Water and Energy: The Case for Distributed Water Treatment and Desalination Systems

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Water and energy are inextricably linked

The cost of water and water energy needs – The California Example

Energy use in RO desalination & opportunities for improving process efficiency

Centralized versus distributed water systems

The benefits of distributed water systems and Research Needs

Examples of small distributed water treatment systems (cooling tower blow down water, seawater, brackish water, graywater)

Modern centralized water treatment plants – R&D Needs
Water and Energy Are Inextricably Linked

Water is used in the generation of 33% of CA electricity

Water-related energy use: 19% of CA electrical energy and 30% (non-power plant) natural gas

Reduced water conveyance and increased water recycling

Decreased energy consumption and smaller carbon footprint
Water Energy Use for Water Production, Treatment & Distribution

Northern California
- Treatment: 57%
- Local Ground/Surface Water Supplies: 17%
- Local Distribution: 26%

Southern California
- Water Treatment: 14%
- Local Distribution: 9%
- Local Ground/Surface Water Supplies: 6%
- Imported Water Supply: 71%
Saline Water Resources in California

- Drought conditions and increasing population necessitate smarter water production and reclamation

- Opportunity to reclaim/produce water from several sources
  - Agricultural drainage water
  - Brackish groundwater
  - Seawater
  - Wastewater

- Agricultural Drainage Water (ADW)
  - Salinity: 5,000 - 30,000 mg/L TDS

- Brackish Ground Water (BGW)
  - Salinity: 2,000 - 15,000 mg/L TDS

- Colorado River Water (CRW)
  - Salinity: 700-1000 mg/L TDS

- Seawater
  - Salinity: ~35,000-38,000 mg/L TDS

- Secondary and Tertiary treated municipal wastewater effluent:
  - 500-1500 mg/L TDS

McCool et al., Desalination, 261, 240-250 (2010)
Establishing Water Policy and Technical Strategies is a Challenge due to Complex Water Pricing

<table>
<thead>
<tr>
<th>Water Source/Customer</th>
<th>~$/AF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>400-900</td>
</tr>
<tr>
<td>MWD Water</td>
<td>366 – 811#</td>
</tr>
<tr>
<td>CA Water Project(^{(c)})</td>
<td>20-300</td>
</tr>
<tr>
<td>SJV Agricultural Water</td>
<td>10 - 600</td>
</tr>
<tr>
<td>Desalted Seawater(^{(b)})</td>
<td>620 -1,200</td>
</tr>
<tr>
<td>Desalted Brackish Water(^{(b)})</td>
<td>200 – 600</td>
</tr>
<tr>
<td>MBR Treated Wastewater(^{(b)})</td>
<td>300 – 600</td>
</tr>
<tr>
<td>Bottled Water</td>
<td>~1x10^6</td>
</tr>
</tbody>
</table>

\(^{(a)}\) low-high estimate; \(^{(b)}\) – excludes conveyance; \(^{(c)}\) – farming and urban
- Average price of consumer delivered water ~$489/AF (AWWA)
- The price of water in various CA locations can exceed the above estimates
- # - replenishment untreated – full Service Treated
- 1 AF = 325,851.4 gallons, 1 U.S. Gallon=3.78 L
Inland versus Seawater RO Desalination

Brackish Water Desalination

- Variable depending on the specific concentration management option
- Brine Disposal
- Antiscalant
- MF Operation
- Electrical Energy
- RO Membrane

Cost reduction potential:
- Increase recovery to minimize brine disposal/management costs
- Lower cost mitigation of mineral scaling/fouling

Seawater Desalination

- Capital 37%
- Electrical Energy 44%
- Membrane Rep. 5%
- Maintenance 7%
- Labor 4%
- Consumables 3%

Cost reduction potential:
- Energy
- Capital cost
- Maintenance/labor
- Membrane & consumables
The Energy Cost of RO Desalination

Rate of pump work: \( \dot{W}_{pump} = \Delta P \times \left( Q_f - \eta_E Q_b \right) / \eta_p \)

Ideal Normalized SEC Curves for Different Scenarios

At the thermodynamic restriction limit, the minimum applied pressure is a function of recovery and rejection \((Y_t, R_t)\):
- When \(Y_t\) is small, more energy is wasted in the brine steam.
- When \(Y_t\) is large, the required applied pressure increases rapidly.

