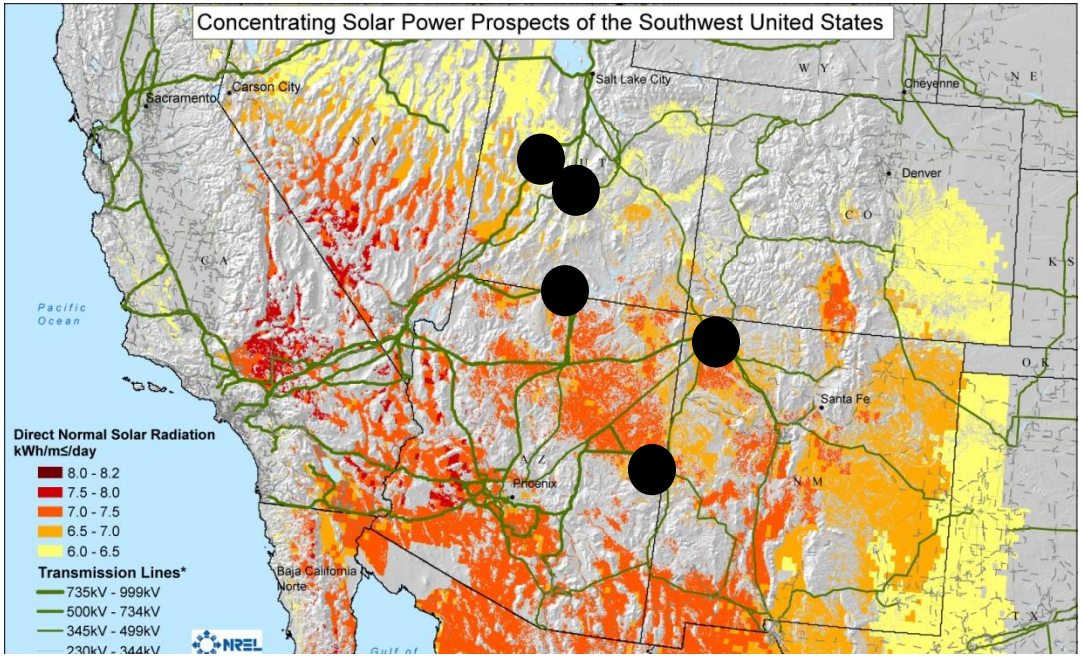
Acknowledgements

- John O'Donnell and GlassPoint Inc.
- Obi Isebor
- Stanford Center for Computational Earth and Environmental Sciences

Questions?

Problem Setup

- Coal Plant in New Mexico, exporting power to Southern California.
- System and component emissions cap at 499 kg / MWh, based on California Law SB 1368.



Optimization Problem

Design Optimization

$$\max_{\mathbf{x} \in X} \mathrm{NPV}(\mathbf{x}, \mathbf{u}) = -C(\mathbf{x}) + \sum_{\tau=1}^{N_{years}} \frac{P_\tau(\mathbf{x},\mathbf{u})}{(1-r)^\tau} \qquad \text{s.t.} \quad \mathbf{h}_{\mathrm{des}} + \mathbf{h}_{\mathrm{op}} \leq \mathbf{0}$$

Operations Optimization

$$\max_{\mathbf{u} \in U} \mathrm{P}(\mathbf{x}, \mathbf{u}) = \sum_{t=1}^{N_{time-steps}} (R_t(\mathbf{x}, \mathbf{u}_t) - E_t(\mathbf{x}, \mathbf{u}_t)) \qquad \text{s.t.} \quad \mathbf{h}_{\mathrm{op}} \leq \mathbf{0}$$

