Robust Design for a Sustainable Future

Solar Desalination for Food and Water Security

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WaterFX, Inc.

Seminar Outline

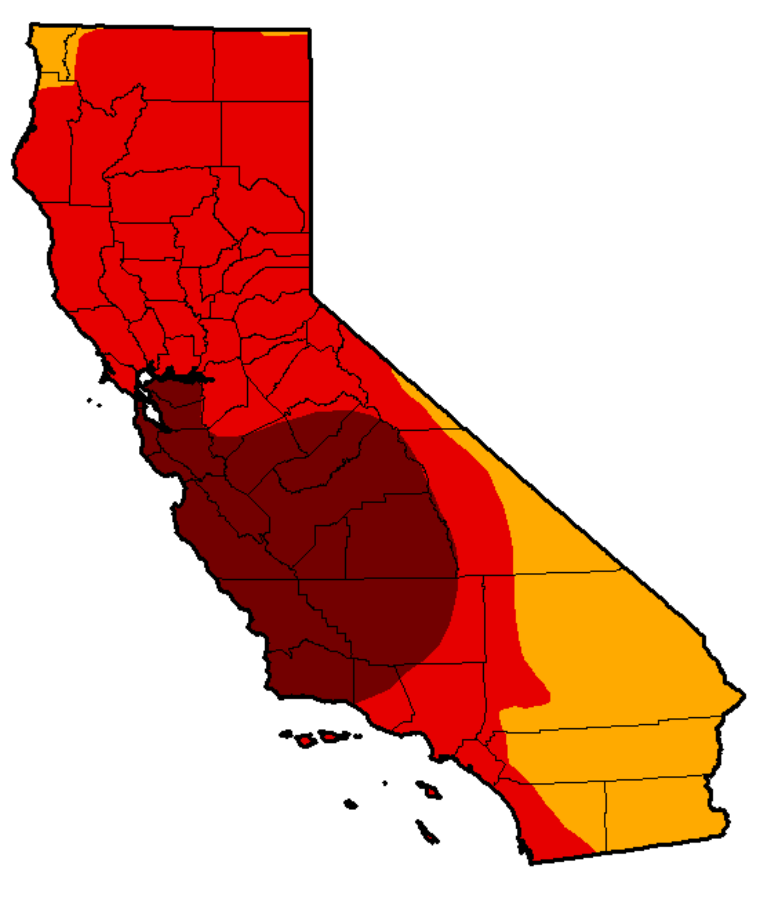
- Introduction to the Problem and Motivation
- Process Design and Modeling a Solution
- Mathematical Problem Formulation
  - Robust Optimization, Semi-Infinite Programming Background and Relevance
- Solution Results and Discussion
- Conclusion

Introduction and Motivation

- CA is home to the most productive agricultural region in the US
- Most recent crop report: $54B in revenue generated
- 99% of the nation's supply and 50% of the world's supply of raisins come from Fresno county
- 79% of human-used water goes to agriculture

Introduction and Motivation
California's Unprecedented Drought

June 2014



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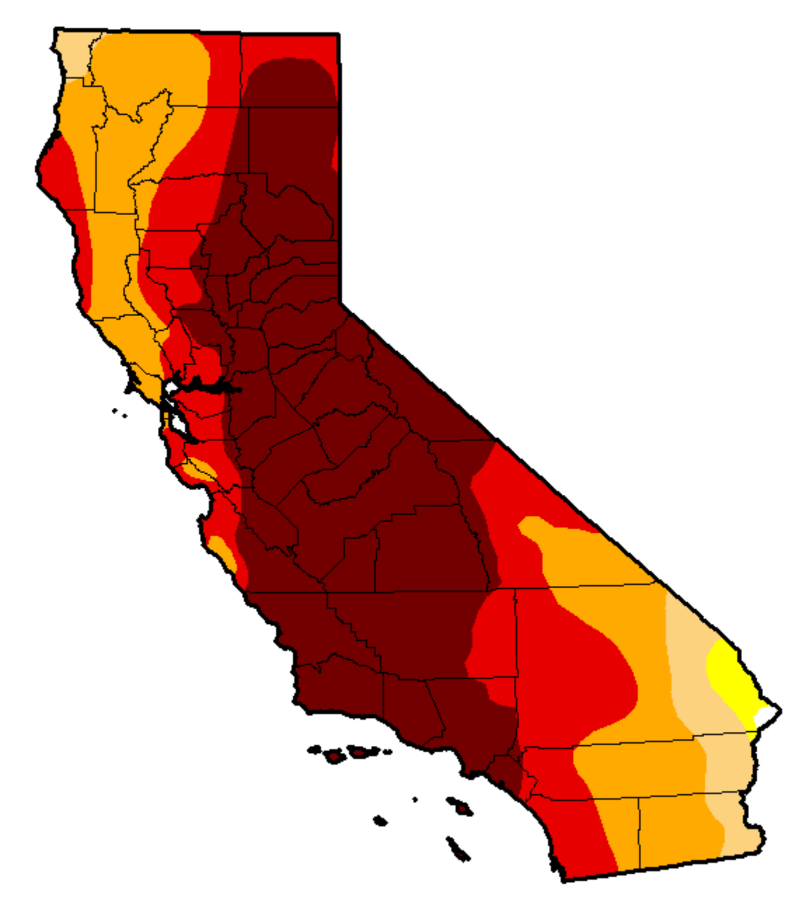

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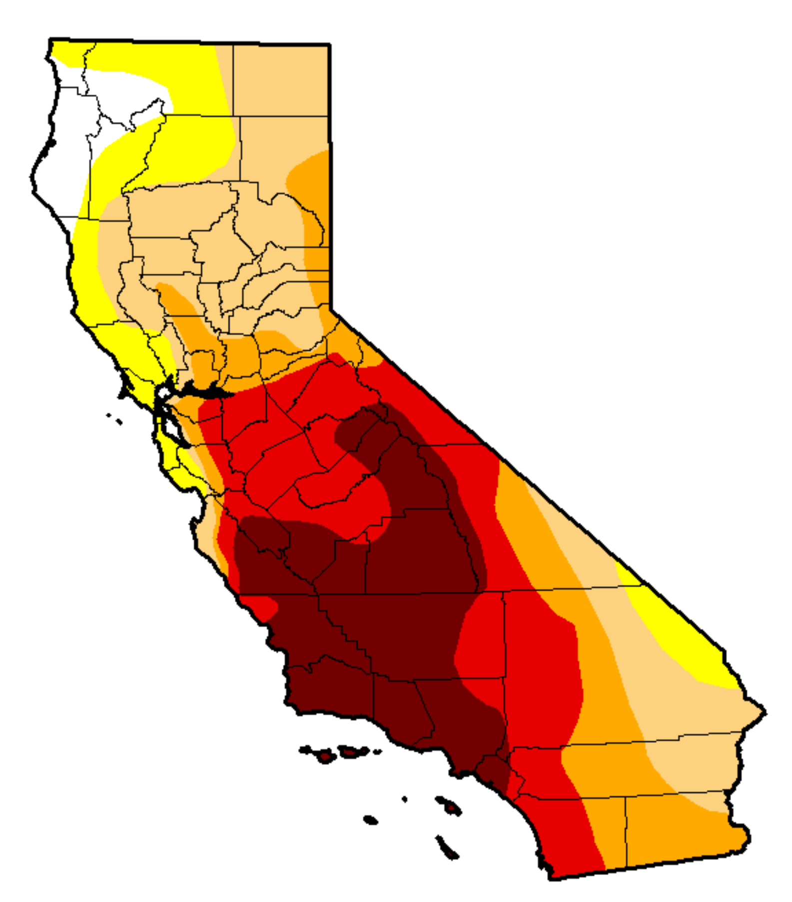
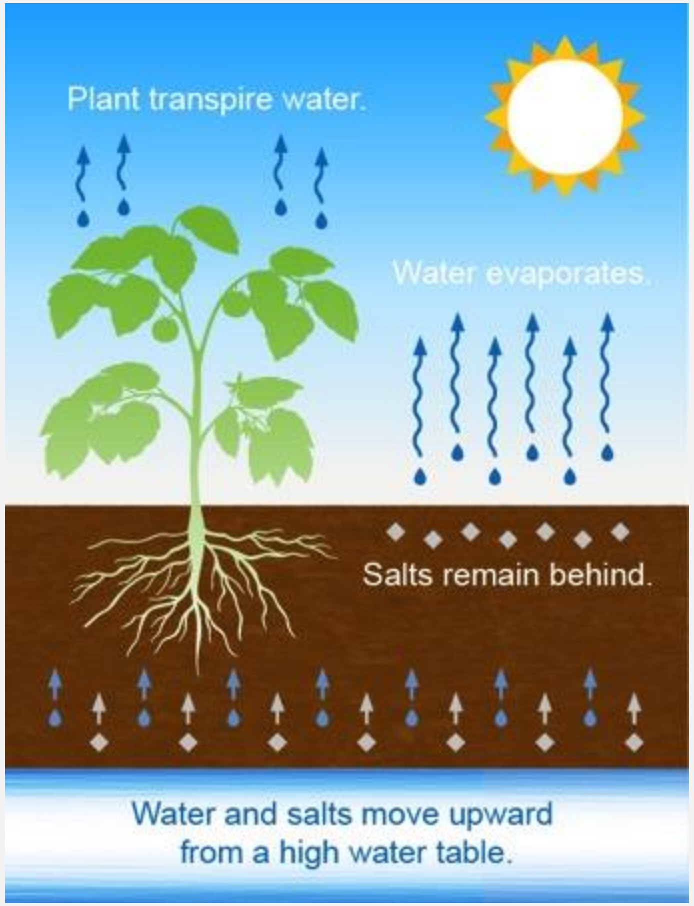
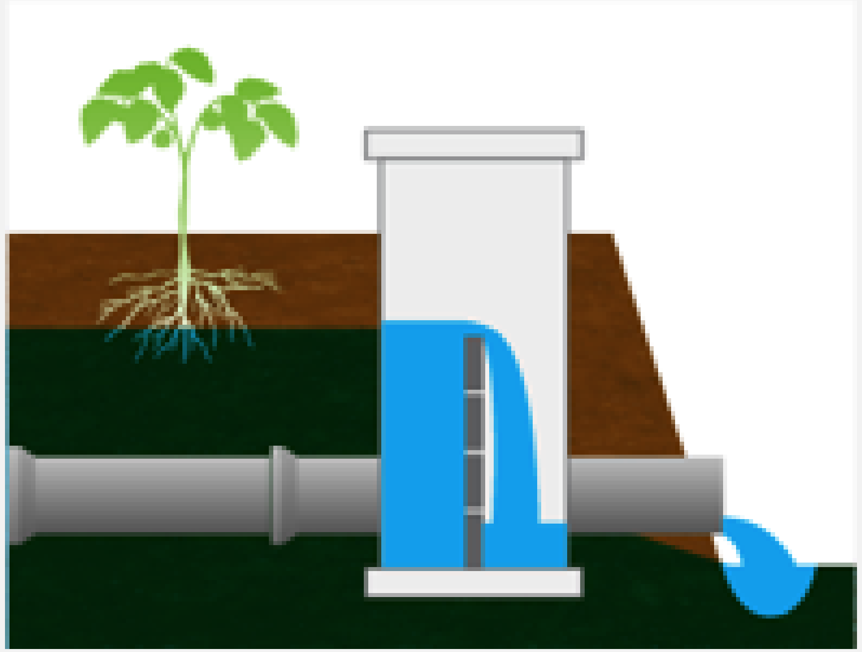