Actual optimal recovery must consider O&M and capital costs.

Global optimum: \(Y_{opt} = 0.5\):
- (w/o ERD)
  - \(SEC_{wo/ERD} = 3.2\) kWh/m\(^3\)
  - \(SEC_{w/ERD} = 1.6\) kWh/m\(^3\)

TDS=35,000 mg/L

\(Q_p = A_m L_p (\Delta P_m - \sigma \Delta \pi) = A_m L_p (NDP)\)
Process Configuration for Reduced RO Energy Consumption

Approach:
- Energy recovery devices
- Multistage with booster pumps

Reduce energy consumption via optimized RO process configuration to enable operation close to the osmotic pressure curve, e.g., - multi-stage RO

System Design will depend on the balance between reduction in energy consumption relative to increased capital cost
Is Seawater Desalination Expensive?

Example: Assume water use of 150 gallons per household per day

Seawater desalination cost (high-end): ~12 kWh/1000 gallons $\rightarrow$ 1.8 kWh per day or ~657 kWh annually

Refrigerator energy use: 511 – 693 kWh annually

A/C Central daily average (based on 3 months use): 3 kWh per day

42” Plasma TV: 219 kWh annually

1 Gallon of Gasoline: ~36 kWh
2013 Chevrolet Volt requires 8.8 kWh/25 miles
Centralized Water Systems

Centralized Water Processing Infrastructure

Municipal User

Municipal User

Industrial User

Regional Water Resources

Water treated to high level of quality irrespective of application
Hyperion Treatment Plant
Los Angeles, CA

Estimated upgrade costs: $1.6B
Centralized Water Systems

Centralized Water Processing Infrastructure

- Municipal User
- Municipal User
- Industrial User

- Energy
- Security
- Suboptimal

Regional Water Resources
Distributed Water Processing:
Water is needed at different levels of purity!

Centralized Water Processing

Surface Water River/Reservoir

Brackish Groundwater

Wastewater

SWS
SWS
SWS

Municipal Potable

Municipal Irrigation

Industrial User

Energy adaptive

Application specific
Water Production, Conveyance and Wastewater Treatment: Distributed and Centralized Management

**Near Urban Areas**
- Distributed Fixed/Mobile Plants
- Distributed Fixed/Mobile Plants
- Satellite “Water “production” / Treatment/Reuse/Disposal Facility

**Remote Areas**
- Distributed Fixed/Mobile Plants
- Distributed Fixed/Mobile Plants
- Satellite “Water “production” / Treatment/Reuse/Disposal Facility

Augment with existing centralized or with satellite water infrastructure for distributed drinking water treatment/ wastewater management
Distributed Water Network

- Water treatment near the “point-of-use” and/or at the source
- Autonomous self-adaptive operation, advanced sensors, fault-detection
- Standardized modular systems
- Central supervisory system/cyberinfrastructure → “smart water systems”

Benefits:
• Reduce water consumption and increased use of underutilized water sources & reuse
• Lower capital investment relative to centralized infrastructure
• Treat water to the required purity level
• Serve remote communities and treat distributed impaired water sources
• Reduce energy cost associated with water conveyance & lower carbon footprint
• Enable integration of local renewable energy resources with water systems
Augmenting Centralized Water Infrastructure with Distributed Water Systems

A Shift in Water Resources & Management Paradigm

Technical Challenges

- Self-adaptive operation
- Flexible system architecture of modular design & Standardization
- Advanced on-board control/monitoring systems
- Remote monitoring/control
- Energy optimal operation
- Fault-detection
- Real-time optimization w.r.t utilization of alt. energy sources (e.g., wind and solar)
- Cyberinfrastructure for remote centralized supervision