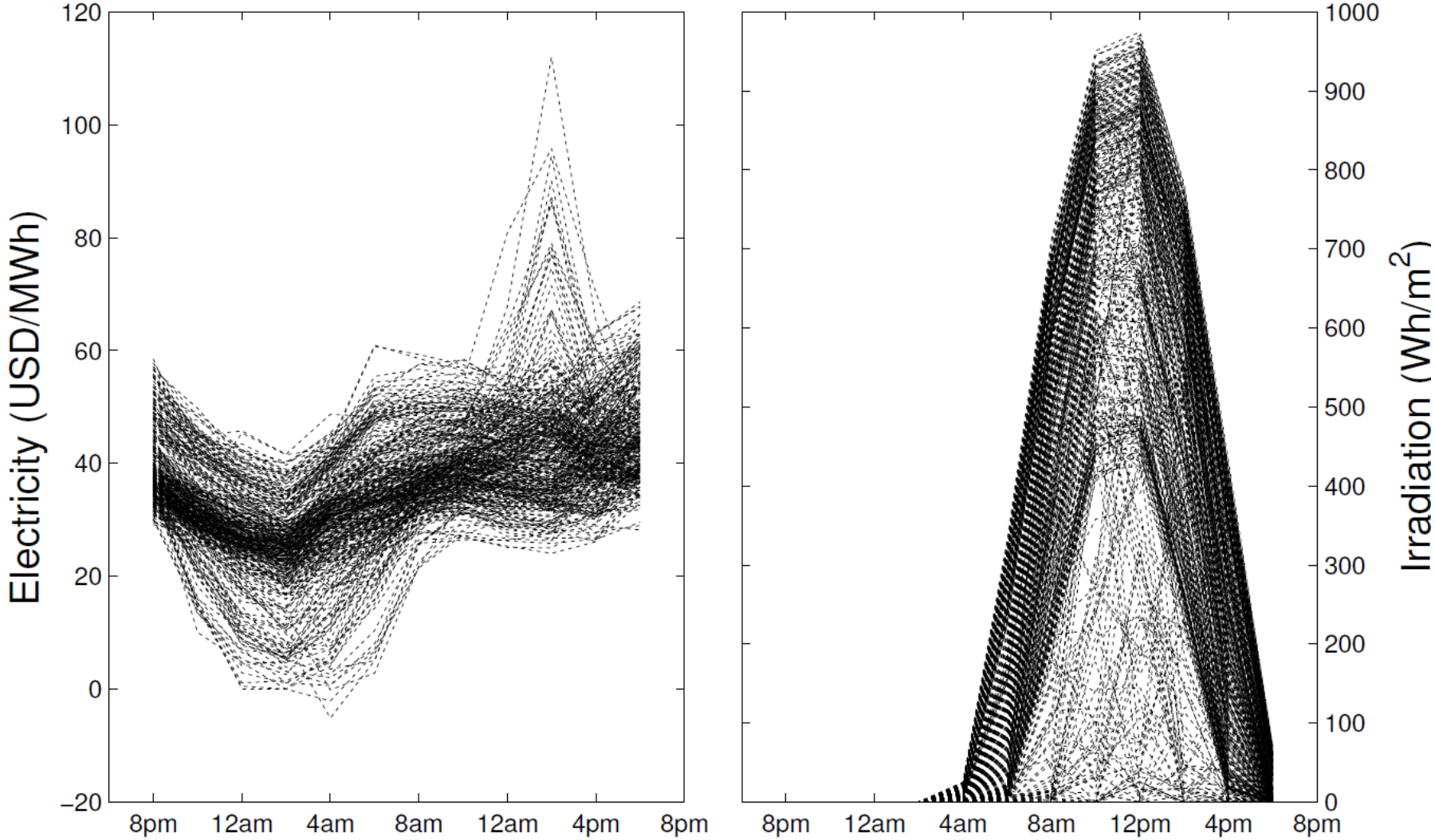
Optimization Algorithms

- Design Algorithm – PSO-MADS
  - Gradient free search
  - Handles discreet and continuous variables
- Dispatch Algorithm – SNOPT
  - Gradient based search algorithm
  - Handles continuous variables

