Robust Design for a Sustainable Future
Solar Desalination for Food and Water Security

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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

June 2015

June 2016
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
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**

\[ \dot{W}, \dot{Q}, h_{\nu} \]

\[ H_2O + \text{impurities} \]

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

\[ \text{sulfates, nitrates, phosphate} \]

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**Product**

**Biomass**

**Waste**
Introduction and Motivation

$\dot{W}, \dot{Q}, h_v$

$H_2O + \text{impurities}$

sulfates, nitrates, phosphate

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

product

biomass

waste
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
Process Design and Modeling a Solution

- Basis for design: multi-effect distillation

Single greatest source of entropy generation
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

**MONTHLY AVG DNI**

<table>
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<tr>
<th>Month</th>
<th>DNI [kWh/m2/day]</th>
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<tbody>
<tr>
<td>Jan</td>
<td>2.56</td>
</tr>
<tr>
<td>Feb</td>
<td>3.87</td>
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<td>Mar</td>
<td>4.44</td>
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<td>Apr</td>
<td>6.53</td>
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<td>May</td>
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<td>Sep</td>
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<td>Oct</td>
<td>5.81</td>
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<tr>
<td>Nov</td>
<td>3.99</td>
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<tr>
<td>Dec</td>
<td>2.93</td>
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</tbody>
</table>
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

Mathematical Problem Formulation
Model Considerations and Assumptions

• Desalinate all available drainage water: 22,500 acre-ft/yr (27.75M m³/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)

Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

• Logical constraint:

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

\[ F_C : \text{parameter (uncertainty) space} \]
\[ F_d : \text{design space} \]
\[ f_{\text{NPV}} : \mathbb{Z} \times \mathbb{R} \times \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R} \]

Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Parametric Optimization

\[
f^*_\text{NPV}(C_{\text{water}}, C_{\text{gas}}) = \max_{N_s, H} f_{\text{NPV}}(N_s, H, C_{\text{water}}, C_{\text{gas}})
\]

s.t. \(N_s \in n \in \mathbb{Z} : 13 \leq n \leq 52\)

\(H \in h \in \mathbb{R} : 0 \leq h \leq 12\)

\(N_s : \) no. of PTCs per module

\(H : \) no. of hours of thermal storage

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

\(C_{\text{gas}} : \) natural gas price $/mmbtu

Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

• Simple Example:

\[ f^*(p) = \max_{x \in [-5, 5]} \left[ -x^2 - p \right] \]
\[ p \in [-2, 2] \]
Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

• Simple Example:

\[ f^*(p) = \max_{x \in [-5, 5]} [-x^2 - p] \]
\[ p \in [-2, 2] \]
Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

• Simple Example:

\[ \eta^* = \min_{p \in [-2,2]} \max_{x \in [-5,5]} \left[ -x^2 - p \right] \]
Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Simple Example:

\[
\eta^* = \min_{p \in [-2,2]} \max_{x \in [-5,5]} [-x^2 - p]
\]
Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

• Parametric Optimization

\[
f_{\text{NPV}}^*(C_{\text{water}}, C_{\text{gas}}) = \max_{N_s, H} f_{\text{NPV}}(N_s, H, C_{\text{water}}, C_{\text{gas}}) \\
\text{s.t. } N_s \in n \in \mathbb{Z} : 13 \leq n \leq 52 \\
H \in h \in \mathbb{R} : 0 \leq h \leq 12
\]

- \(N_s\) : no. of PTCs per module
- \(H\) : no. of hours of thermal storage
- \(C_{\text{water}}\) : water contract price $/acre-ft
- \(C_{\text{gas}}\) : natural gas price $/mmbtu

Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

• Min-Max formulation

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

s.t. \( N_s \in n \in \mathbb{Z} : 13 \leq n \leq 52 \)
\( H \in h \in \mathbb{R} : 0 \leq h \leq 12 \)
\( C_{\text{water}} \in c \in \mathbb{R} : 1800 \leq c \leq 2200 \)
\( C_{\text{gas}} \in c \in \mathbb{R} : 6 \leq c \leq 9 \)

Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Semi-infinite programs:
  \[
  \max_{p} f(p) \\
  \text{s.t. } g(x, p) \leq 0, \ \forall x \in X
  \]

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

\[
\eta^* = \min_{p \in [-2,2], \eta \in \mathbb{R}} \eta
\]

\[
\text{s.t. } -x^2 - p - \eta \leq 0, \ \forall x \in [-5,5]
\]

\[
\eta^* = \min_{p \in [-2,2], \eta \in \mathbb{R}} \eta
\]

\[
\text{s.t. } \eta \geq \max_{x \in [-5,5]} [-x^2 - p]
\]
Mathematical Problem Formulation
Robust Optimization and Worst-Case Feasibility

- Semi-infinite program reformulation

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

\[ p = (C_{\text{water}}, C_{\text{gas}}) \]
\[ d = (N_s', H) \]
\[ P \subseteq F_C \]
\[ D \subseteq F_d \]

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

Solution Results and Discussion

Parametric Optimal Design Performance

\[
\begin{align*}
\text{Monthly Thermal Energy Usage,}$ \$/\text{mmbtu} & \\
\text{Jan} & \text{Feb} & \text{Mar} & \text{Apr} & \text{May} & \text{Jun} & \text{Jul} & \text{Aug} & \text{Sep} & \text{Oct} & \text{Nov} & \text{Dec} \\
\text{KWh} & \text{KWh} & \text{KWh} & \text{KWh} & \text{KWh} & \text{KWh} & \text{KWh} & \text{KWh} & \text{KWh} & \text{KWh} & \text{KWh} & \text{KWh} \\
\end{align*}
\]

\[
\begin{align*}
\text{Thermal Load} & \quad \text{Usable Solar Energy} & \quad \text{Total Solar Energy} \\
\end{align*}
\]

For $\$6/\text{mmbtu}$:

- \[f_s^* = 30.15\%\]

For $\$7/\text{mmbtu}$:

- \[f_s^* = 62.91\%\]

For $\$8/\text{mmbtu}$:

- \[f_s^* = 58.09\%\]

For $\$9/\text{mmbtu}$:

- \[f_s^* = 65.07\%\]
Solution Results and Discussion
Parametric Optimal Design Economics

$1800/acre-ft M&I Contract

$2000/acre-ft M&I Contract

$2200/acre-ft M&I Contract
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?
• Single-tank packed-bed thermal storage
  • Spherical concrete packing
  • 12” tank insulation
  • Reverse-flow charging/discharging