Technology Transfer: Fundamentals ➔ Laboratory ➔ Field
UCLA SIMS Treatment and Recycling of Cooling Tower Blow Down Water at the UCLA Co-Gen Plant

- Disposal of up to ~66,000-152,000 gallons/day
- Water unit price= $7.6/1000 Gallons
- 1,000-2,000 mg/L TDS
- Turbidity= 1.4-14 NTU
- Annual savings to UCLA ~$90K

- Process models
- Control and optimization
- Soft sensors
- Membrane characterization
- Software design
- Advanced system design concepts

6/23/2013
com2ro

- UCLA designed and built system operating (Since September 2010) at US Navy seawater desalination test facility at Port Hueneme
- Integrated self-adaptive operation of compact & modular UF-RO technology
- Operation without intermediate tanks (for RO feed or UF backwash)

Cohen et al, Patent Pending
Wastewater Treatment and Reuse Applications

Sources
- **Black Water**
  - Toilet

- **Light Graywater**
  - Laundry
  - Shower & Sink

- **Dark Graywater**
  - Kitchen

Treatment
- Primary Treatment
- Secondary Treatment
- Tertiary and Disinfection

Uses
- City Sewer
- Onsite Treatment
- Irrigation
- Spray Irrigation
- Laundry
- Toilet
- Car Wash

~40-70% of generated household wastewater

Serve a single residential or multiple neighboring homes

Low cost and low maintenance

Treat Graywater water to Title 22 for indoor use

Challenge: restrictive and conflicting regulations in the 50 States

Capacity: 560 GPD

UCLA Gray2Blue Vertical Wetland for Residential Graywater Treatment
Modern Water Treatment Facilities make use of a Sophisticated Process Train

Water Sources:
- Seawater
- Surface Water
- Groundwater
- Reclaimed Water
- Agricultural Drainage Water

Pretreatment
- Particle Removal
- Biofouling Control
- Disinfection
- Microorganisms
- Organics Removal

Solute Rejection
- Inorganics
- Organics
- Viruses
- Bacteria

Membrane Concentrate
- Minimization
- Treatment
- Disposal

Product Waters:
- Potable Water
- Industrial Water
- Irrigation Water
- Agricultural Water

- Modern MWT plants require significant energy (e.g., conveyance, mixing and aeration)
- Opportunities exist for increased level of energy/resource recovery
Modern Water Treatment Facilities make use of a Sophisticated Process Train

- Pretreatment:
  - Particle Removal
  - Biofouling Control
  - Disinfection
  - Microorganisms
  - Organics Removal

- Solute Rejection:
  - Inorganics
  - Organics
  - Viruses
  - Bacteria

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Current membrane-based water treatment processes lack robust control, automation and advanced process monitoring to deal with the variability of feed water quality, fouling and scaling, real-time optimization for energy minimization & reasonable cost ZLD for inland water
Distributed Water Treatment/Desalination Technologies: R&D Needs

Control:
- Soft sensors & physical monitoring
- Optimal System & Process Design
  - Reduced Plant Footprint

Membranes:
- Improve fouling resistance
- Increase water permeability

Inland water:
- Concentrate disposal
  - Target high recovery

Operational:
- Reduce use of feed pretreatment additives
- Reduce energy consumption