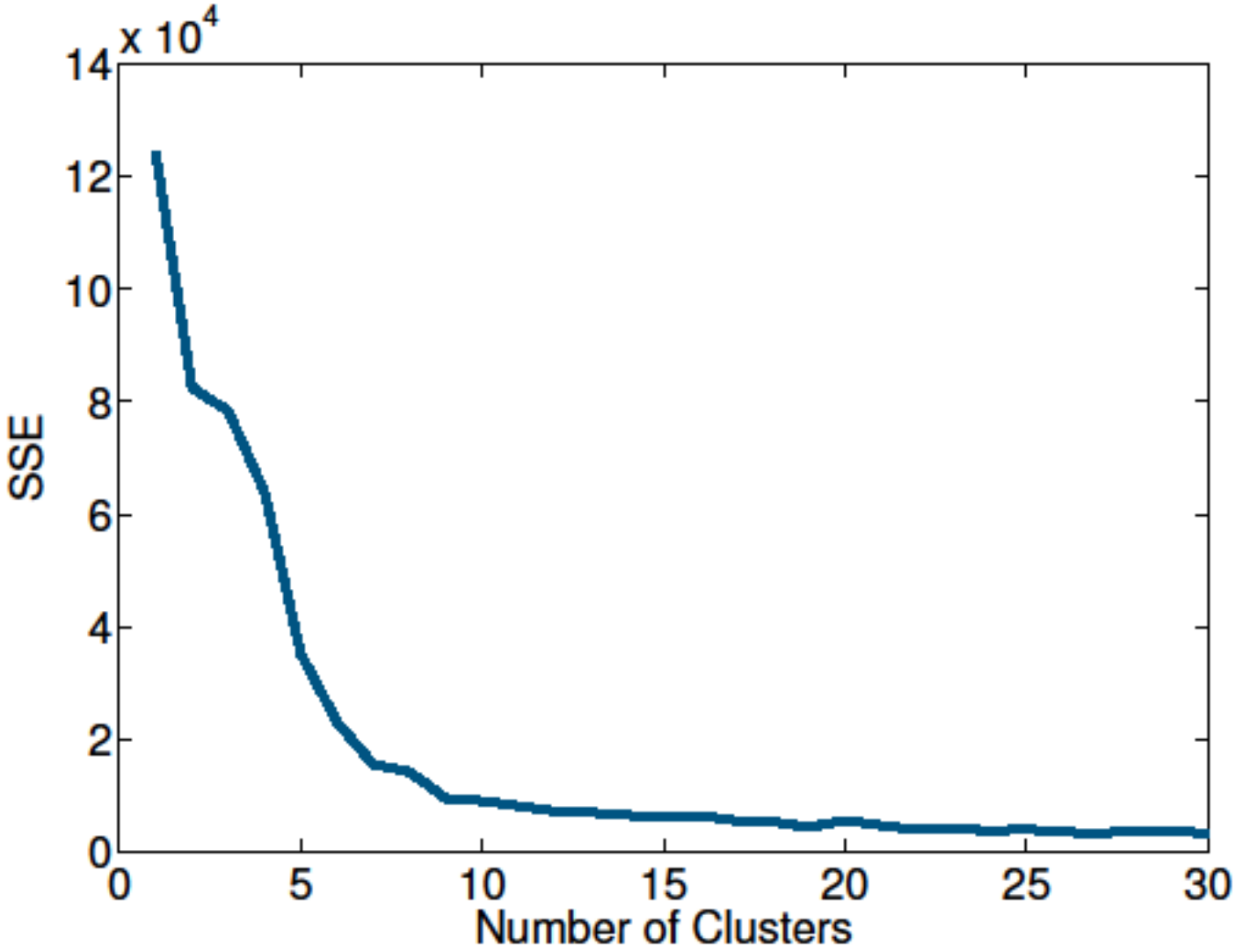
System Constraints

- CO_2 intensity – system and subsystems
- Total power production – limited to twice the coal plant capacity
- Mass balances

