MOTIVATION

- 60% of land area in India underlain with water that is too salty to drink

- Tata Projects foresees needing 2000 village scale desalination plants per year, aggressively scaling to a potential market of 50,000 units. Currently they use exclusively RO

- Interest in ED due to opportunity for lower energy consumption and higher recoveries

- Need to reduce capital cost of plant to <$3000 to be competitive with RO

Tata Projects on-grid RO plant
RESEARCH OVERVIEW

VOLTAGE-REGULATED BATCH

TIME-VARIANT PV-ED OPERATION

THE EFFECT OF CURRENT DENSITY ON COST

SPIRAL STACK DESIGN

OPTIMAL FLOW-PATH GEOMETRIES
ELECTRODIALYSIS (ED)
OVERVIEW OF GOVERNING PHYSICS

- Voltage across Cation (CEM) & Anion Exchange (AEM) Membranes drives ion transport.

- Ion flux is represented with a current density, \( i \) [A/m\(^2\)]

- Salt concentration boundary layer bounds maximum current density, so \( i < i_{\text{lim}} \)
ELECTRODIALYSIS

BATCH VS. CONTINUOUS OPERATION STRATEGIES

**BATCH RECIRCULATION MODE**
- Flow is recirculated to achieve desired concentration reduction
- Production Rate ≠ Flow Rate

**CONTINUOUS MODE**
- Flow path designed to achieve desired concentration reduction in single pass
- Production Rate = Flow Rate
THE EFFECT OF CURRENT DENSITY ON COST
CURRENT DENSITY VS. LIMITING CURRENT DENSITY

ILLUSTRATIVE EXAMPLE - CONVENTIONAL VOLTAGE BATCH

- Batch desalination – Flow is recirculated to achieve required desalination.

- Diluate is desalinated from feed to product concentration over one batch cycle.

- Conventionally, voltage is constant.
CURRENT DENSITY

CONVENTIONAL BATCH – CONSTANT VOLTAGE

\[ i > i_{\text{lim}} \]

EXCEEDING LIMITING CURRENT

\[ i_{\text{lim}} \propto C \]

START OF BATCH CYCLE

END OF BATCH CYCLE

Dilute Concentration [mg/L]

Current Density, \( i \) [A/m²]

TIME

100 mg/L (A)
CURRENT DENSITY
CONVENTIONAL BATCH – CONSTANT VOLTAGE

\[ i > i_{\text{lim}} \quad \text{EXCEEDING LIMITING CURRENT} \]

\[ i_{\text{lim}} \propto C \]

Constant-voltage batch operation

Constraint at the end of batch

CURRENT DENSITY

CONVENTIONAL BATCH - CONSTANT VOLTAGE LIMITATIONS

Relaxing product concentration requirement allows higher current density

EXCEEDING LIMITING CURRENT

\[ i > i_{\text{lim}} \]

\[ i_{\text{lim}} \propto C \]

Constant-voltage batch operation

\[ i < i_{\text{lim}} \]

constraint at the end of batch

CURRENT DENSITY TRAJECTORY

KEY INSIGHT

WASTED CAPACITY

KEY INSIGHT: Capture this capacity to raise current density $\bar{i}$ and decrease capital cost.
RESEARCH OVERVIEW

VOLTAGE-REGULATED BATCH

THE EFFECT OF CURRENT DENSITY ON COST

TIME-VARIANT PV-ED OPERATION

OPTIMAL FLOW-PATH GEOMETRIES

SPIRAL STACK DESIGN
VOLTAGE-REGULATED BATCH
IMPLEMENTED CONTROLLER TO VARY VOLTAGE IN TIME
VOLTAGE-REGULATED BATCH

EXPERIMENTALLY-Demonstrated Improvement in Performance

- Recovery ratio = 82%, VR – 0.6 indicates voltage regulated to maintain $\frac{i}{i_{lim}} = 0.6$

