ELECTRODIALYSIS STACK DESIGN AND OPERATION

JEFFREY COSTELLO

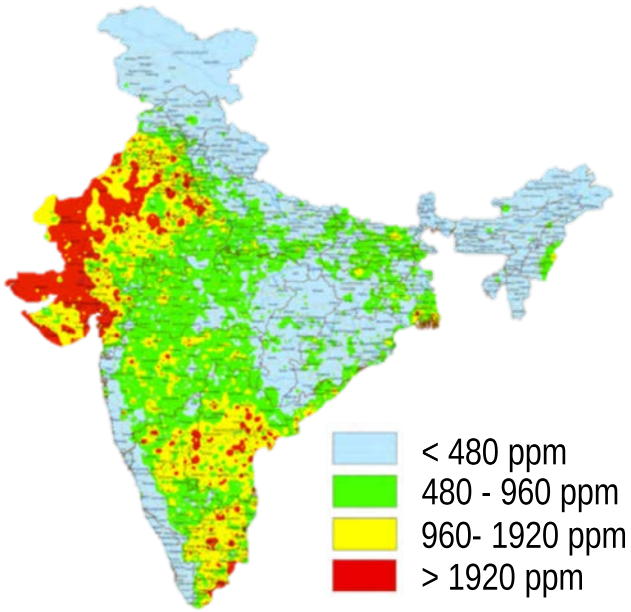
PROFESSOR AMOS G. WINTER, V

GLOBAL ENGINEERING AND RESEARCH LAB

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MOTIVATION

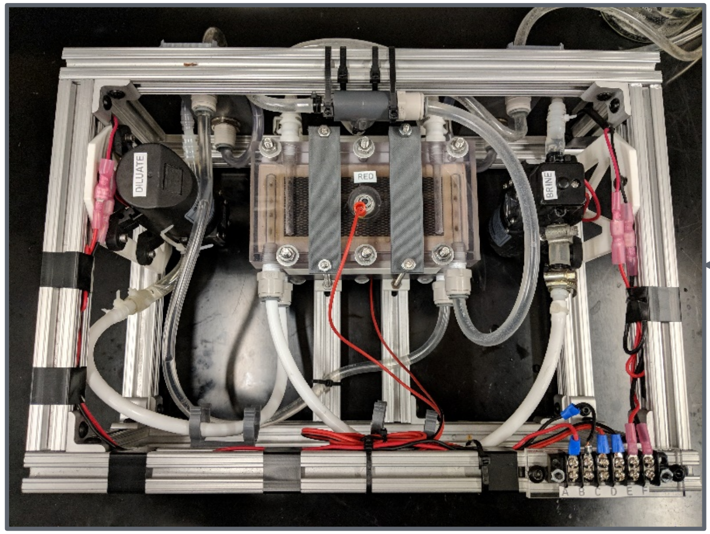
- 60% of land area in India underlain with water that is too salty to drink
- Tata Projects foresees needing 2000 village scale desalination plants per year, aggressively scaling to a potential market of 50,000 units. Currently they use exclusively RO
- Interest in ED due to opportunity for lower energy consumption and higher recoveries
- Need to reduce capital cost of plant to <$3000 to be competitive with RO

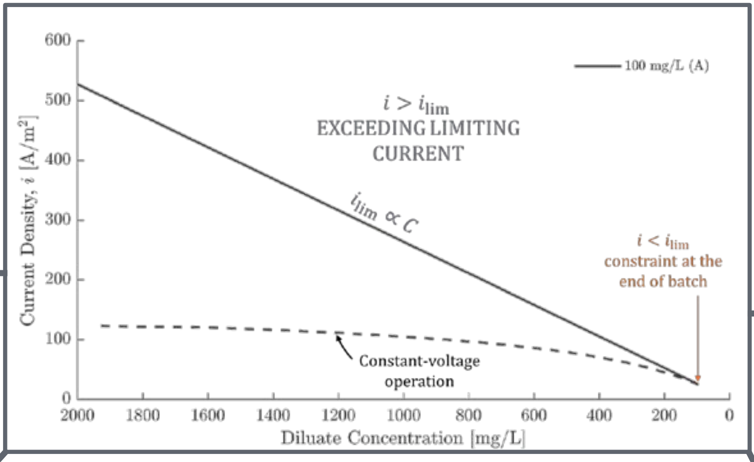


Tata Projects on-grid RO plant

RESEARCH OVERVIEW

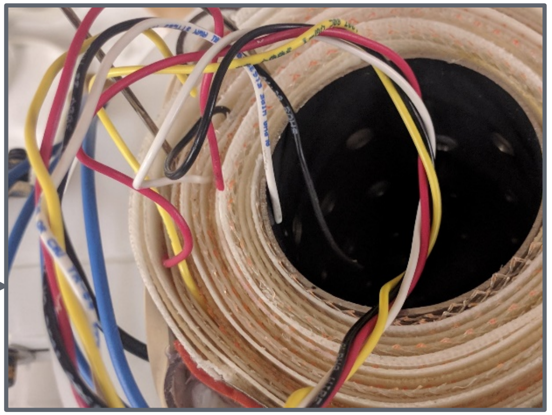
VOLTAGE-REGULATED BATCH



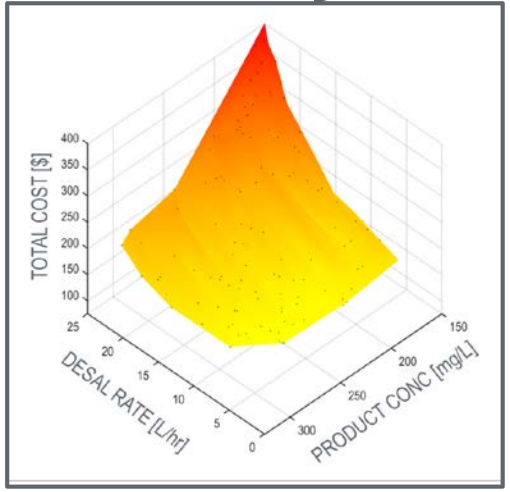


THE EFFECT OF CURRENT DENSITY ON COST

SPIRAL STACK DESIGN



TIME-VARIANT PV-ED OPERATION

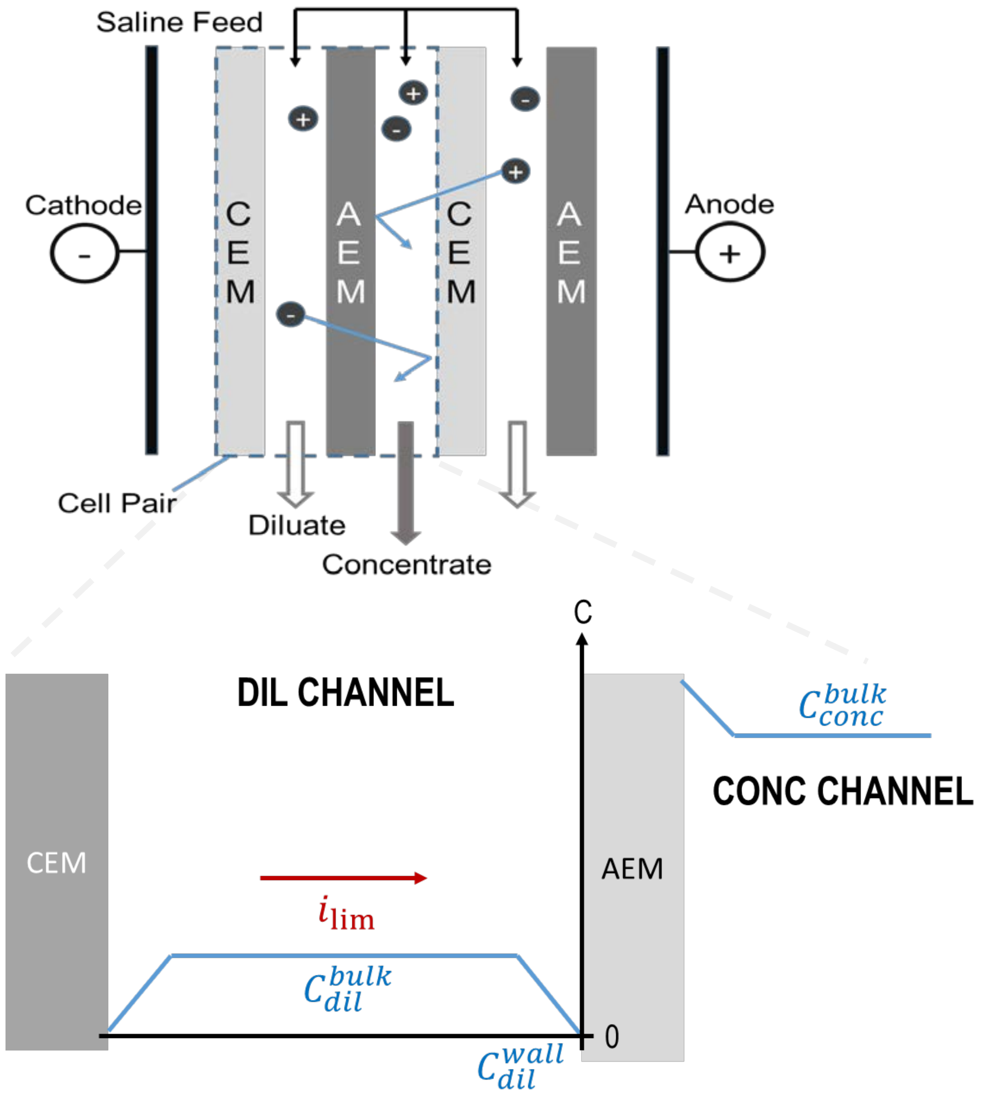


OPTIMAL FLOW-PATH GEOMETRIES

ELECTRODIALYSIS (ED)