Paired Electricity and Irradiation Data



Accuracy vs Number of Clusters



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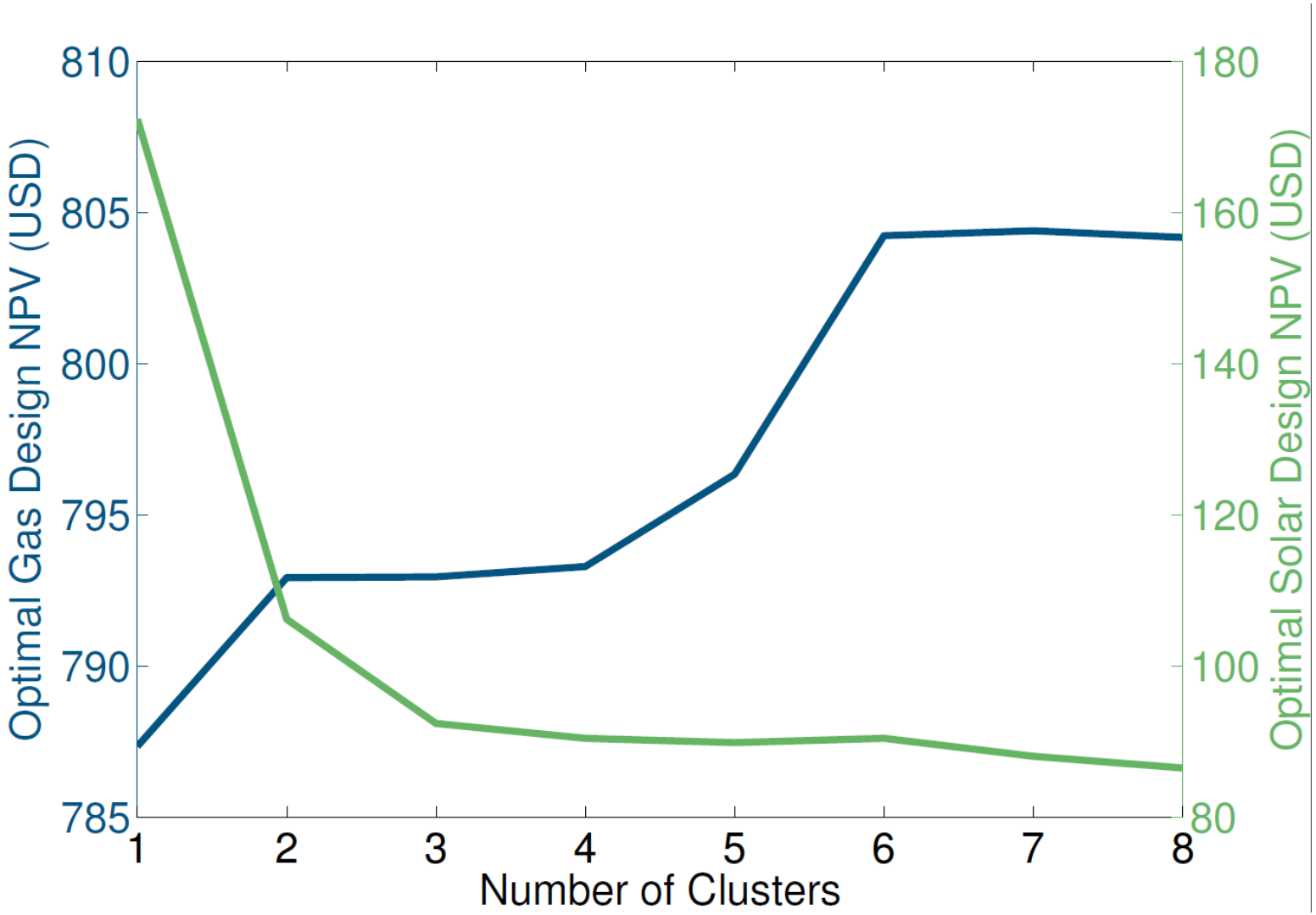