Introduction and Motivation
Salt Imbalance

accumulation = in – out + generation - consumption





Introduction and Motivation
Salt Imbalance

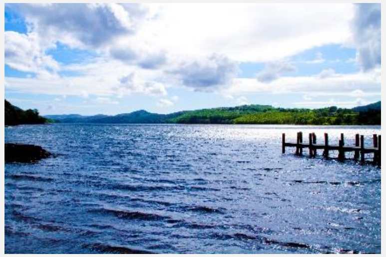
- Natural processes and agricultural irrigation operations accumulate salts in the region
  - 275tons/hr (2001 report rate[1])
  - includes materials classified hazardous
- Unique soil conditions make groundwater shallow
  - Water applied to the soil saturates crop root zones, dissolving salts, and become toxic to crops
- By 2030, 15% of arable land will need to be retired, 40% on the west side of the San Joaquin Valley[2]

1. CA DWR, Water Facts: Salt Balance in the San Joaquin Valley, No. 20, 2001
2. R. Howitt, J. Kaplan, D. Larson, D. MacEwan, J. Medellín-Azuara, G. Horner, et al., The Economic Impacts of Central Valley Salinity, Tech. rep., University of California Davis, 2009

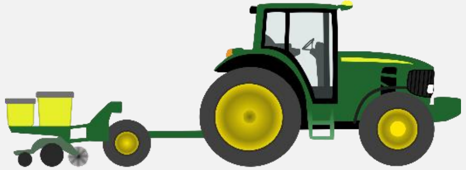
Introduction and Motivation
Summary

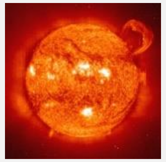
- Limited and unreliable water supply
  - Climate change driven drought, economic and population growth
- Irrigation causes salt accumulation in soil
  - Impairs soil, environmentally hazardous, reduces productivity
- Soil salinity control produces extraordinary quantities of saltwater

Introduction and Motivation



$\dot{W}, \dot{Q}, h\nu$





H_2O + impurities

$$\frac{dm_{\text{salt}}}{dt} > 0 \Rightarrow \frac{d\eta}{dt} < 0$$

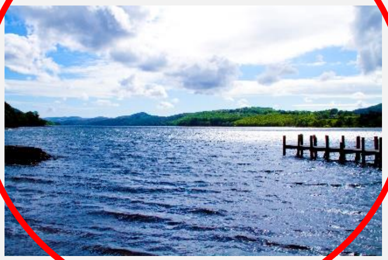
sulfates, nitrates, phosphate

product

biomass

waste

Introduction and Motivation



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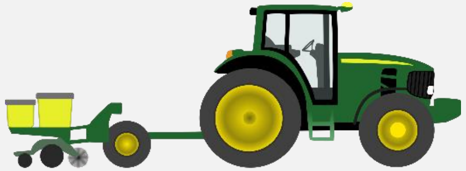

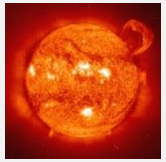

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Process Design and Modeling a Solution Objective

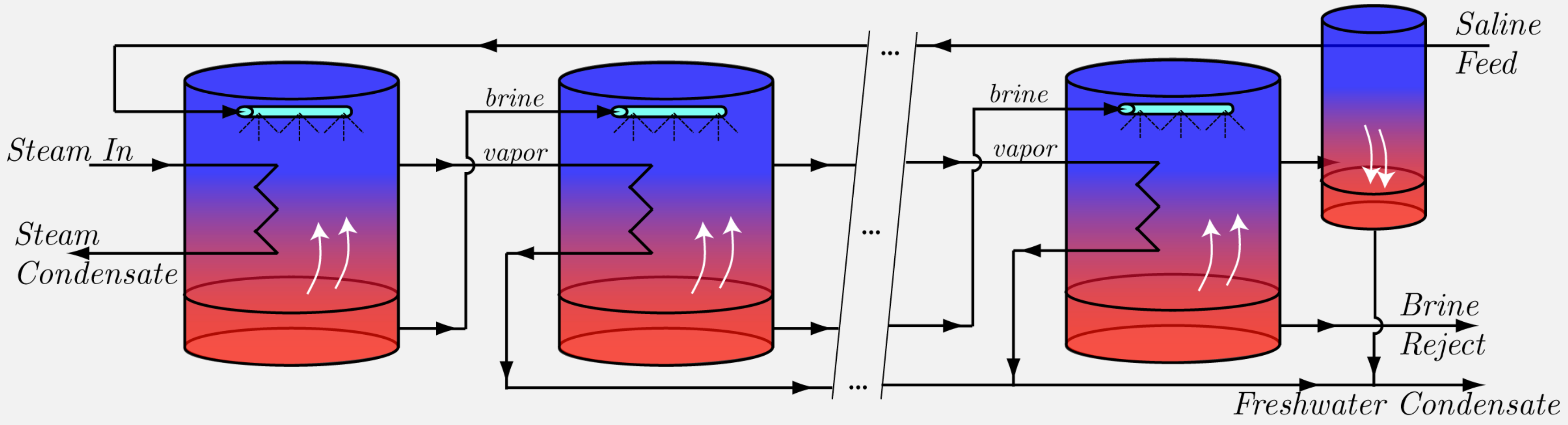
- Primary Objective: Treat the saline wastewater to very high recovery, sequester the salts, and return freshwater
  - Increase the overall water-use efficiency of the sector
  - Reduce and eventually eliminate salt accumulation problem (and its effects)
  - Increase the production efficiency of the land through sustainable drainage management

Process Design and Modeling a Solution
Design Criteria and Constraints

- Flexibility: varying feed quality/chemistry
- Robust: high salinity, scaling, crystallization, corrosion
- Reduced dependence on fossil fuels and grid power, reduced emissions
- Near-zero to zero liquid discharge, solids recovery