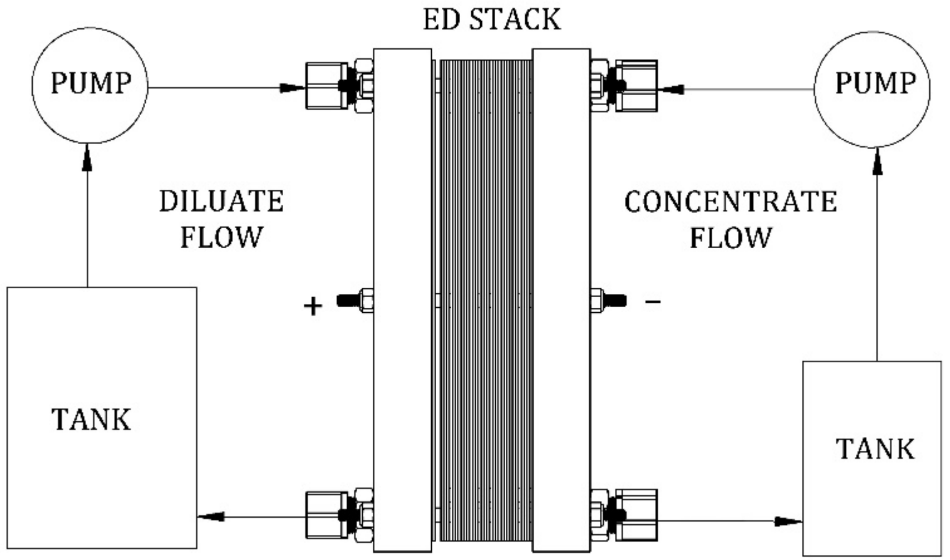
OVERVIEW OF GOVERNING PHYSICS

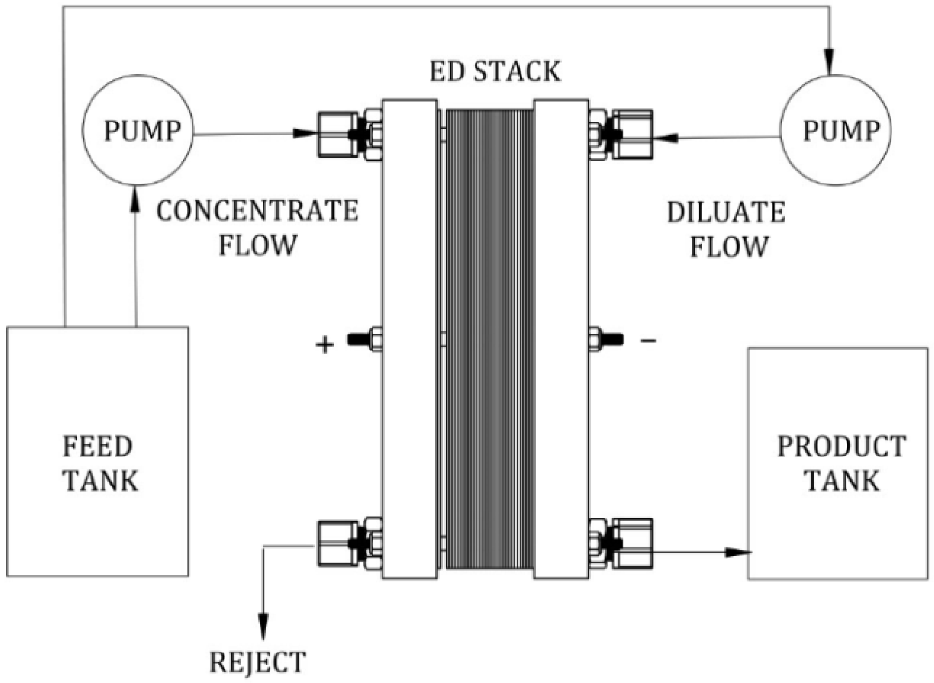
- Voltage across Cation (CEM) & Anion Exchange (AEM) Membranes drives ion transport.
- Ion flux is represented with a current density, i [A/m^2]
- Salt concentration boundary layer bounds maximum current density, so $i < i_{\text{lim}}$



ELECTRODIALYSIS

BATCH VS. CONTINUOUS OPERATION STRATEGIES





BATCH RECIRCULATION MODE

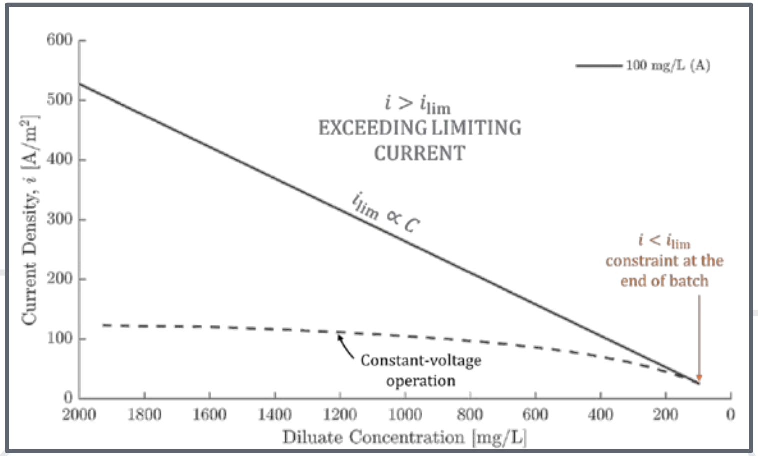
- Flow is recirculated to achieve desired concentration reduction
- Production Rate ≠ Flow Rate

CONTINUOUS MODE

- Flow path designed to achieve desired concentration reduction in single pass
- Production Rate = Flow Rate