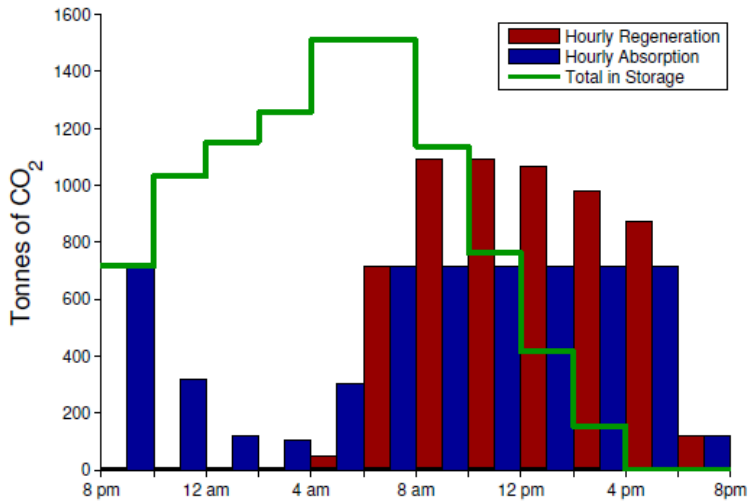
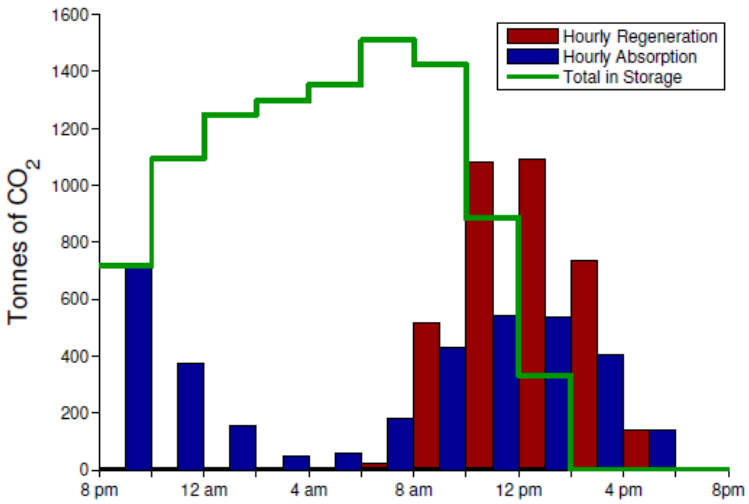
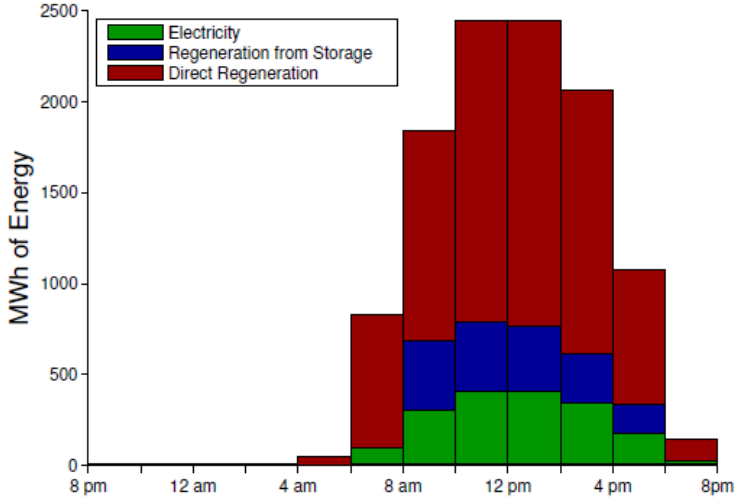
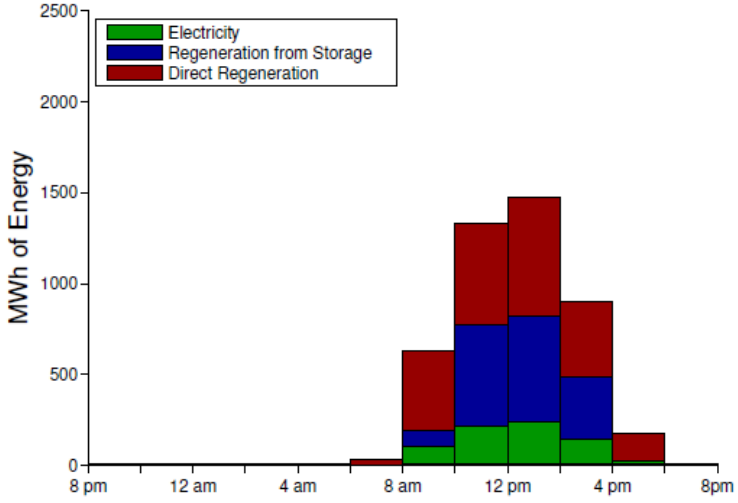