Process Design and Modeling a Solution

- Basis for design: multi-effect distillation



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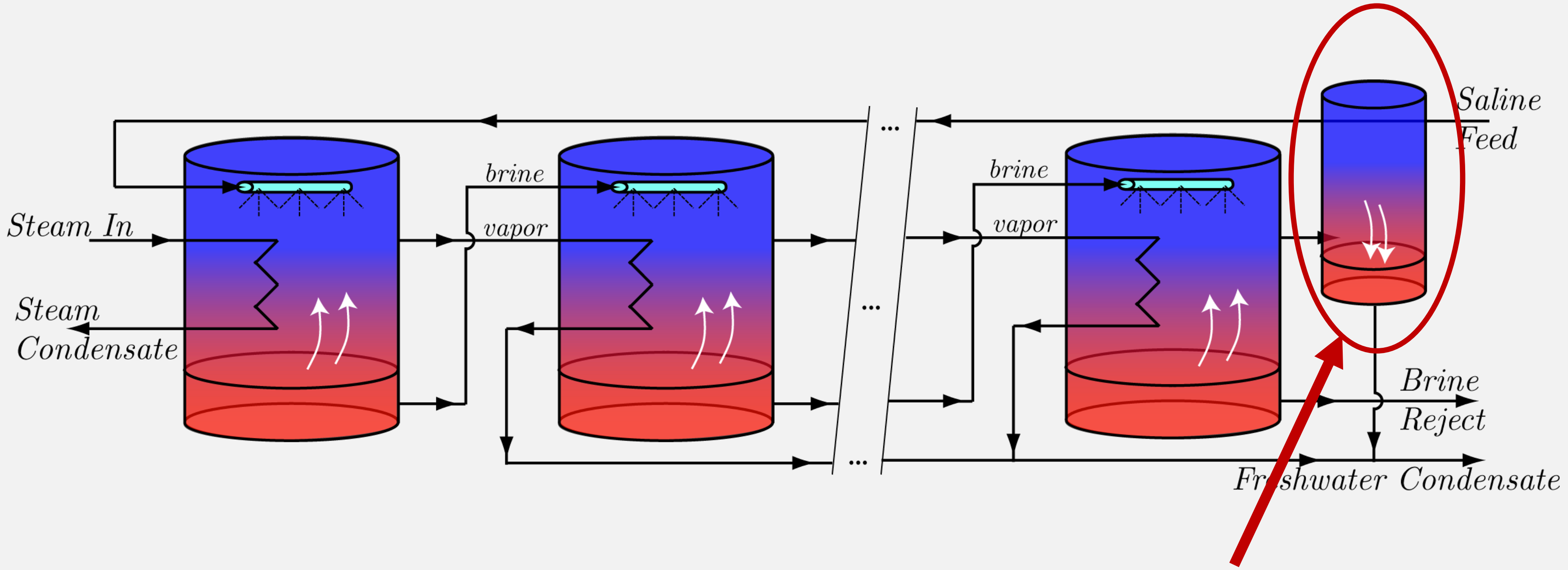
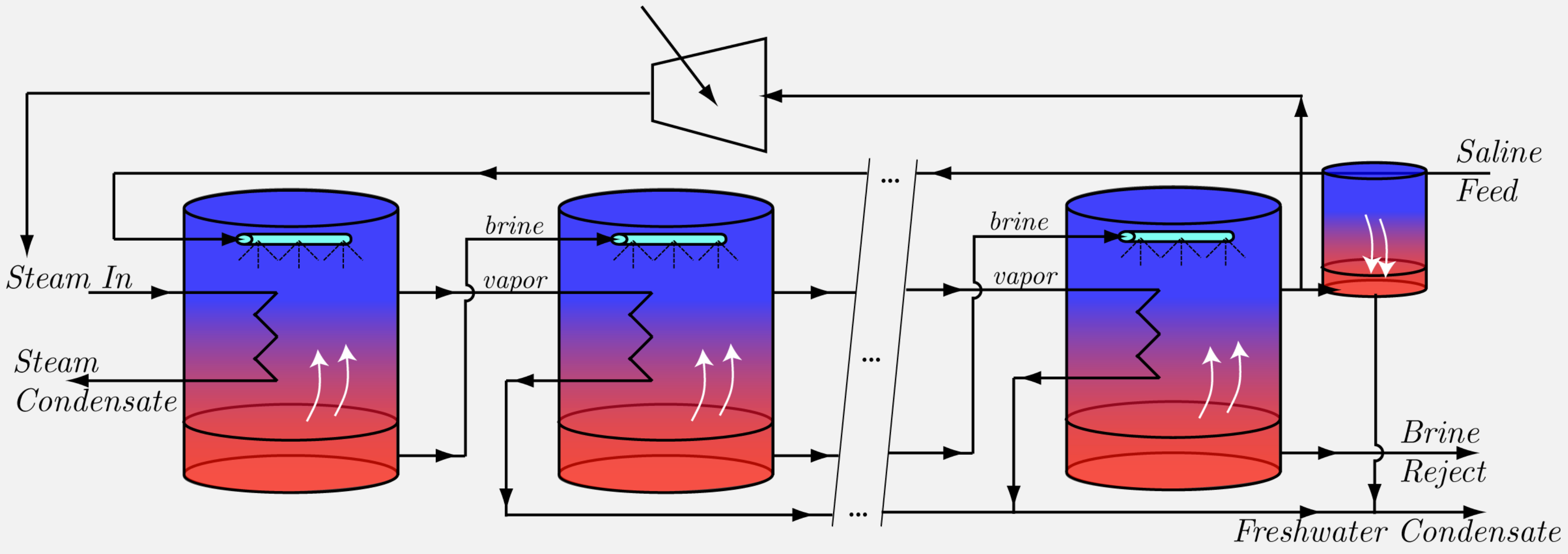
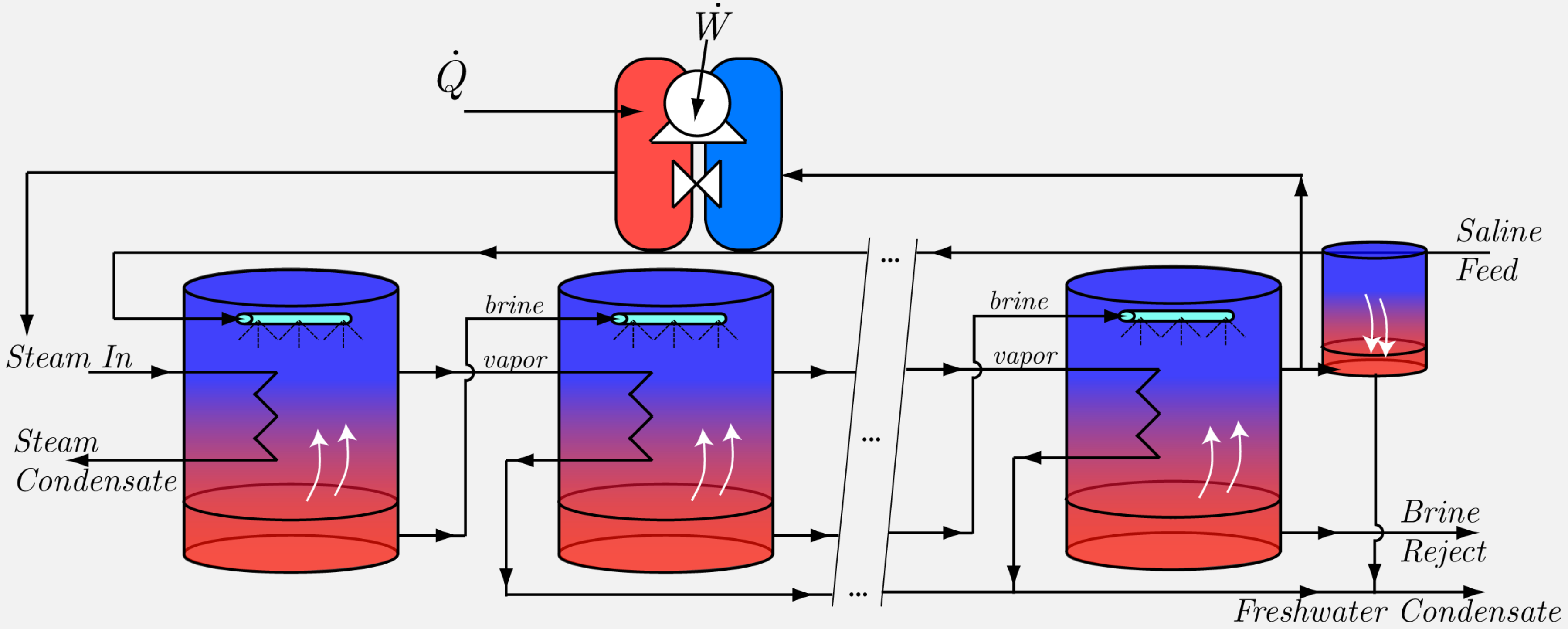


Single greatest source of entropy generation

Process Design and Modeling a Solution Waste-Heat Recovery

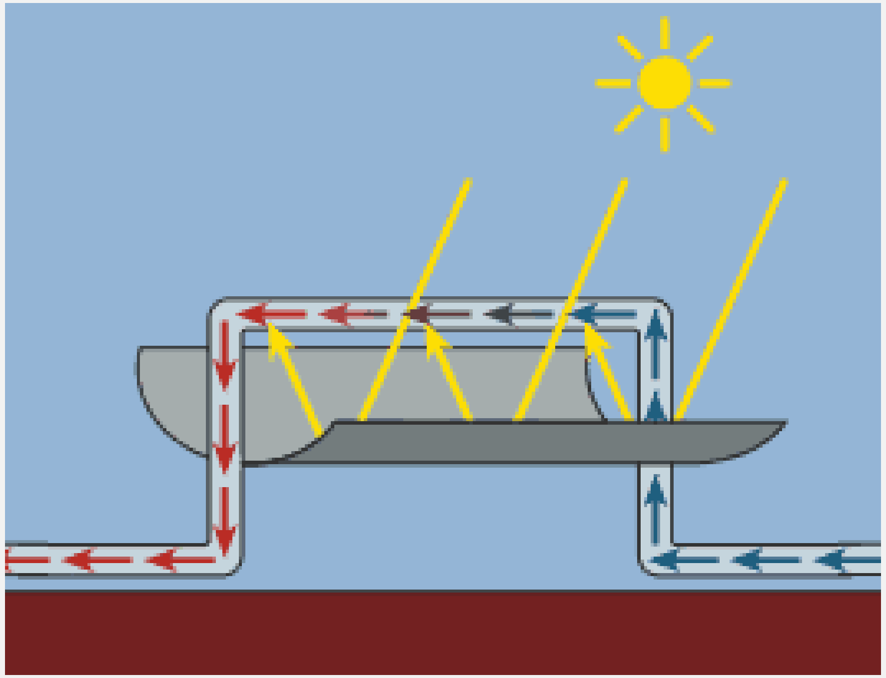


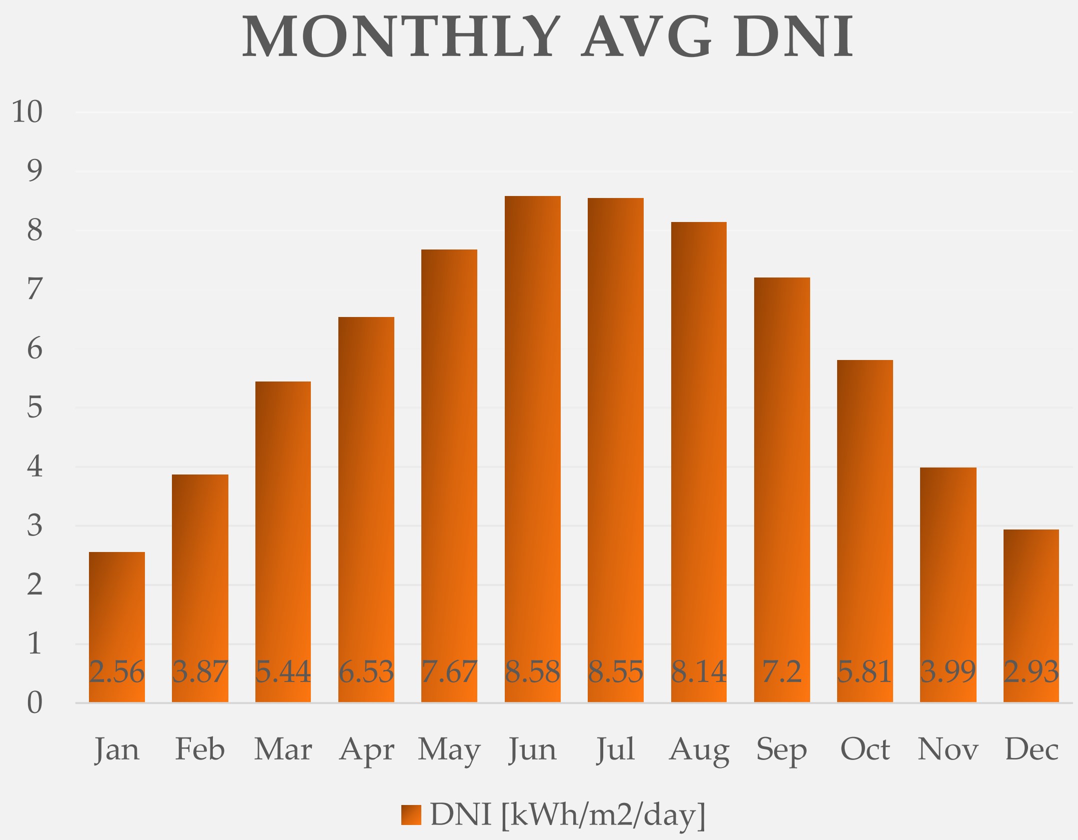
Process Design and Modeling a Solution Waste-Heat Recovery