RESEARCH OVERVIEW

VOLTAGE-REGULATED BATCH



THE EFFECT OF CURRENT DENSITY ON COST

SPIRAL STACK DESIGN

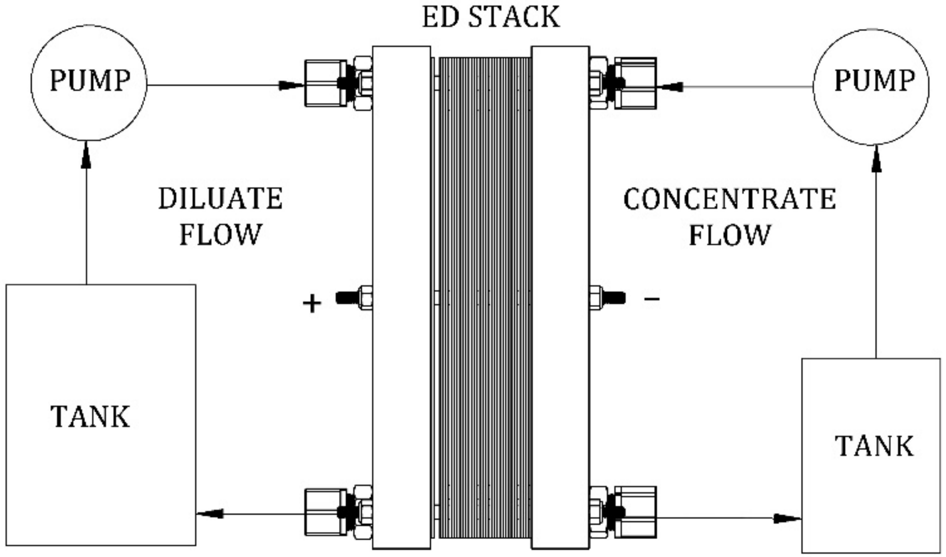
TIME-VARIANT PV-ED OPERATION

OPTIMAL FLOW-PATH GEOMETRIES

CURRENT DENSITY VS. LIMITING CURRENT DENSITY

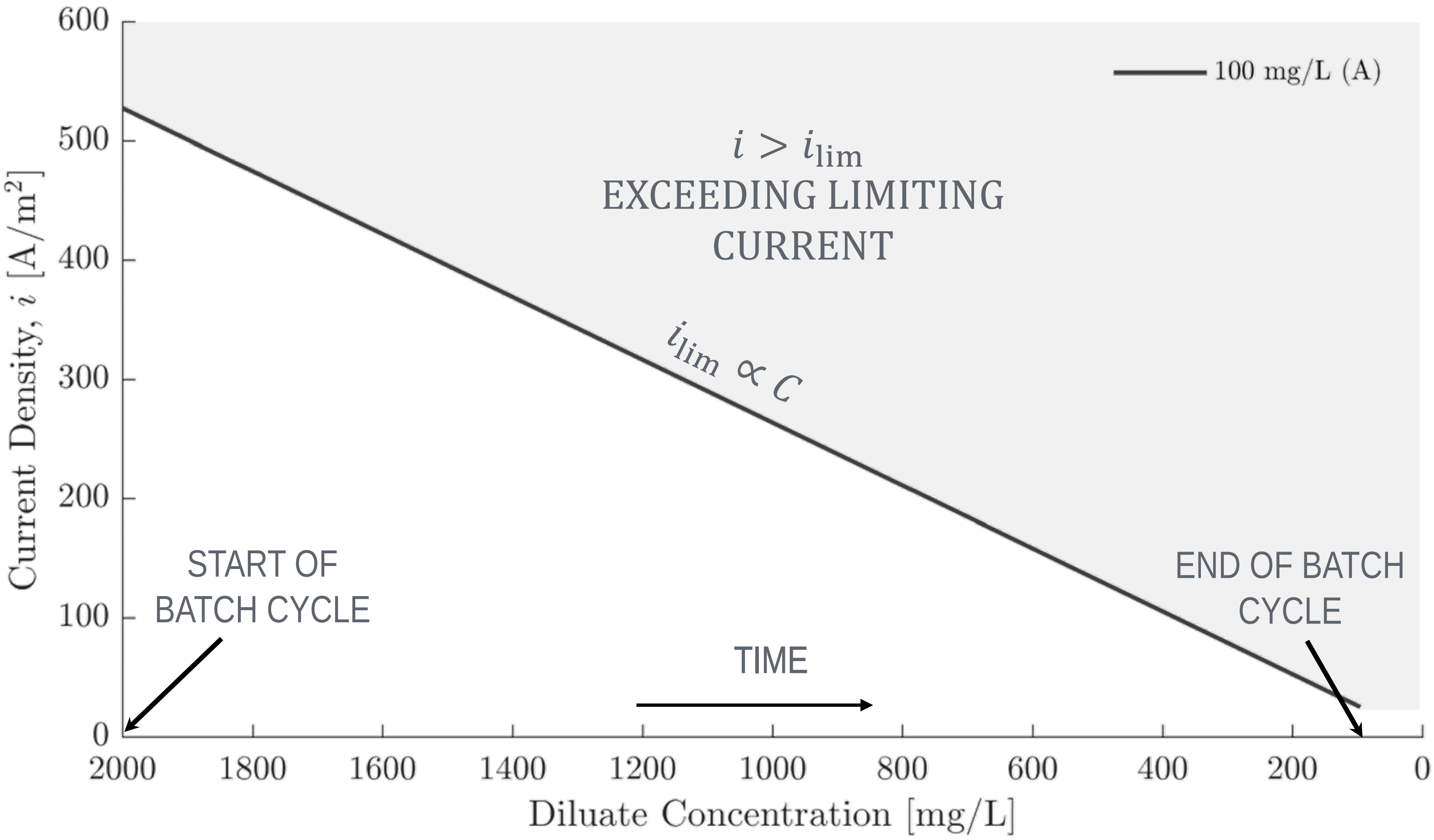
ILLUSTRATIVE EXAMPLE - CONVENTIONAL VOLTAGE BATCH

- 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

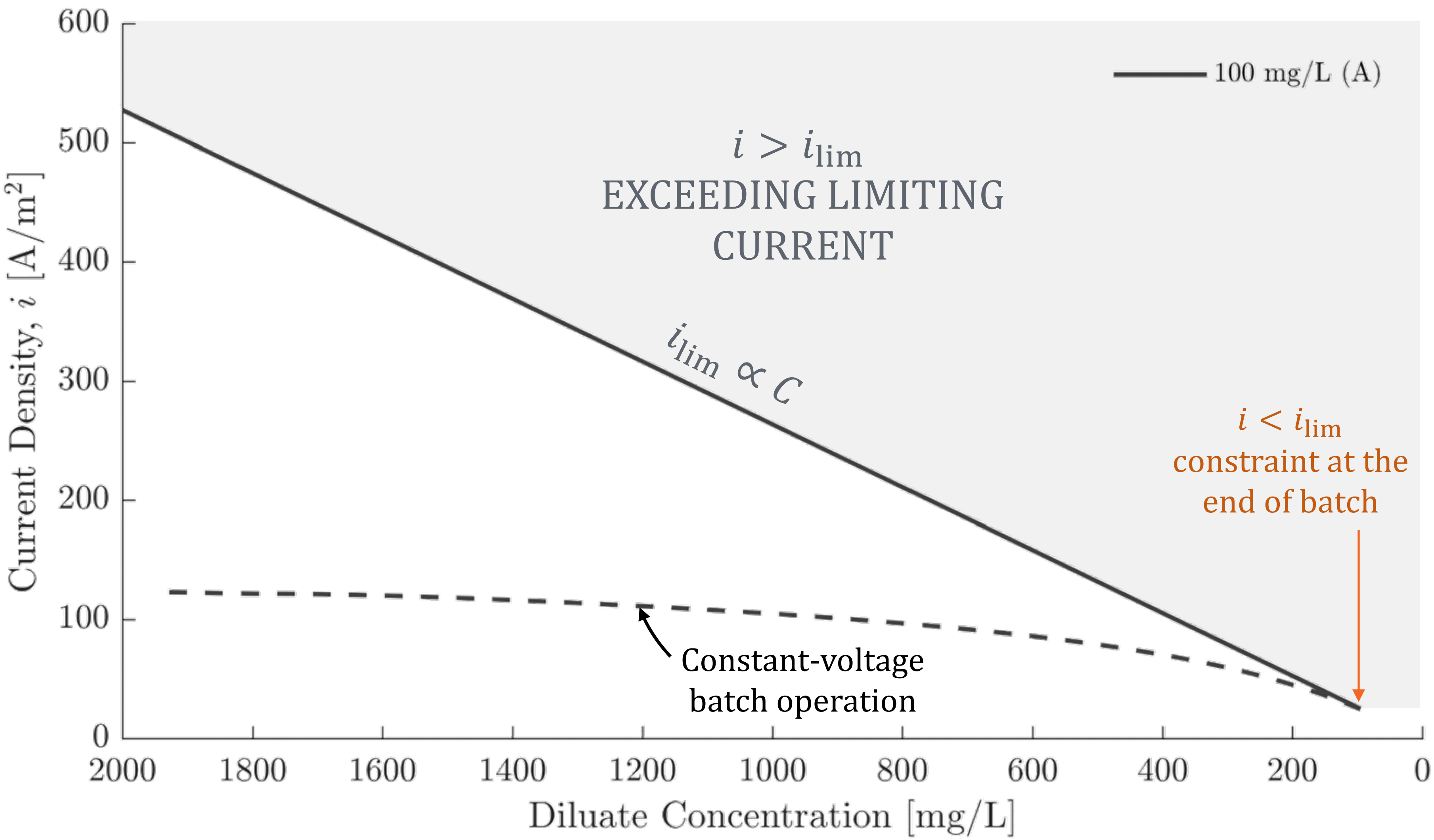
CONVENTIONAL BATCH – CONSTANT VOLTAGE



S. R Shah., N.C. Wright, P. Nepsky, and A.G. Winter V., “Optimal Design of a Batch Electrodialysis System for Domestic Desalination," IDA World Congress 2017, São Paulo. Oct 15-20, 2017.