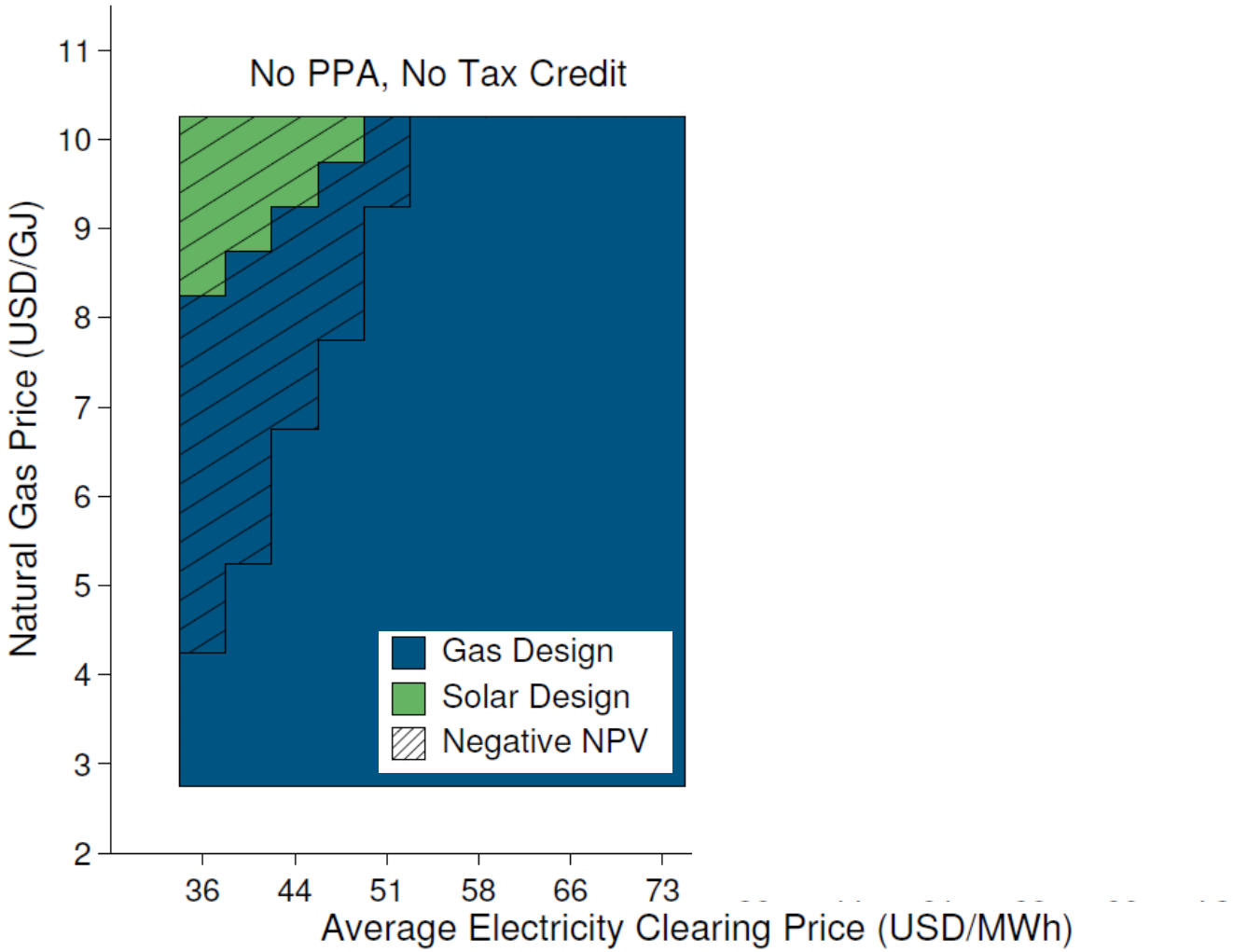




Early Summer Cluster

Winter Cluster

Solar / Natural Gas NPV Comparison (8% Real DR)