- 10-effect MED
- Heat integration with inter-stage preheating and vapor absorption

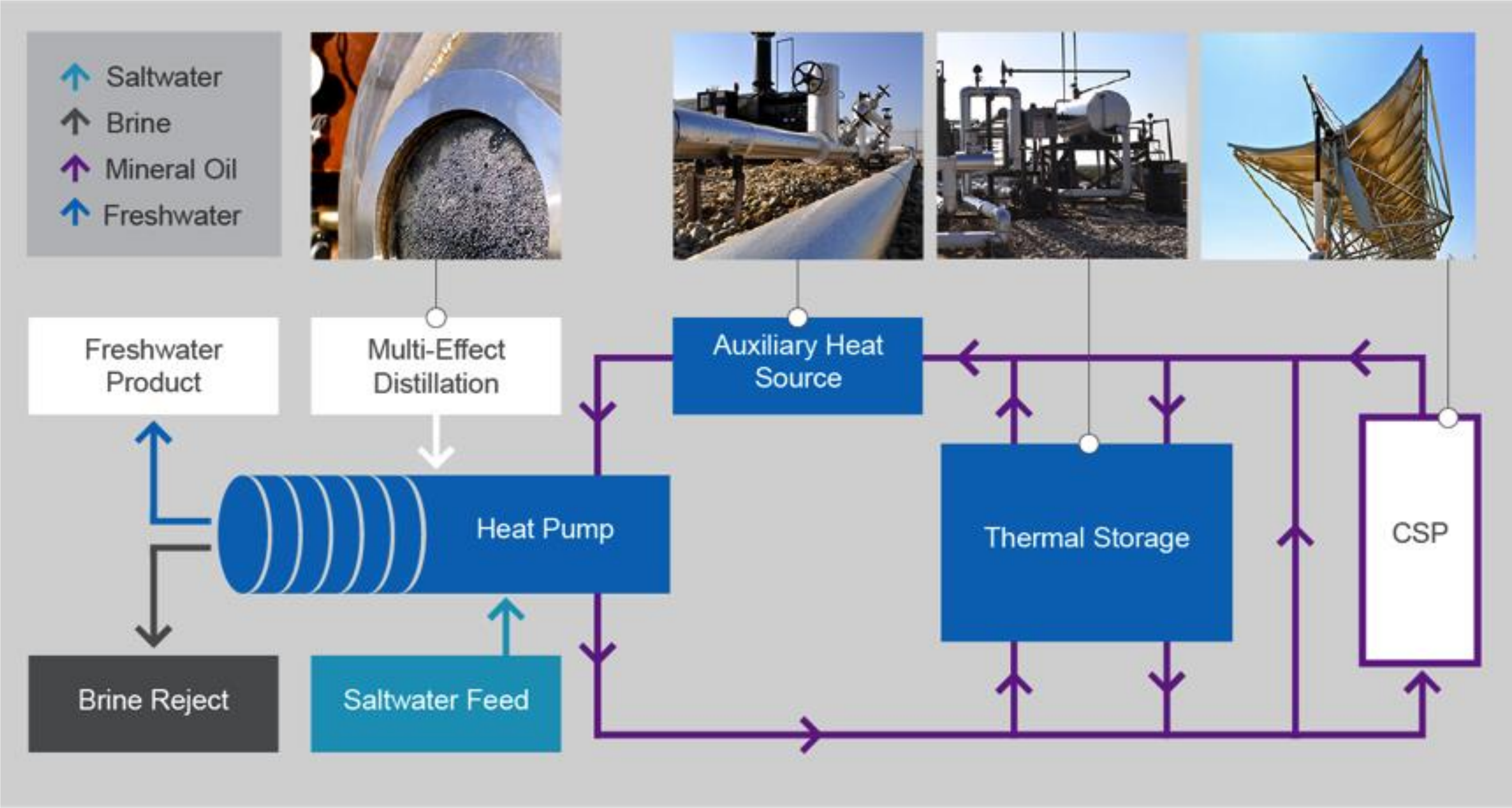
Process Design and Modeling a Solution
Concentrated Solar



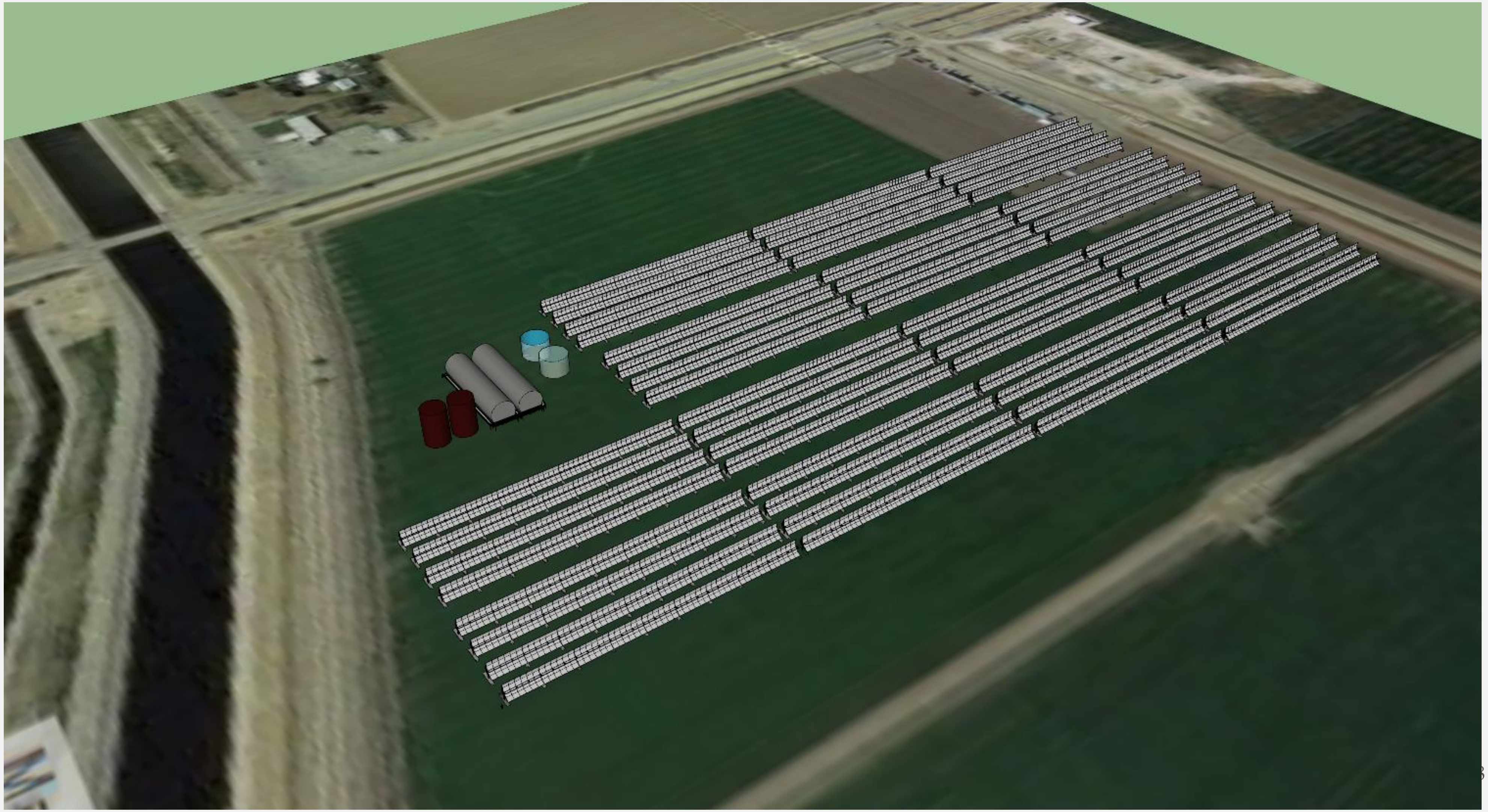


- Single-axis tracking large-aperture parabolic trough
  - Vacuum tube receiver
  - N-S orientation
- Solar resource data input from the NREL database
  - Specific coordinates
  - 8760h/year format

Process Design and Modeling a Solution



Process Design and Modeling a Solution
Large-Scale Deployment



Mathematical Problem Formulation
Model Considerations and Assumptions

- Without a solution, retire 10% growing region by 2035 due to salt impairment
  - Continue irrigation and operate agribusiness
- Desalination for drainage reuse
  - Prevent growing region retirement (salt impairment)
  - Reduce water footprint of agriculture
  - Generate a new income source for growers (M&I sales)
  - Increase water for municipal use

Stuber, M D, Optimal design of fossil-solar hybrid thermal desalination for saline agricultural drainage water reuse. *Renewable Energy*, 89, pp 552-563, 2016.