CURRENT DENSITY

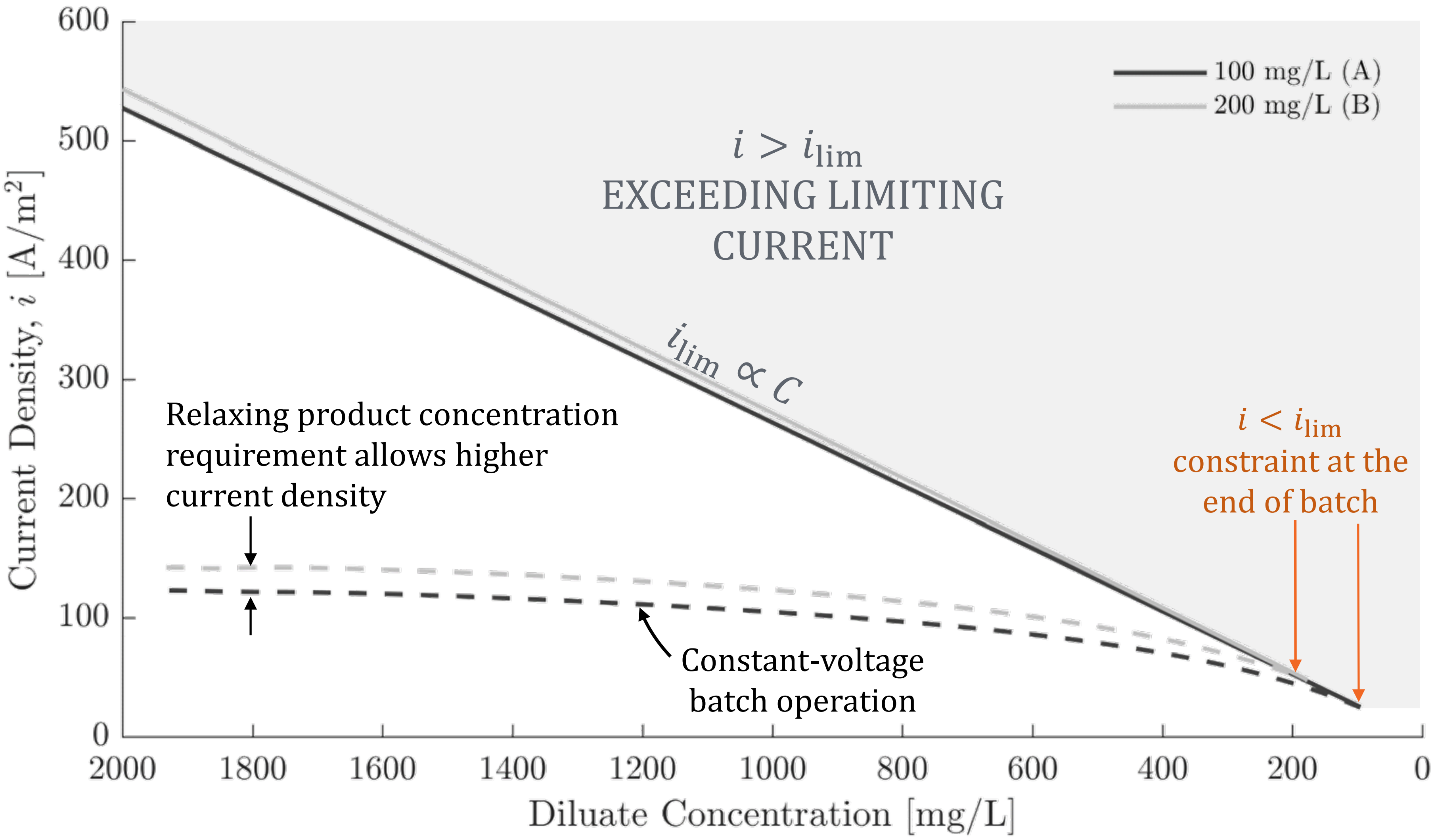
CONVENTIONAL BATCH – CONSTANT VOLTAGE



S. R Shah., N.C. Wright, P. Nepsky, and A.G. Winter V., "Optimal Design of a Batch Electrodialysis System for Domestic Desalination," IDA World Congress 2017, São Paulo. Oct 15-20, 2017.

CURRENT DENSITY

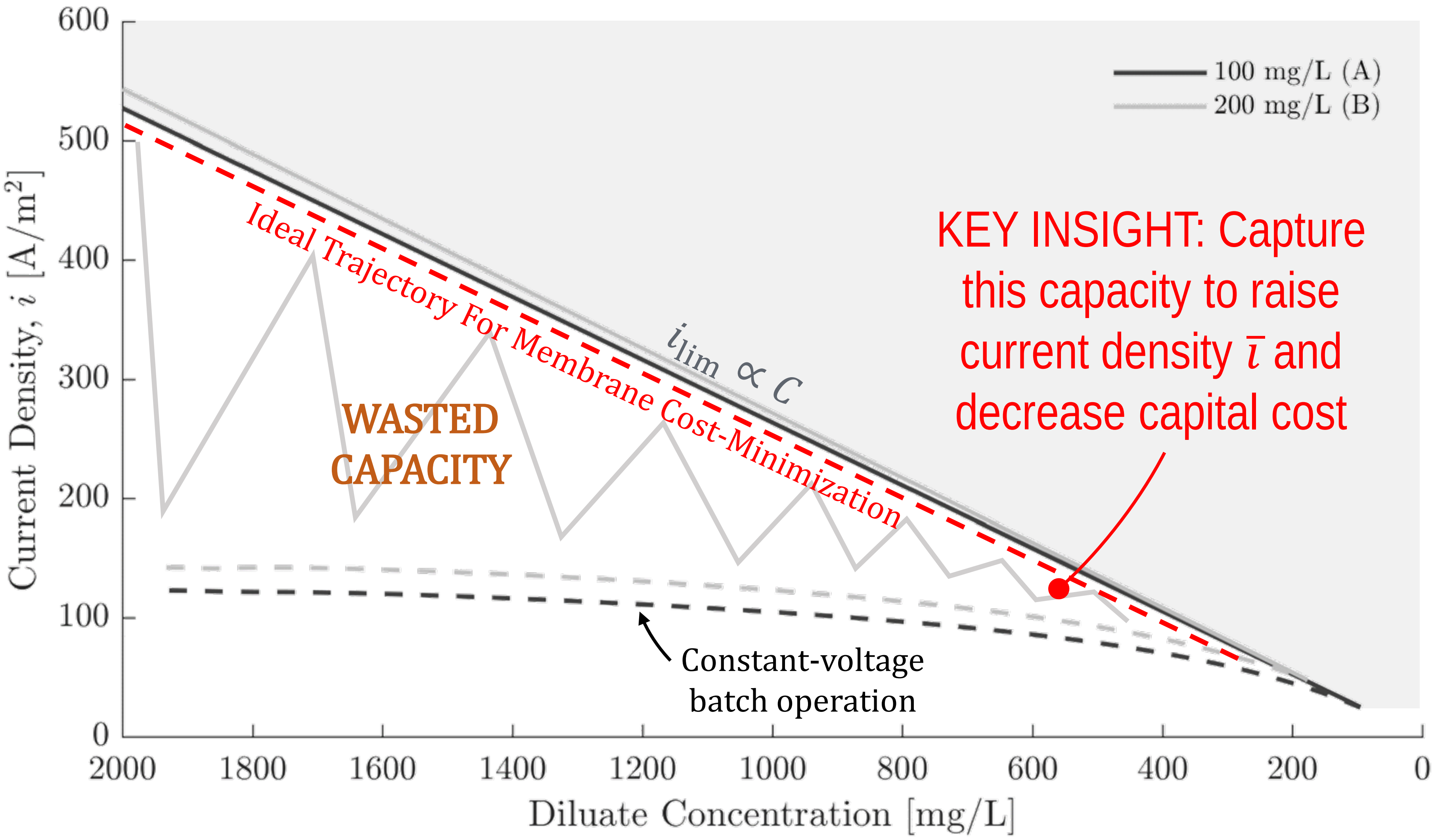
CONVENTIONAL BATCH - CONSTANT VOLTAGE LIMITATIONS



S. R Shah., N.C. Wright, P. Nepsky, and A.G. Winter V., "Optimal Design of a Batch Electrodialysis System for Domestic Desalination," IDA World Congress 2017, São Paulo. Oct 15-20, 2017.

CURRENT DENSITY TRAJECTORY

KEY INSIGHT



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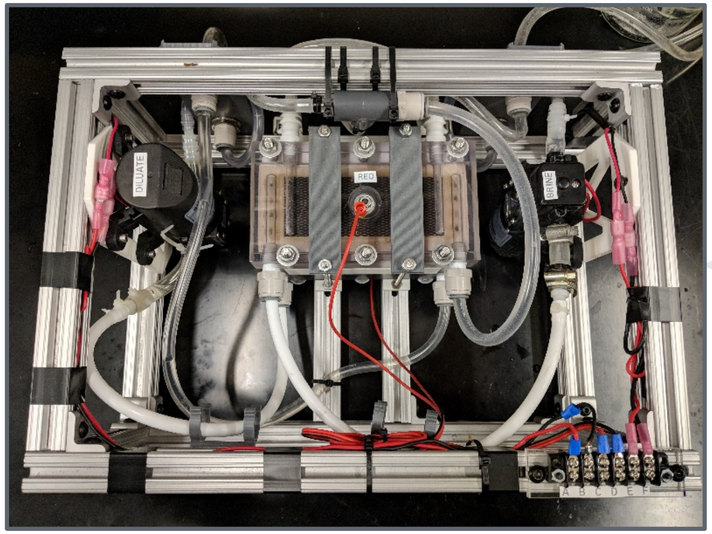
RESEARCH OVERVIEW