Distributed Water Systems

Field Studies/Demos

Theory & Lab Studies
\[
[CO_3^{2-}]_e = [TC]_e \cdot K_{a1} \cdot K_{a2}/([H^+]_e^2 + K_{a1} \cdot [H^+]_e + K_{a1} \cdot K_{a2})
\]

\[
\bar{N}(t) = \hat{J}_N \int_0^t (1 - \phi(t'))dt'
\]

\[
P(k; J_N) = \frac{(J_N \Delta t)^k e^{-J_N \Delta t}}{k!}
\]

\[
\bar{U} \cdot \nabla C = \nabla \cdot D \nabla C
\]

\[
\bar{U} \cdot \nabla (\rho \bar{U}) = -\nabla p + \nabla \cdot \eta \nabla \bar{U}
\]

\[
\frac{dr}{dt} = k_e' \frac{K_{zp}}{\gamma_{Ca^{2+}}(SO_4^{2-})(SI_g - 1)}
\]

\[
J_N = A_N \exp \left( -\frac{FV_m^2 \sigma^3 f(\theta) N_a}{(RT)^3 (\ln (SI))^2} \right) = A_N \exp \left( -\frac{a_N}{(\ln (SI))^2} \right)
\]

\[
X_{Ca} = \frac{1}{2} \left( \Gamma_i + 1 \right) - \sqrt{(\Gamma_i + 1)^2 - 4 \cdot \left( \Gamma_i - \frac{K'_{CaCO_3}}{K_{a2}} \cdot \left( \frac{[H^+]_e^2}{K_{a1}} + [H^+]_e \right) + K'_{CaCO_3} \right)} / \left( Ca^{2+} \right)_i^2)
\]

QUESTIONS?
Energy Production from Salinity Gradients: Pressure Retarded Osmosis

Energy Production:

\[ E_{PRO} = J_v A \Delta P_m = A L_p (\sigma \Delta \pi - \Delta P_m) \Delta P_m \]

Maximum energy production

\[ \frac{\partial E}{\partial \Delta P_m} = 0 \]

Approximate analysis based on average flux and osmotic pressure

\[ (\Delta P_m)_{\text{max}} = \frac{1}{2} \Delta \pi \]

\[ (E_{\text{max}})_{\text{net}} = \frac{A L_p}{2} (\Delta \pi)^2 \left( \sigma - \frac{1}{2} \right) - Q_{df} \Delta P_{df} - E_p \]

Osmotic energy production (ideal when \( \sigma = 1 \))

Pumping energy of draw solution

Reported \( E_{\text{max}} \):

\~ 1.3-10 w/m²

Opportunities for PRO?

• Locations where the draw sol’n salinity is >> seawater salinity
• Co-location of RO/FO/PRO plants & wastewater plants
Water Source-Supply Management

• The water balance:

\[ \alpha = \text{Rate of change of water storage} = \]
\[ \text{Water input/capture (natural + reclaimed water recharge)} - \]
\[ \text{water loss (natural + usage)} \]

Water sustainability requires that \( \alpha \geq 0 \)

Water-side solution to the Water-Energy Nexus:

• Reduce water use
  • Water use efficiency, water conservation
• Develop new water sources for potable and non-potable use
  • Reclaimed municipal, industrial, agricultural water sources
  • Upgrade unused/impaired water sources
  • Decrease both the energy and capital cost of water desalination
• Utilize renewable energy sources
• Environmental stewardship
Oil & Gas: Produced Water

- > 15 billion barrels of water produced with oil and gas each year, (~9.5 barrels of water per barrel of oil)
- Produced water quality can vary with respect to “water quality” (e.g., salinity and composition of inorganic ions, hydrocarbons, temperature and pH)
- Treatment and disposal costs
- Potential impact of surface discharge on vegetation, soil, and streams
- Can treated produced water become a valuable resource?
- Constraints on Coal Bed Natural Gas Production due to environmental concerns with respect to produced water
Reducing Water Related Energy Use

• Distributed smart (self-adaptive) water systems for water treatment and production

Renewable Energy for water treatment/production:

• Solar powered desalination
• Water disinfection using solar radiation
• Mechanical wind pumps (windmills)
• Energy from biomass (e.g., Biodiesel)
• Coupling of geothermal energy with water production
• Wave energy for water production (desalination)

Use of Waste heat:

• Desalination, disinfection, organic destruction
Process Control for Self-Adaptive Operation

- Model based approach to controller design