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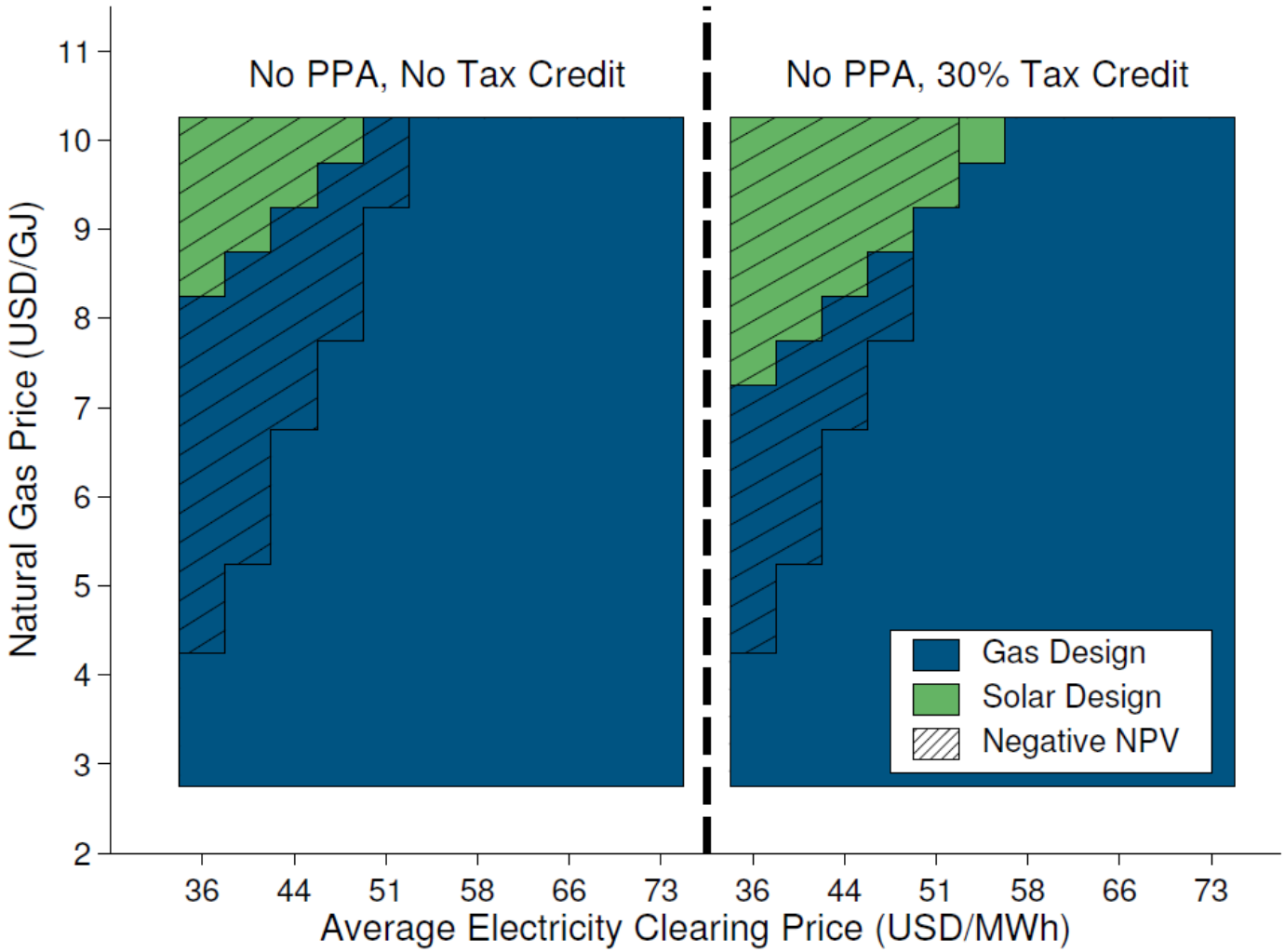