VOLTAGE-REGULATED BATCH



SPIRAL STACK
DESIGN

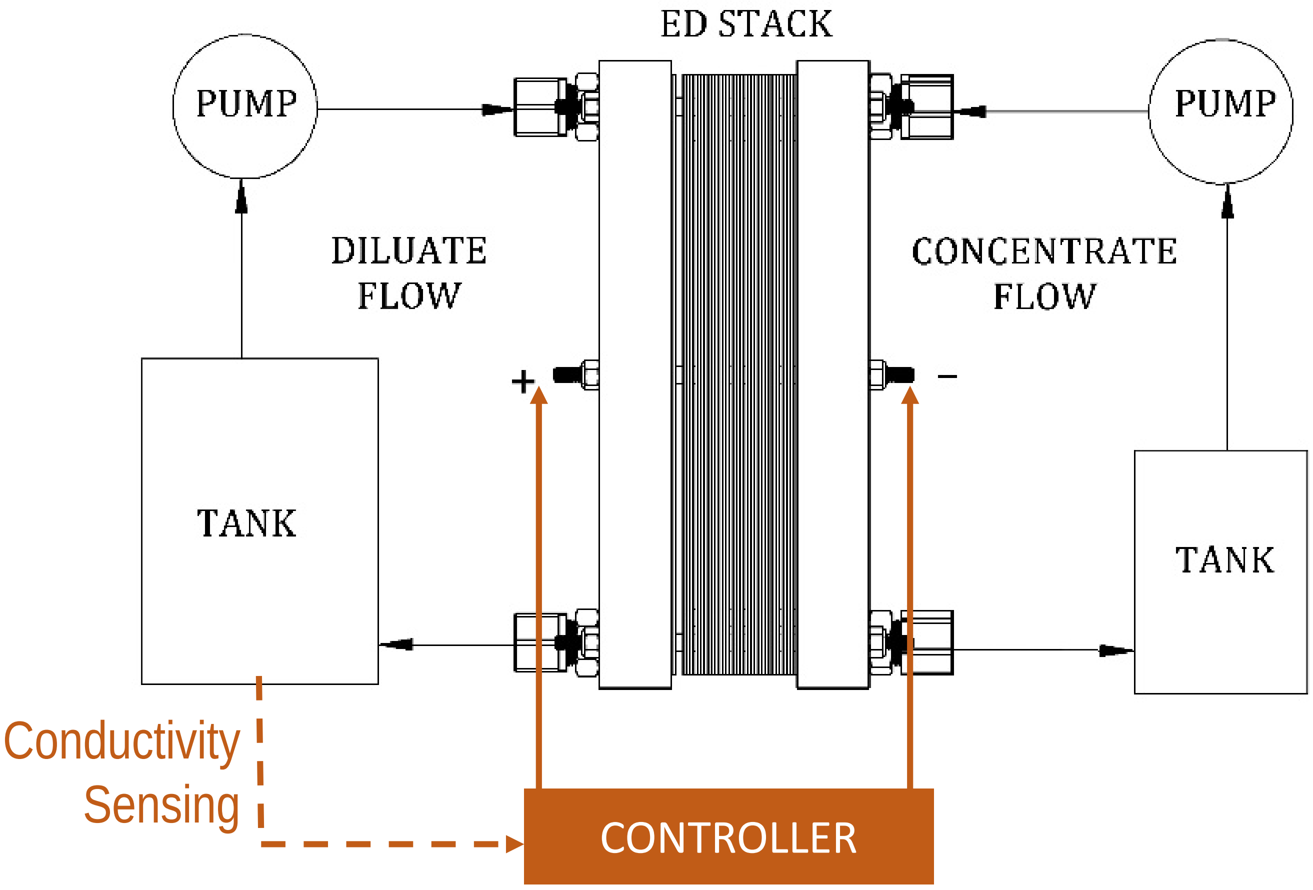
THE EFFECT OF CURRENT
DENSITY ON COST

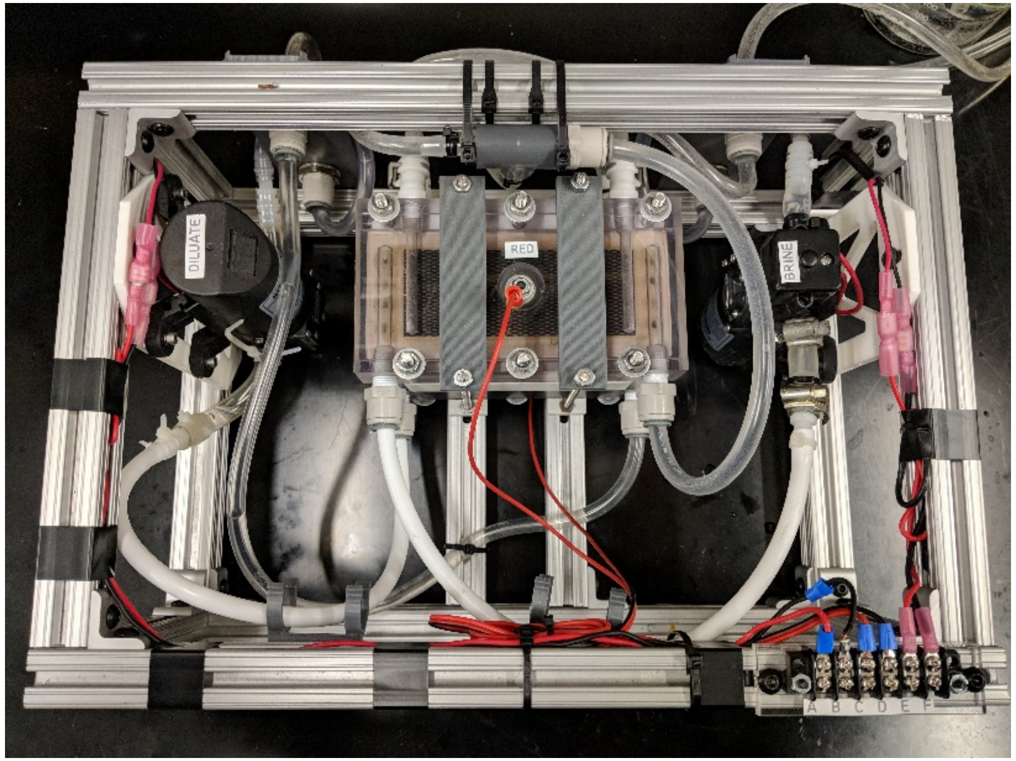
OPTIMAL FLOW-PATH
GEOMETRIES

TIME-VARIANT
PV-ED OPERATION

VOLTAGE-REGULATED BATCH

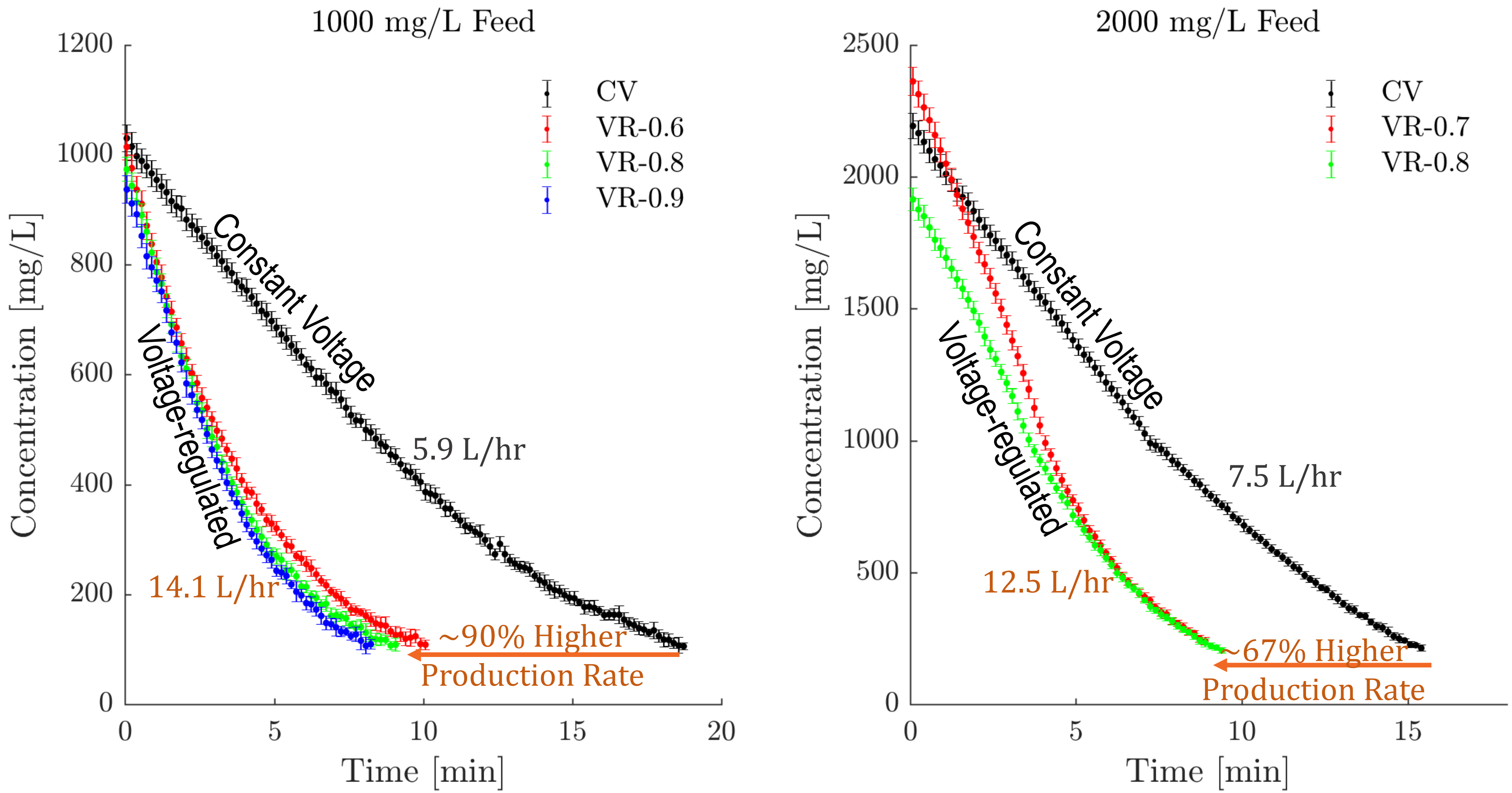
IMPLEMENTED CONTROLLER TO VARY VOLTAGE IN TIME