1000 mg/L Feed

- Constant Voltage
- Voltage-regulated

- 5.9 L/hr
- 14.1 L/hr ~90% Higher Production Rate

2000 mg/L Feed

- Constant Voltage
- Voltage-regulated

- 7.5 L/hr
- 12.5 L/hr ~67% Higher Production Rate
RESEARCH OVERVIEW

VOLTAGE-REGULATED BATCH

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SPIRAL STACK DESIGN

OPTIMAL FLOW-PATH GEOMETRIES
ELECTRODIALYSIS
DRAWING PARRALLELS TO VOLTAGE REGULATION

BATCH RECIRCULATION MODE
VOLTAGE REGULATION

CONTINUOUS MODE
FLOW GEOMETRY
CONTINUOUS OPERATION
RECTANGULAR FLOW PATHS HAVE WASTED CAPACITY

Decreasing Concentration

WASTED CAPACITY
(Pumping Power/Membrane Area)

GE MkIV-2, 2000 mg/L to 477 mg/L,
7 cm/s Flow Velocity, 0.84 V/cell-pair
50% Recovery
TAPERED FLOW PATHS CAN DECREASE PRESSURE DROP

COMPARISON TO SUEZ MkIV-2 SPACER

SAME PARAMETERS

2000 to 722 mg/L, 80% Recovery
Production Rate: 35 Liters Per Hour/Cell-pair
Applied Voltage: 0.62 V/Cell-Pair
Maximum $i/i_{\text{lim}} = 0.7$

3 % Membrane Area Increase
48 % Pumping Power Decrease
0 % Desalination Power Change

SUEZ MkIV-2

IDEAL FLOW-PATH
TAPERED FLOW PATHS CAN DECREASE MEMBRANE USAGE

COMPARISON TO SUEZ MkIV-2 SPACER

SAME PRODUCTION
BUT DIFFERENT VOLTAGES

2000 to 722 mg/L, 80% Recovery
Production Rate: 35 Liters Per Hour/Cell-pair
Maximum $i/i_{lim} = 0.7$

SUEZ MkIV-2
0.62 V/cell-pair

13 %
Membrane Area Decrease

0 %
Pumping Power Decrease

13%
Desalination Power Increase

IDEAL FLOW-PATH
0.7 V/cell-pair
RESEARCH OVERVIEW

VOLTAGE-REGULATED BATCH

THE EFFECT OF CURRENT DENSITY ON COST

TIME-VARIANT PV-ED OPERATION

OPTIMAL FLOW-PATH GEOMETRIES

SPIRAL STACK DESIGN
A SPIRAL ARCHITECTURE ALLOWS FOR DECREASING APPLIED CURRENT DENSITY

- Feed water enters in center tube
- Spirals outward, separating into concentrate and diluate
- Applied current density AND limiting current density decrease as water moves to the outer turns

Membranes and spacers rolled around a perforated titanium center tube

Sample tubes and wires inserted for mid-stack measurements

Resin and clamps used for sealing
A STANDARD ARCHIMEDEAN SPIRAL DOESN’T GIVE THE EXPECTED BENEFIT

Concentration decreases linearly with turn number; applied current density does not.

The ideal spiral represents a 39% reduction in capital cost, 21% reduction in total specific cost ($/kWh), as compared to a standard Archimedean spiral.
RESEARCH OVERVIEW

VOLTAGE-REGULATED BATCH

SPIRAL STACK DESIGN

THE EFFECT OF CURRENT DENSITY ON COST

OPTIMAL FLOW-PATH GEOMETRIES

TIME-VARIANT PV-ED OPERATION
The conventional design sequentially design desalination sub-system and solar power sub-system, without considering connection between solar power and ED behaviors.
The time-variant PV-ED system can vary voltage and flow rate to significantly:

- Increase the instantaneous solar energy utilization rate
- Increase desalination rate
- Increase m³ of produced water per unit membrane area
- Reduce required battery capacity

The enhanced flexibility of time-variant PV-ED system leads to lower system cost and lower water cost.
Experimental assessment of the time-variant PV-ED system’s benefits is on-going
Preliminary experimental results proved the system’s capability of controlling current
The increased current by controlling voltage or/and flowrates led to the increased desalination rate
Next steps: evaluate the time-variant system performance improvement in responding to the daily solar variations (e.g. solar energy utilization or solar-to-water ratio, etc.)
CONCLUSIONS