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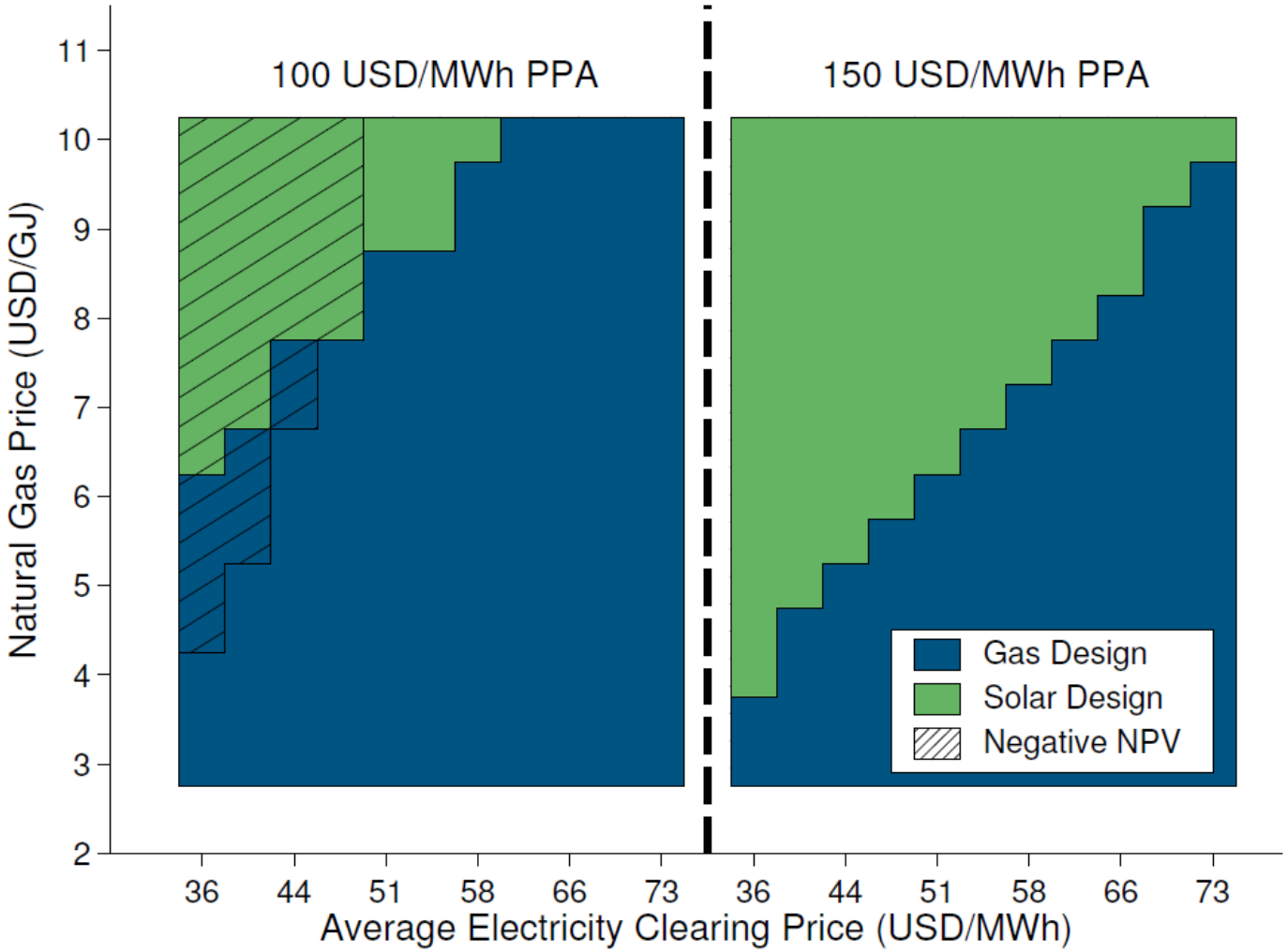

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