VOLTAGE-REGULATED BATCH

EXPERIMENTALLY-DEMONSTRATED IMPROVEMENT IN PERFORMANCE



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

RESEARCH OVERVIEW

VOLTAGE-REGULATED BATCH

THE EFFECT OF CURRENT DENSITY ON COST

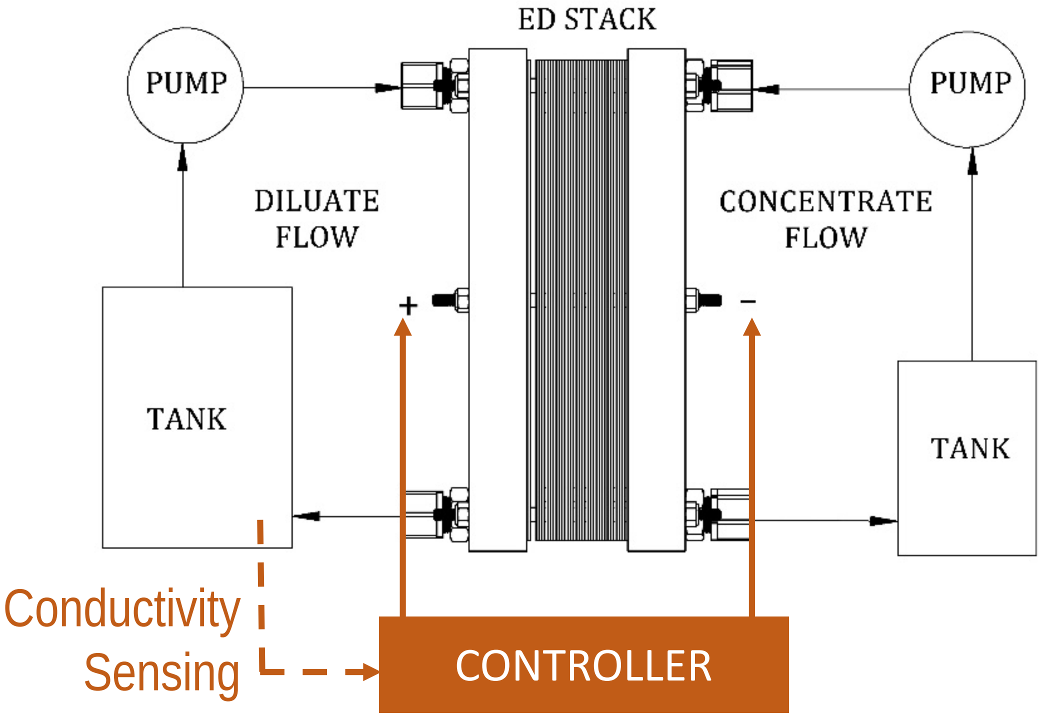
SPIRAL STACK DESIGN

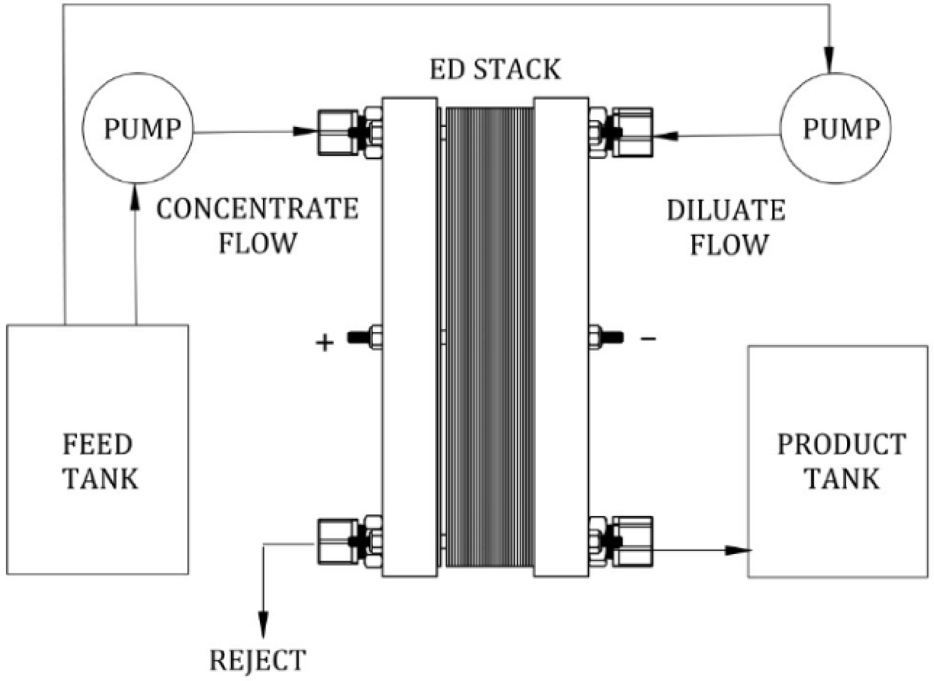
TIME-VARIANT PV-ED OPERATION

OPTIMAL FLOW-PATH GEOMETRIES

ELECTRODIALYSIS

DRAWING PARRALLELS TO VOLTAGE REGULATION





BATCH RECIRCULATION MODE

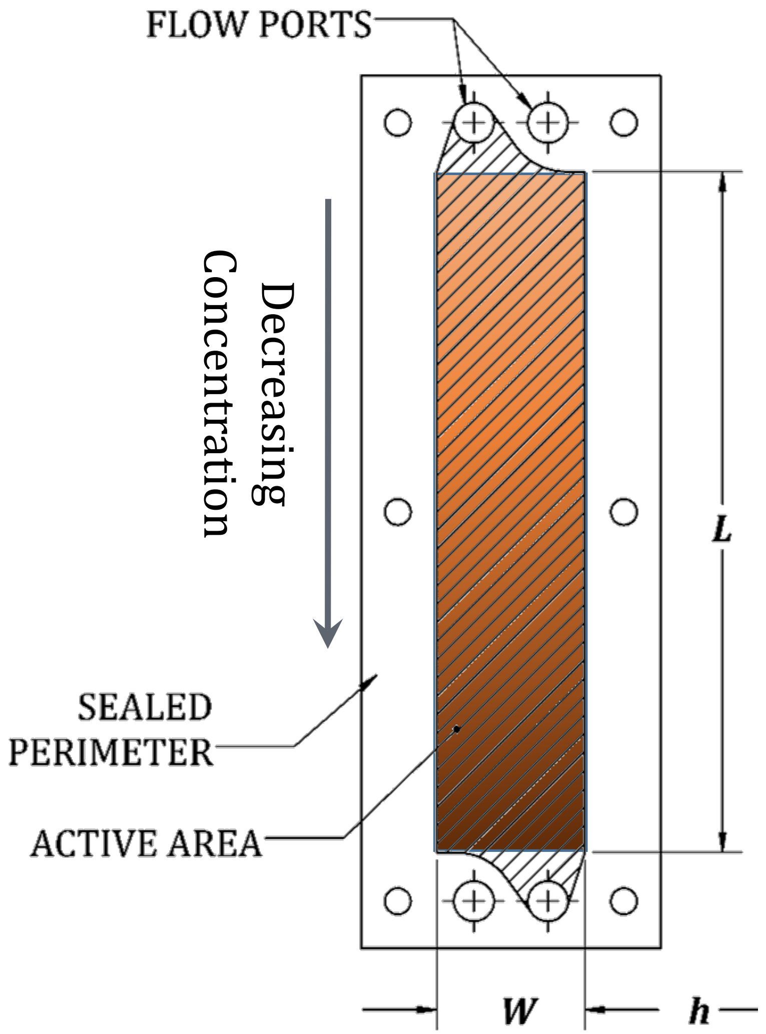
VOLTAGE REGULATION

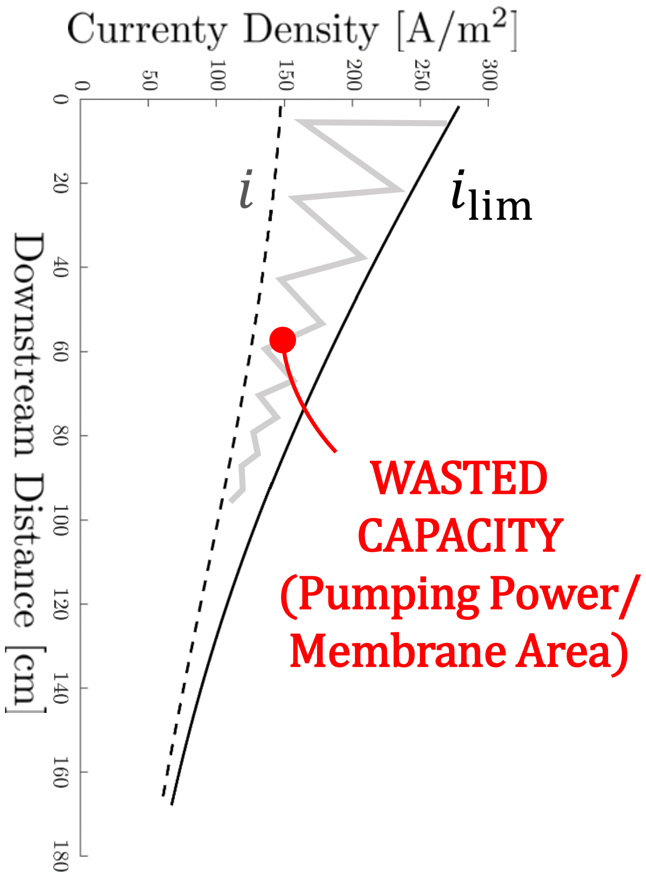
CONTINUOUS MODE

FLOW GEOMETRY

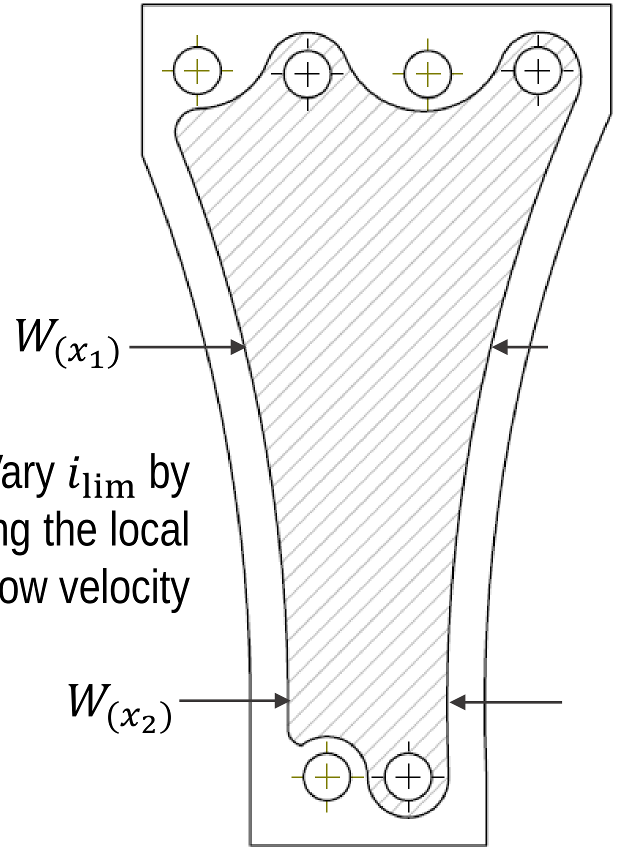
CONTINUOUS OPERATION

RECTANGULAR FLOW PATHS HAVE WASTED CAPACITY





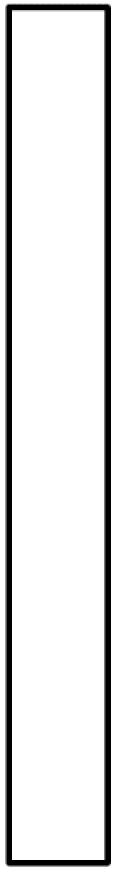
GE MkIV-2, 2000 mg/L to 477 mg/L, 7 cm/s Flow Velocity, 0.84 V/cell-pair 50% Recovery