Mathematical Problem Formulation
Model Considerations and Assumptions

- Desalinate all available drainage water: 22,500 acre-ft/yr (27.75M m^3/yr)
- Fixed inflation on food/ag revenues and energy prices
- Debt financing, 10y amortization, 20y project
- Optimal design of solar field and storage for natural gas offset
- Water sales at market rates (parameter)
- Uncertainty in natural gas pricing (parameter)

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Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Logical constraint:

$$\forall \; C_{\text{water}}, C_{\text{gas}} \; \in F_C \exists \; N_S, H \; \in F_d : f_{\text{NPV}} \geq 0$$

$$F_C \; : \text{parameter (uncertainty) space}$$

$$F_d \; : \text{design space}$$

$$f_{\text{NPV}} \; : \mathbb{Z} \times \mathbb{R} \times \mathbb{R} \times \mathbb{R} \to \mathbb{R}$$

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Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Parametric Optimization

$$f^*_{\mathrm{NPV}}(C_{\mathrm{water}}, C_{\mathrm{gas}}) = \max_{N_s, H} f_{\mathrm{NPV}}(N_s, H, C_{\mathrm{water}}, C_{\mathrm{gas}})$$

$$\text{s.t. } N_s \in \; n \in \mathbb{Z} : 13 \leq n \leq 52$$

$$H \in \; h \in \mathbb{R} : 0 \leq h \leq 12$$

$$C_{\mathrm{water}} \in \; h \in \mathbb{R} : 1800 \leq c \leq 2200$$

$$C_{\mathrm{gas}} \in \; c \in \mathbb{R} : 6 \leq c \leq 9$$

N_{S} : no. of PTCs per module

H : no. of hours of thermal storage

C_{water} : water contract price \$/acre-ft

C_{gas} : natural gas price \$/mmbtu

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Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Simple Example:

$$f^*(p) = \max_{x \in [-5,5]} [-x^2 - p]$$

$$p \in [-2, 2]$$

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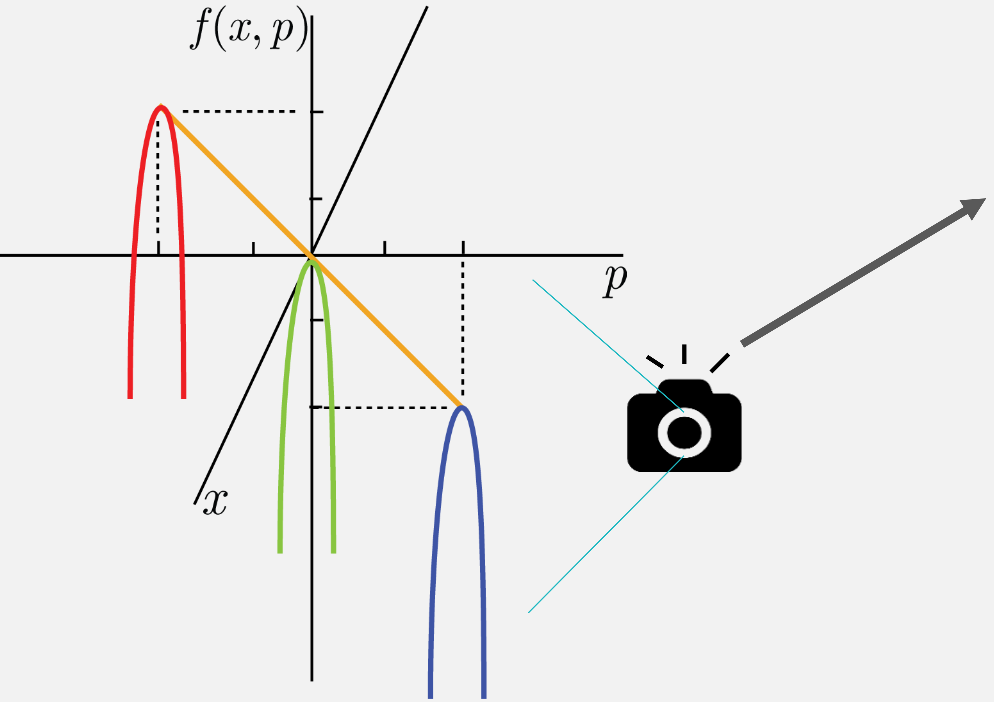
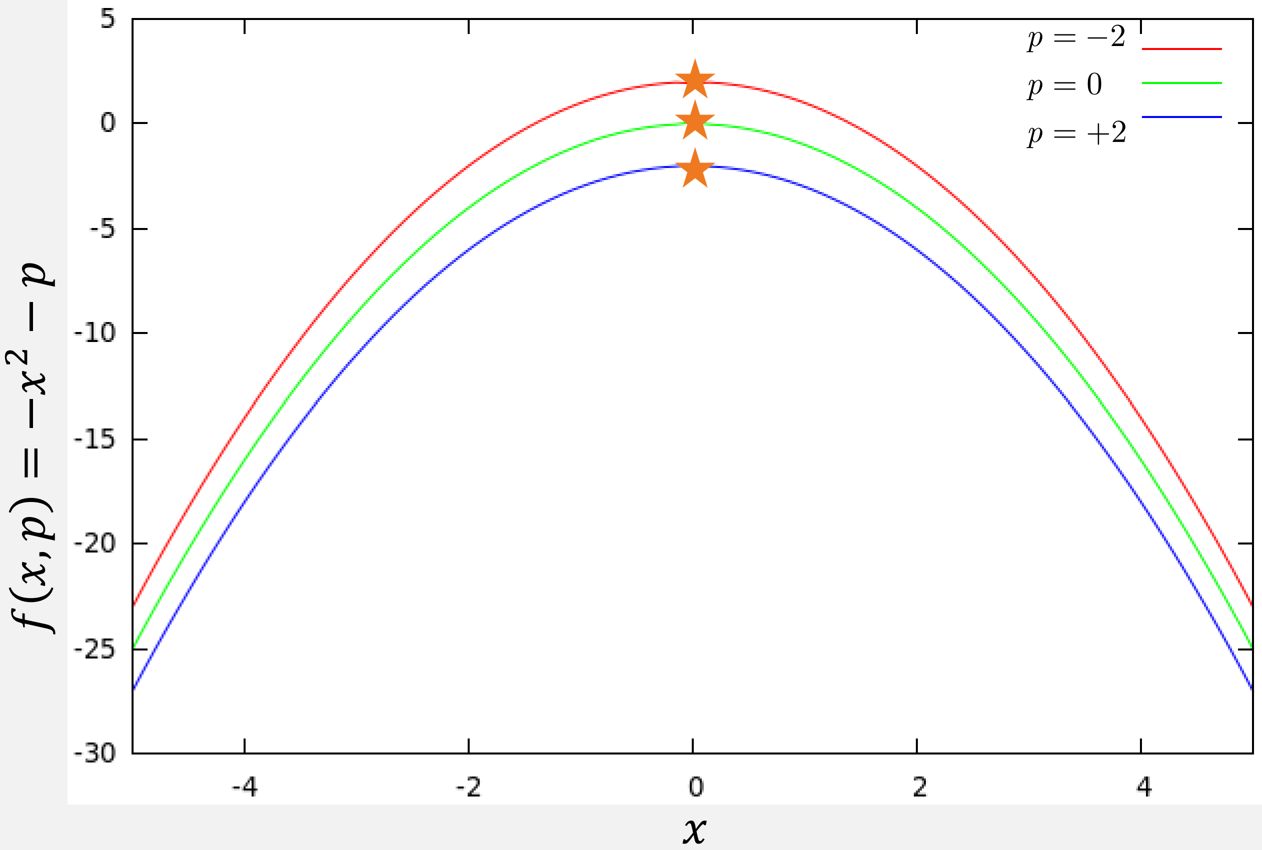
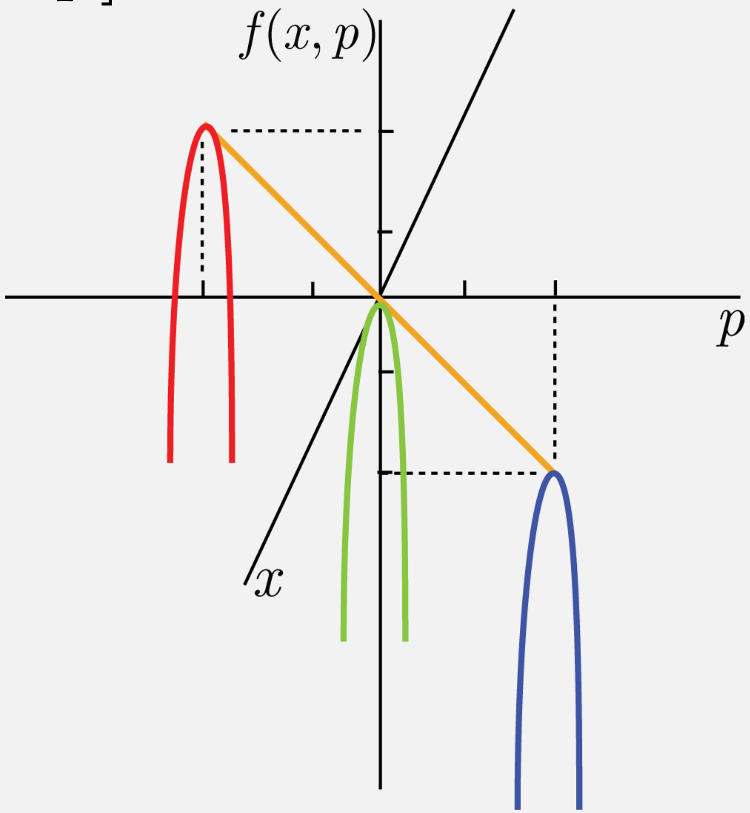




Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Simple Example:

$$\eta^* = \min_{p \in [-2,2]} \max_{x \in [-5,5]} [-x^2 - p]$$



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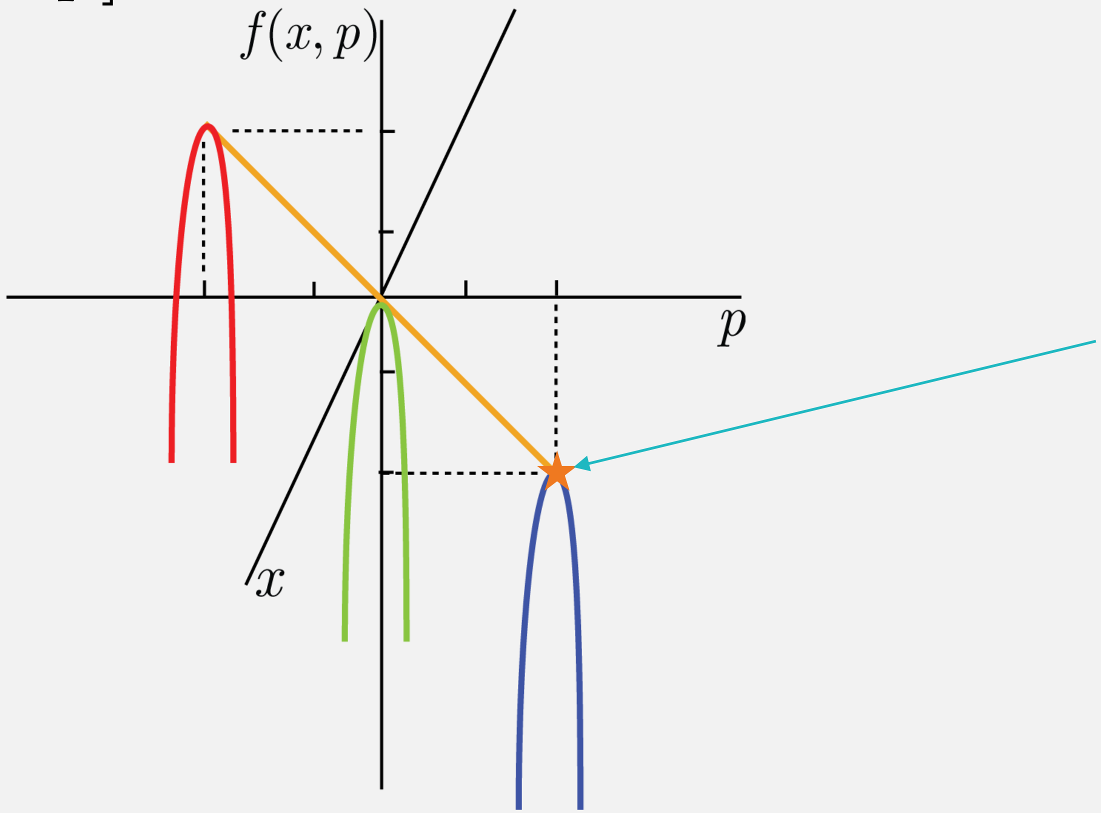

Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

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Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Min-Max formulation

$$\eta^* = \min_{C_{\text{water}}, C_{\text{gas}}} \max_{N_s, H} f_{\text{NPV}}(N_s, H, C_{\text{water}}, C_{\text{gas}})$$

$$\text{s.t. } N_s \in \; n \in \mathbb{Z} : 13 \leq n \leq 52$$

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Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Semi-infinite programs:

$$\max_{p} f(p)$$
$$\text{s.t.}\, g(x,p) \leq 0, \forall x \in X$$

$$\min_{p\in[-2,2]} \max_{x\in[-5,5]} [-x^2 - p]$$

$$\eta^* = \min_{p\in[-2,2],\eta\in\mathbb{R}} \eta$$
$$\text{s.t.}\ \eta \geq \max_{x\in[-5,5]} [-x^2 - p]$$

$$\eta^* = \min_{p\in[-2,2],\eta\in\mathbb{R}} \eta$$
$$\text{s.t.} -x^2 - p - \eta \leq 0, \forall x \in [-5,5]$$

Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Semi-infinite program reformulation

$$\eta^* = \min_{\mathbf{p}\in P, \eta\in\mathbb{R}} \eta$$
$$\text{s.t. } f_{\text{NPV}}(\mathbf{p}, \mathbf{d}) - \eta \le 0, \forall \mathbf{d} \in D$$

$$\mathbf{p} = (C_{\text{water}}, C_{\text{gas}})$$
$$\mathbf{d} = (N_s, H)$$
$$P \subset F_C$$
$$D \subset F_d$$

$$\eta^* > 0 \Rightarrow \text{robust feasibility}$$
$$\eta^* < 0 \Rightarrow \text{not}$$
$$\eta^* = 0 \Rightarrow \text{further analysis required}$$

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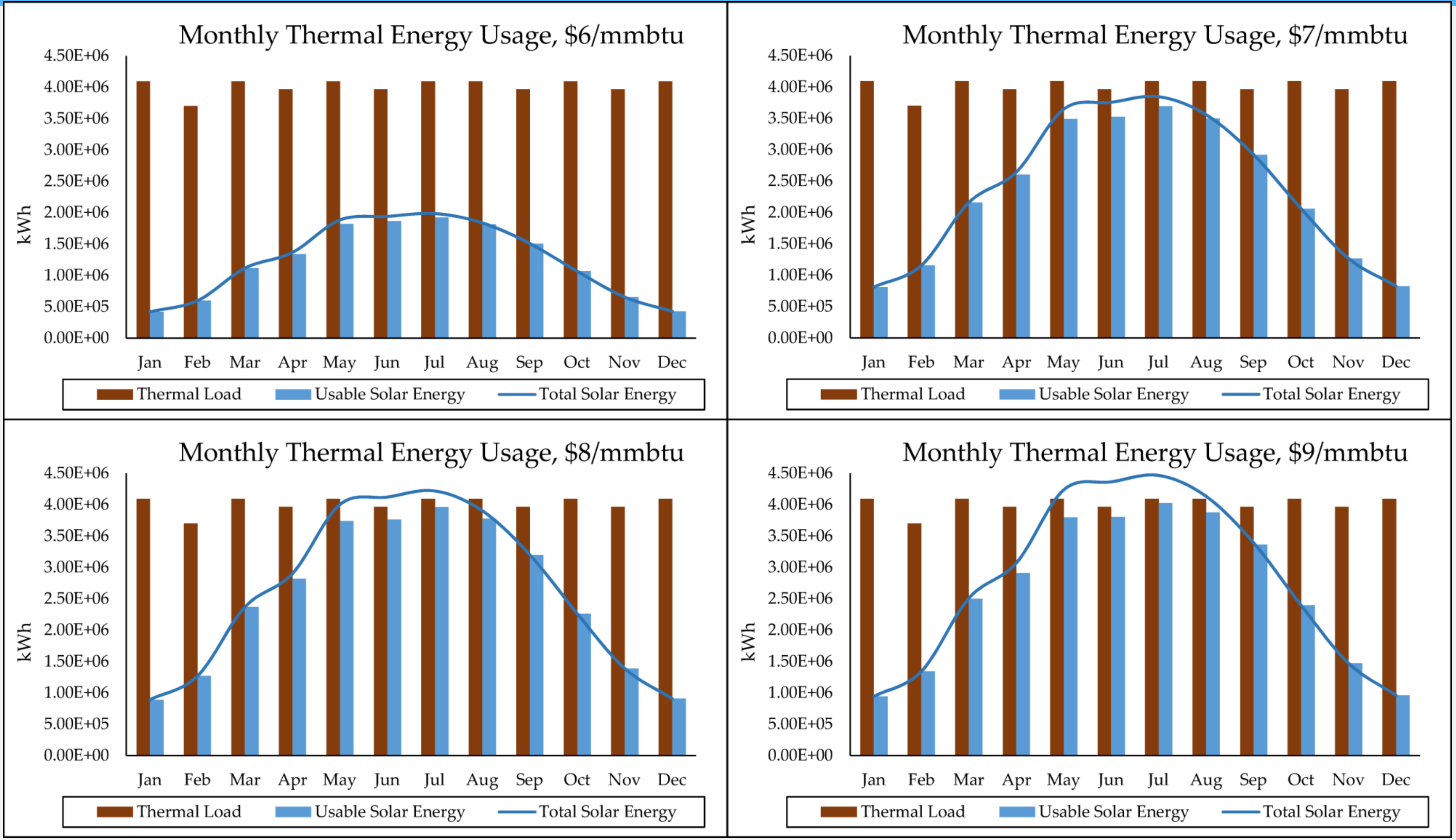
Solution Results and Discussion
Parametric Optimal Design Performance