- GEAR Lab is developing methods to reduce ED capital cost, by raising the current density during operation.
- We have experimentally shown how voltage regulated batch can increase production rates, or decrease membrane usage, by 67-90%, compared to constant voltage batch.
- Modeling indicates ~13% membrane area decrease and 48% pressure decrease is achievable by implementing tapered flow paths, compared to SUEZ flow path.
- An ideal spiral ED stack would allow for a constant voltage, continuous process, with effective use of all membrane area. Modeling indicates ~39% capital cost decrease for the ideal spiral, compared to the standard spiral.
- The proof-of-concept of the time-variant system in maximizing desalination rate under an arbitrary power input has been demonstrated on the field.
Appendix Slides
Slides from Wei

• Cost saving by the co-optimal design method
  • What is the conventional design method
  • What is co-optimal design method
  • Does the co-optimal design work? How much cost is saved? Will be the co-optimal design cost-viable?
• Motivation of researching the time-variant ED operation
  • Benefits of operating an ED in a time-variant way
  • On-going test and its objectives
Conventional system design method

The conventional design sequentially design desalination sub-system and solar power sub-system, without considering connection between solar power and ED behaviors.
A holistic PV-ED model bridging solar intermittence and water demand variance

The holistic model provides more degrees of freedom to operate, control and design a PV-ED system for achieving low-cost and high-performance.
Building and testing PV-ED field pilot in rural India

Working with Tata Project Ltd., we built and tested the prototype in rural India.

PV panels

Batteries and inverter

ED stack, hydraulics, control panel, etc.
Results and water cost of the field pilot in India

- The holistic model is validated by the field pilot testing data
- The PV-ED field pilot is able to provide enough amount of water expected
Results and water cost of the field pilot in India

The PV-ED field pilot has a potential to achieve the cost affordability
The time-variant PV-ED system can significantly:

- Increase the instantaneous solar energy utilization rate
- Increase desalination rate
- Increase membrane effectiveness in m³ product water per membrane
- Reduce required battery capacity

The enhanced flexibility of time-variant PV-ED system leads to lower system cost and lower water cost
Field pilot of time-variant PV-ED prototype in New Mexico

Experimental assessment of the time-variant PV-ED system’s benefits is on-going
Experimental measurements align well with modeled values

Tested at five different feed concentrations and applied voltages

Measured energy consumption within 1-15% of modeled values (average 7%)

Measured desalination rate within 1-11% of modeled values (average 4%)

Sample data here shown for: Feed concentration - 1060 mg/L  Applied voltage - 14 V  Flow Rate - 1.5 L/min
Cost Optimal Archimedean Spiral vs. Ideal Spiral Designs

- 40% reduction CC
- 25% reduction TC

*from 57 m² to 30 m² total membrane area
Staging for more reasonable electrode radii

Radii decrease if use more turns of the spiral. But this increases the amount of membrane area required.

What happens if we stick to one turn, but put 3 spirals in series, each with CR = 2?

For example: CR=8 could be 2000 mg/L to 250 mg/L
Staging for more reasonable electrode radii

Single Stage Ideal

Three Stage Ideal
Relationship between limiting and applied current density

Three electrical stage continuous operation
Fully Optimized vs. Optimized within Commercial Constraints

Allowing the membrane width and length, channel gap, to change from that of the standard Suez product line results in significant gains in both capital and total cost.

\[ \downarrow \text{TC 37\%, } \downarrow \text{CC 47\%} \]

\[ \downarrow \text{CC 25\%} \]
Optimized Utilizing Suez Components, Operating in Voltage-Regulated Hybrid

84 Cell Pairs
19.7 x 168 cm flow channels (U-shaped)
Stack Cost: $3588

386 Cell Pairs
21 x 19 cm flow channels
Stack Cost: $1631

Stack cost reduction of ~55%