Vary i_{lim} by changing the local flow velocity

TAPERED FLOW PATHS CAN DECREASE PRESSURE DROP

COMPARISON TO SUEZ MkIV-2 SPACER



SUEZ MkIV-2

SAME PARAMETERS

2000 to 722 mg/L, 80% Recovery

Production Rate: 35 Liters Per Hour/Cell-pair

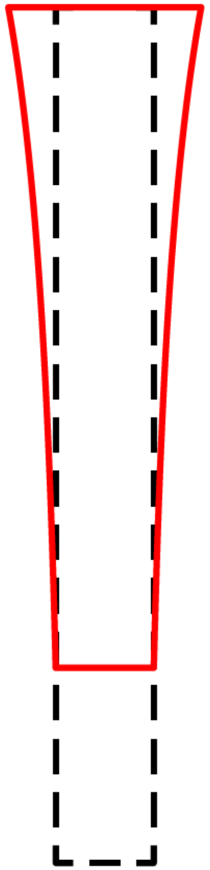
Applied Voltage: 0.62 V/Cell-Pair

Maximum $i/i_{\mathrm{lim}} = 0.7$

3 %
Membrane Area Increase

48 %
Pumping Power Decrease

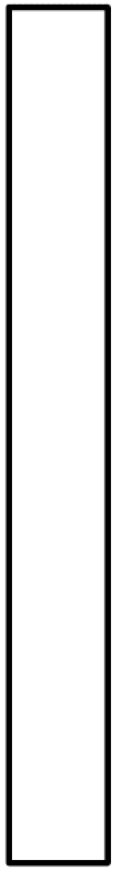
0%
Desalination Power Change



IDEAL FLOW-PATH

TAPERED FLOW PATHS CAN DECREASE MEMBRANE USAGE

COMPARISON TO SUEZ MkIV-2 SPACER



SUEZ MkIV-2
0.62 V/cell-pair

SAME PRODUCTION
BUT DIFFERENT VOLTAGES

2000 to 722 mg/L, 80% Recovery

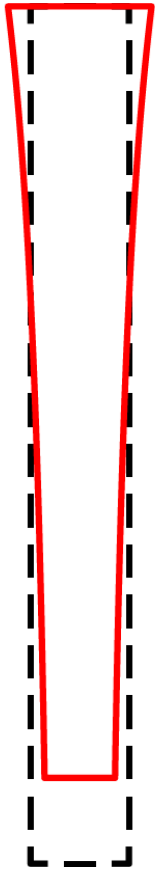
Production Rate: 35 Liters Per Hour/Cell-pair