$f_s^* = 30.15\%$

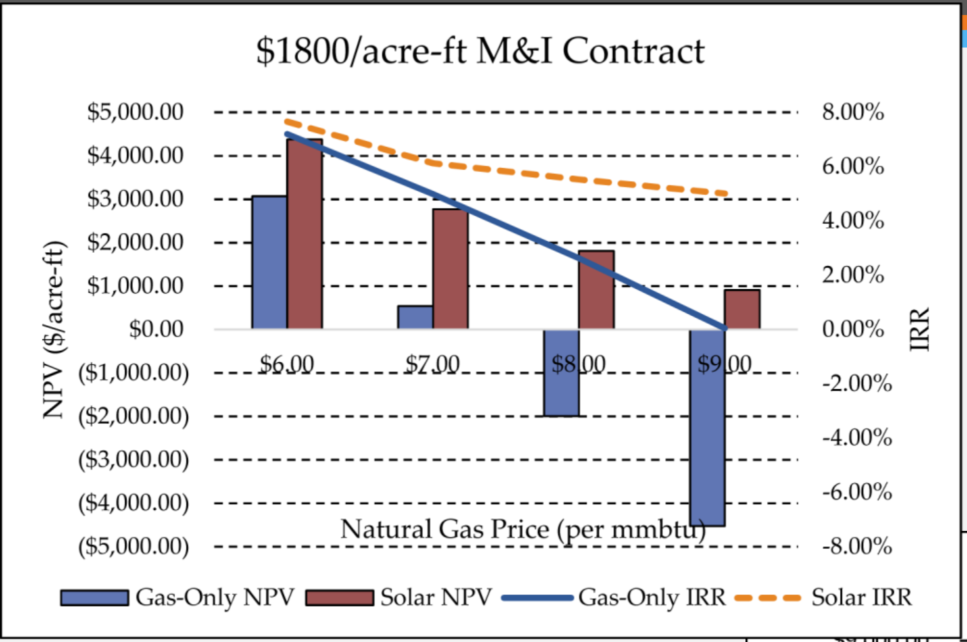
$f_s^* = 58.09\%$

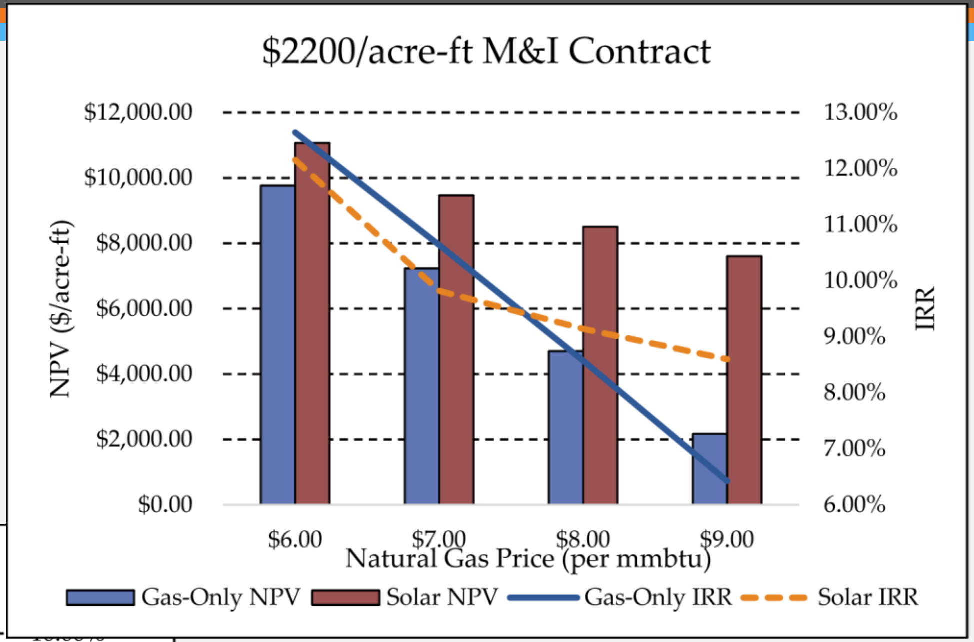


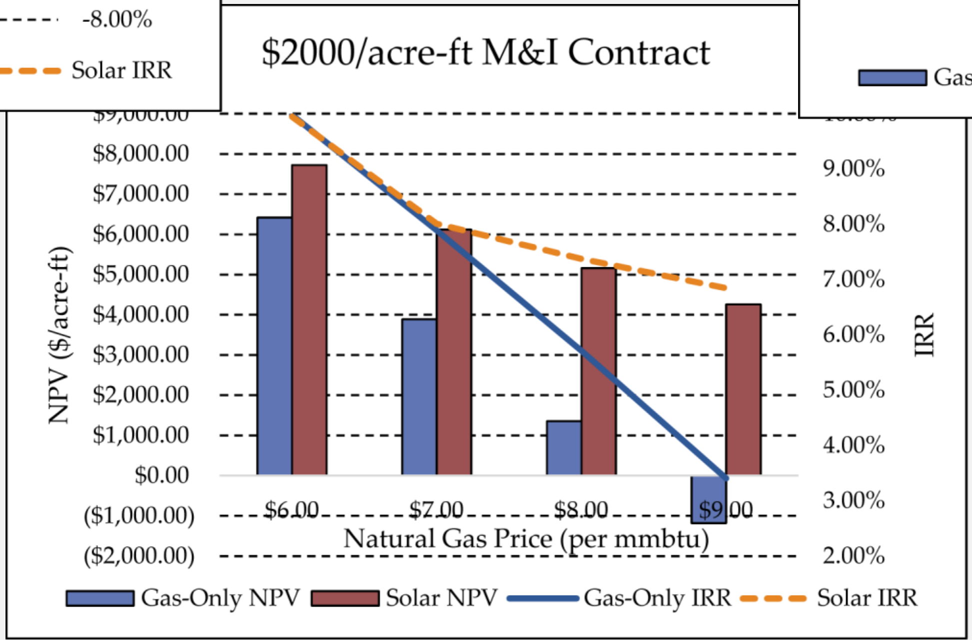
$f_s^* = 62.91\%$

$f_s^* = 65.07\%$

Solution Results and Discussion
Parametric Optimal Design Economics

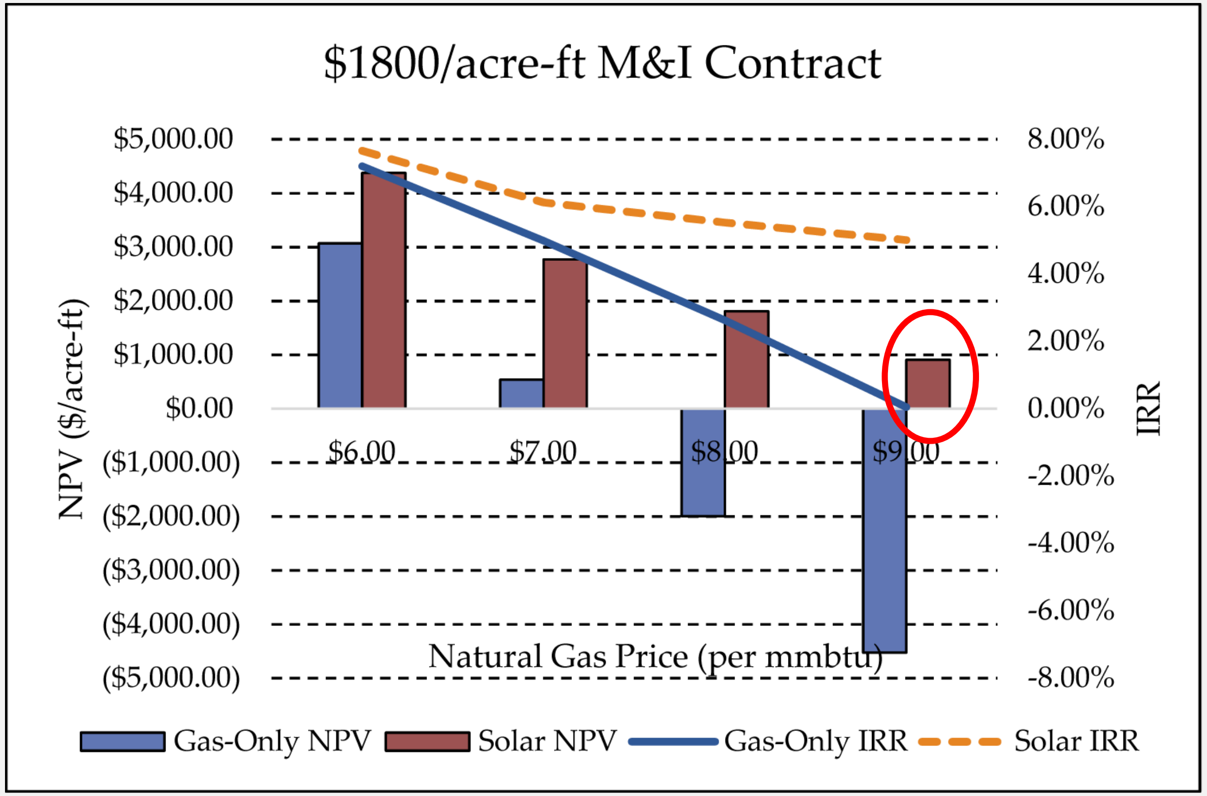




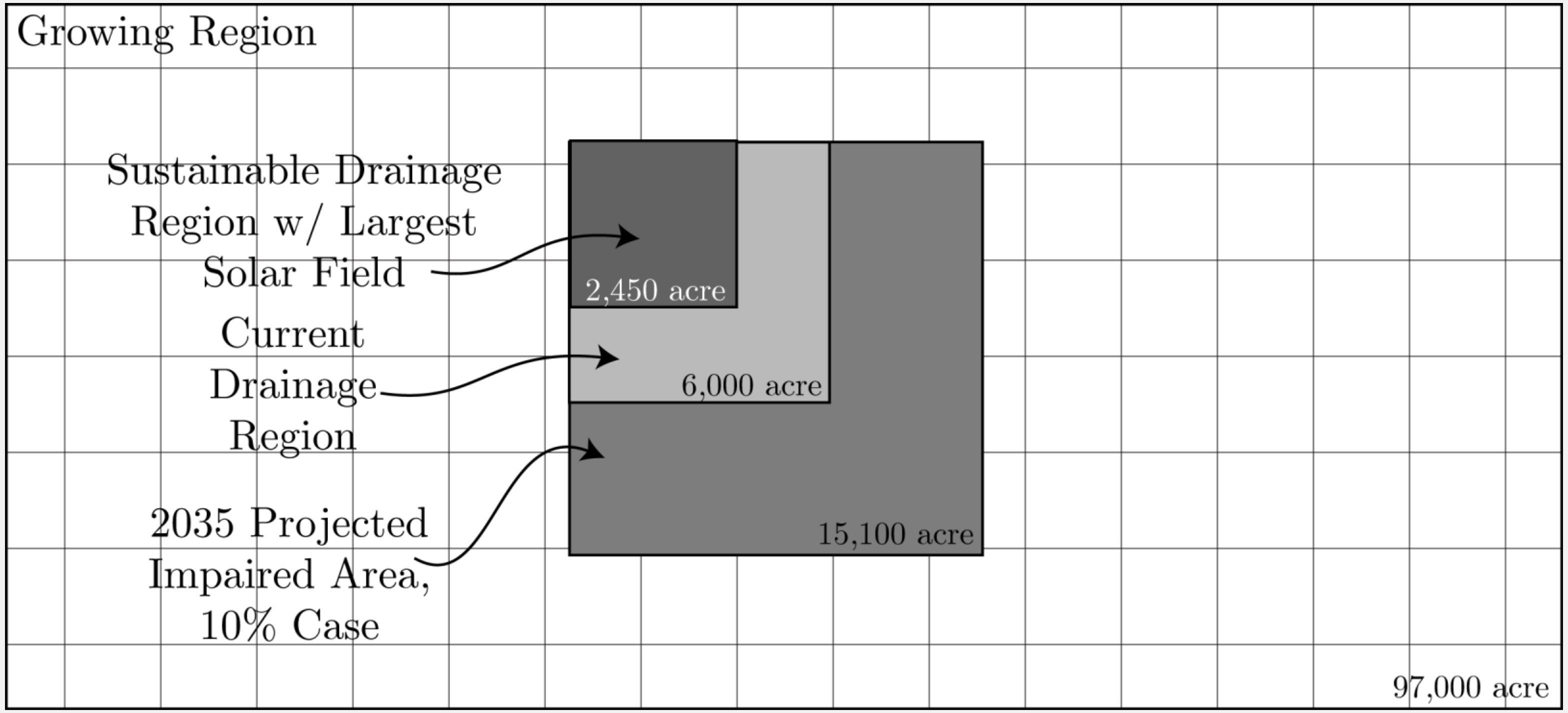


Solution Results and Discussion
Worst-Case Feasibility

- Solving the semi-infinite program yielded a feasible design:



Solution Results and Discussion

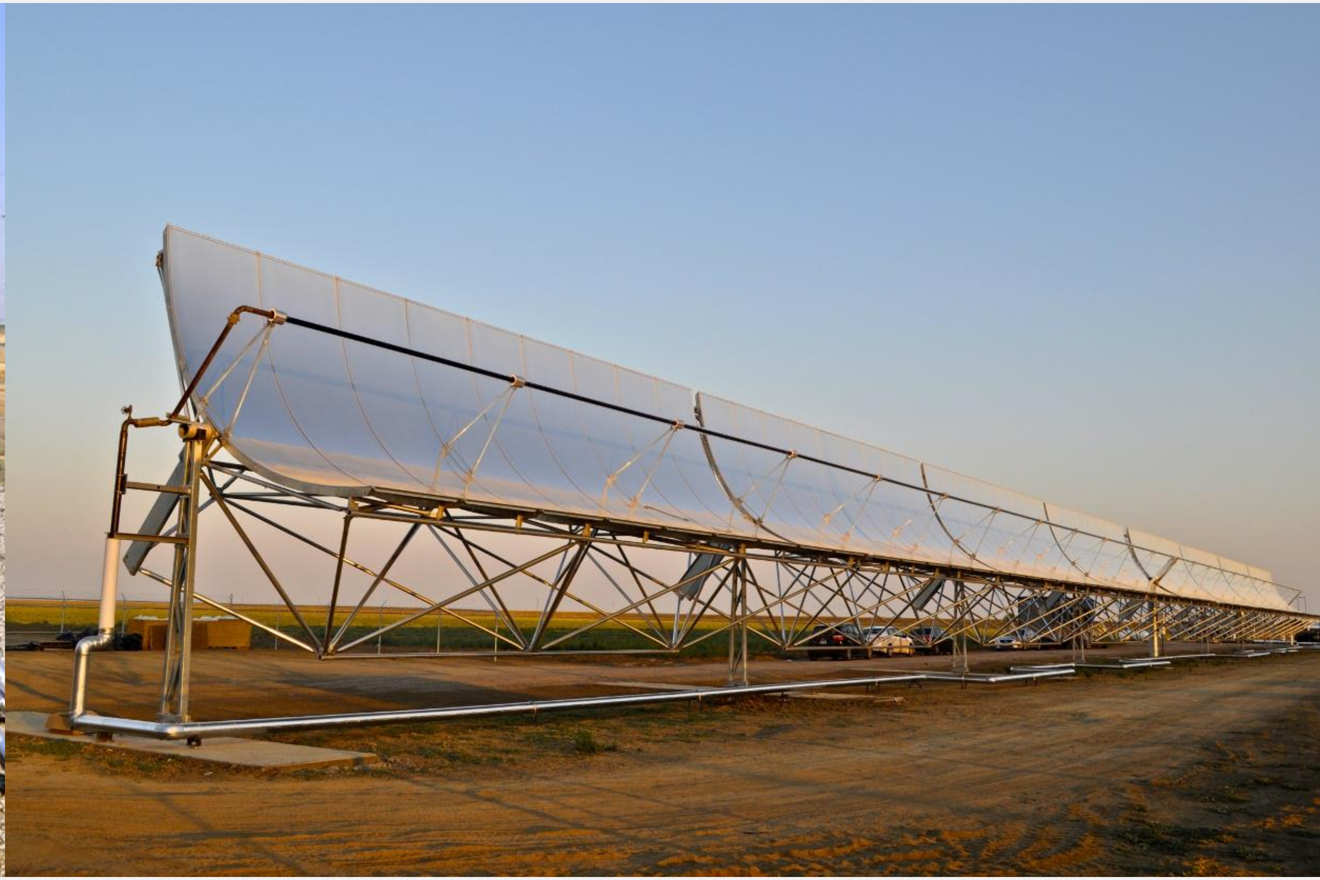


Conclusion

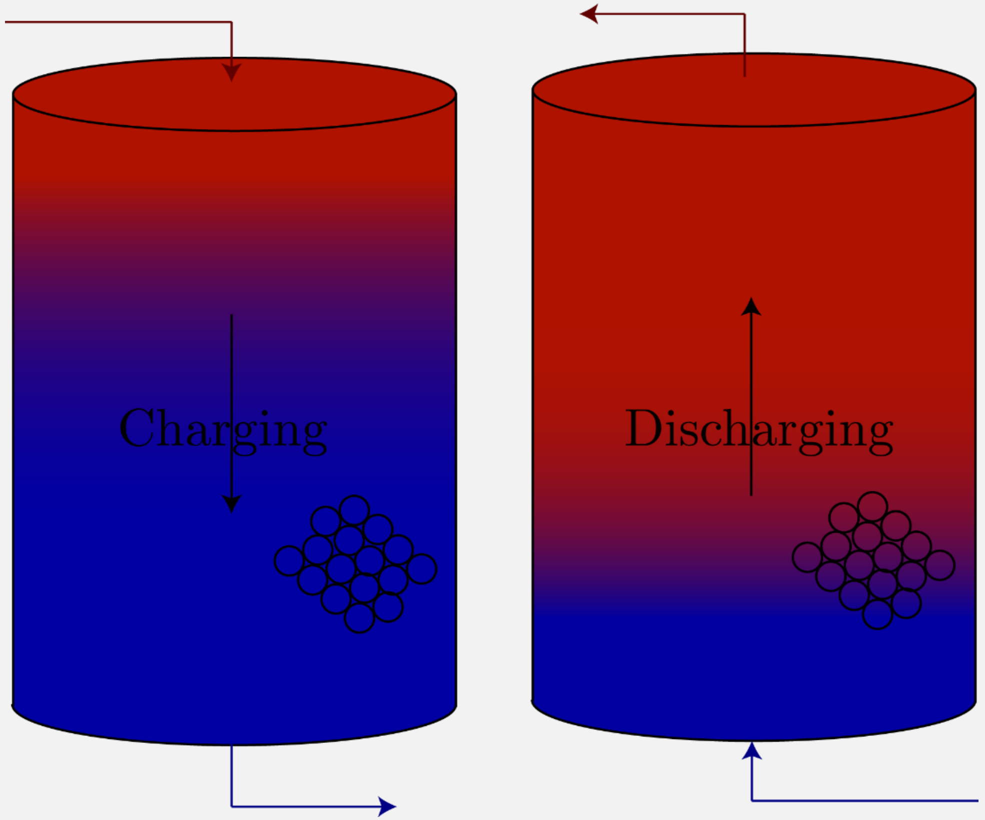
- The worst-case economics support investment in solar desalination for a sustainable agribusiness
- On its own, desalinated water is considered "too expensive" by farmers
  - Systems-view solution and optimal design methodology make it profitable
- Results provide further support for capital investment vs. uncertain futures (e.g., pay now for renewables or risk energy market volatility)

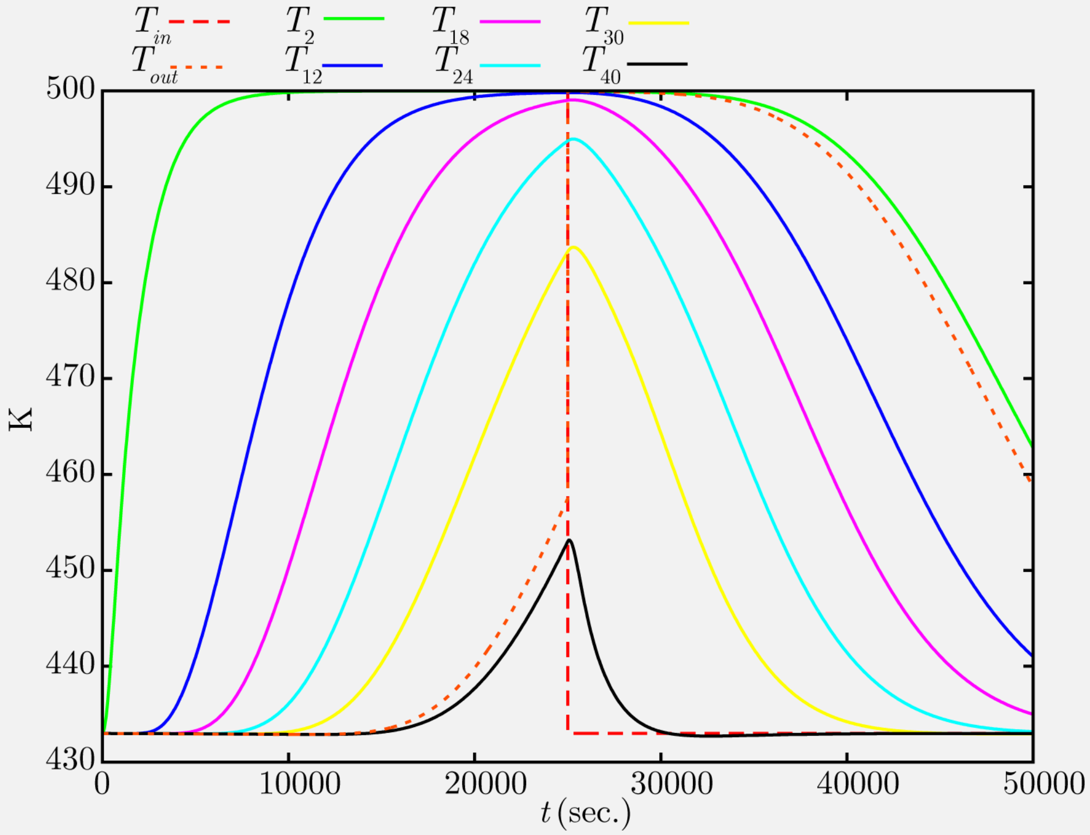
Thank YOU!

Any Questions?



Process Design and Modeling a Solution Solar Thermal Energy Storage





- Single-tank packed-bed thermal storage
  - Spherical concrete packing
  - 12″ tank insulation
  - Reverse-flow charging/discharging