Maximum $i/i_{\text{lim}} = 0.7$

13 %
Membrane Area
Decrease

0 %
Pumping Power
Decrease

13%
Desalination Power
Increase



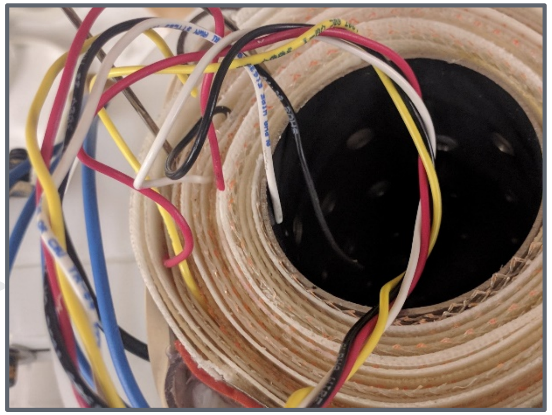
IDEAL FLOW-PATH
0.7 V/cell-pair

RESEARCH OVERVIEW

VOLTAGE-REGULATED BATCH

THE EFFECT OF CURRENT DENSITY ON COST

SPIRAL STACK DESIGN

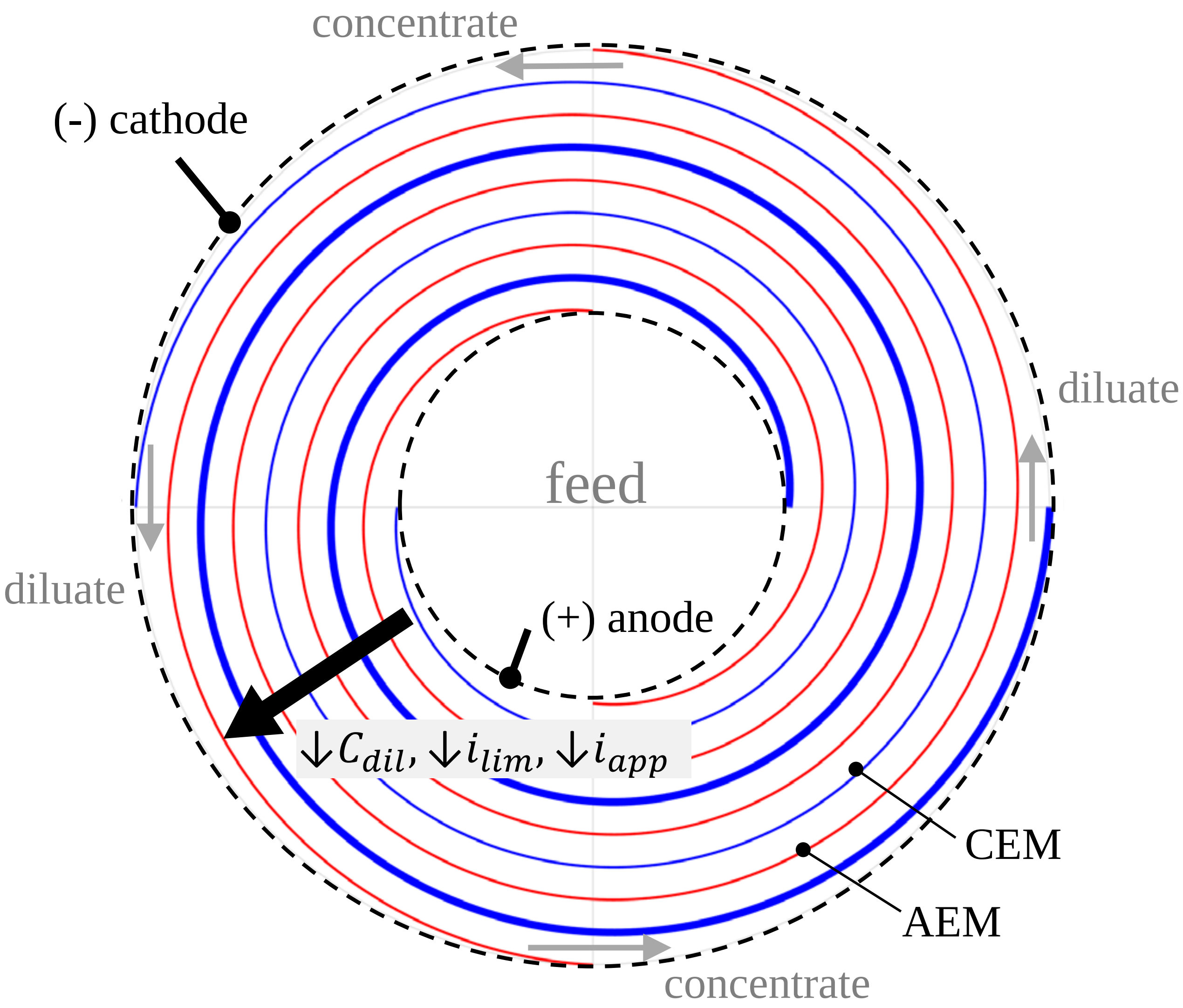


TIME-VARIANT PV-ED OPERATION

OPTIMAL FLOW-PATH GEOMETRIES

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**

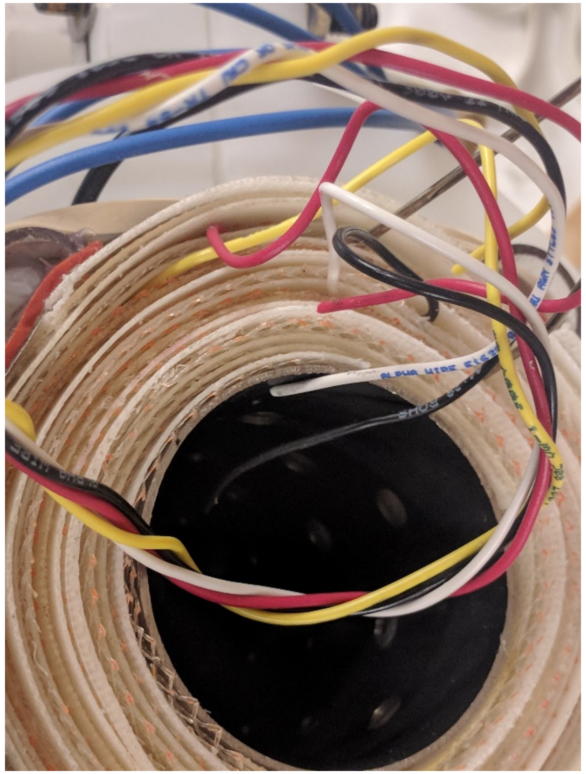


Wen. et. al. Spirally wound electrodialysis (SpED) modules. *Desalination* (1995).
N. C. Wright and A. G. Winter V., "Model and Experimental Validation of a Spiral-Wound Electrodialysis Module." *In Proceedings of the IDA World Congress* (October 2017).

PROTOTYPE SPIRAL USED FOR MODEL VALIDATION

TWO CELL PAIRS MAKING FOUR REVOLUTIONS, MODEL/EXPERIMENTAL AGREEMENT WITHIN 15%

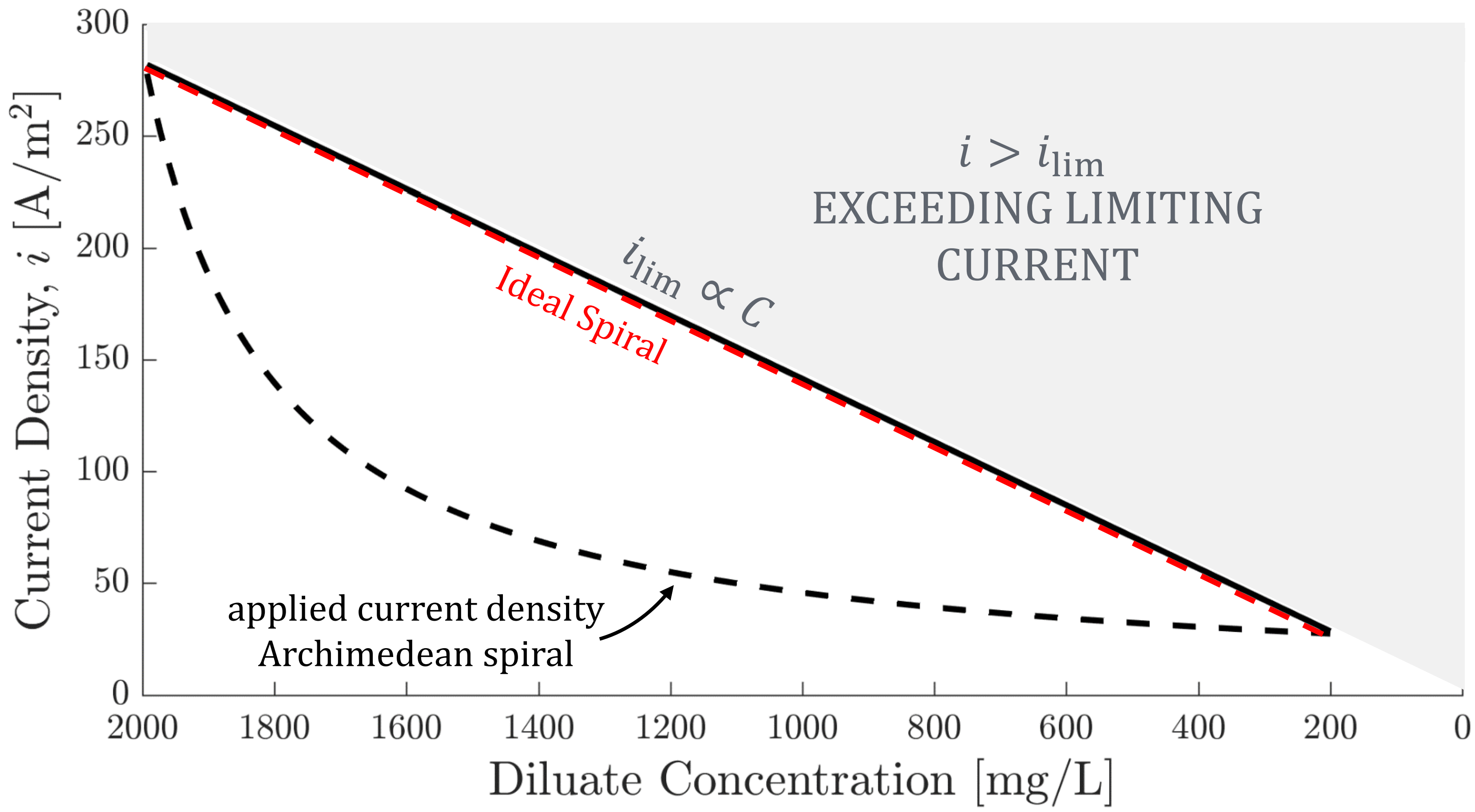
Membranes and spacers rolled around a perforated titanium center tube

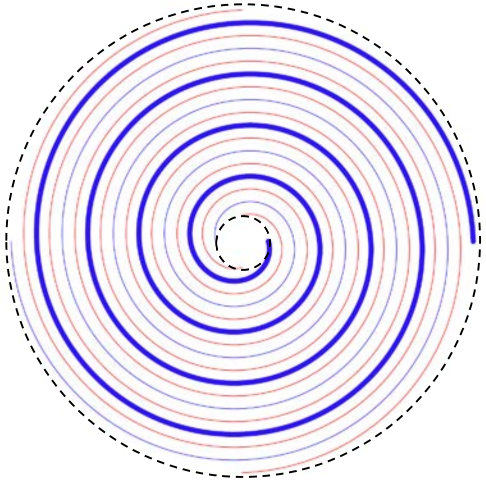


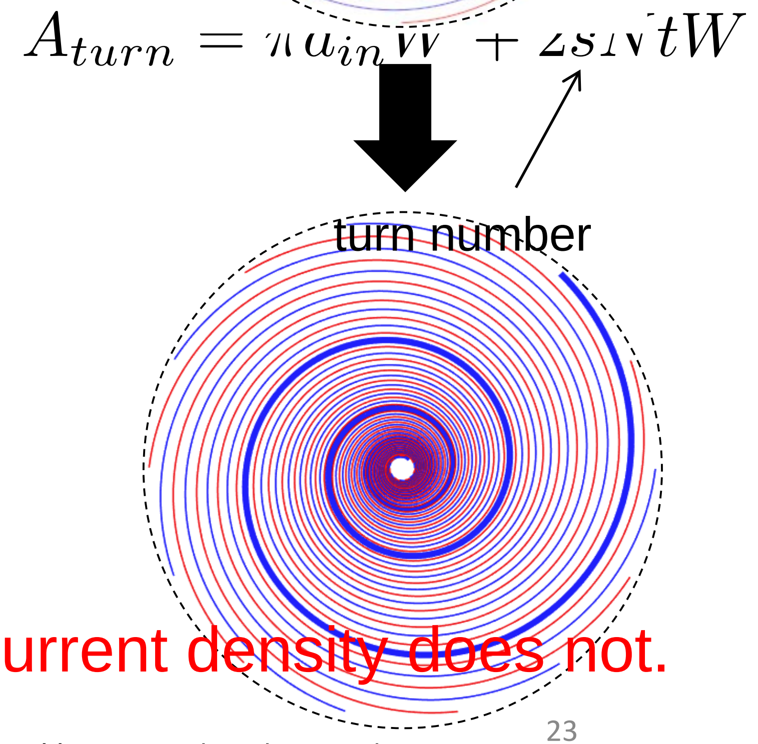
Sample tubes and wires inserted for mid-stack measurements

Resin and clamps used for sealing

A STANDARD ARCHIMEDEAN SPIRAL DOESN'T GIVE THE EXPECTED BENEFIT



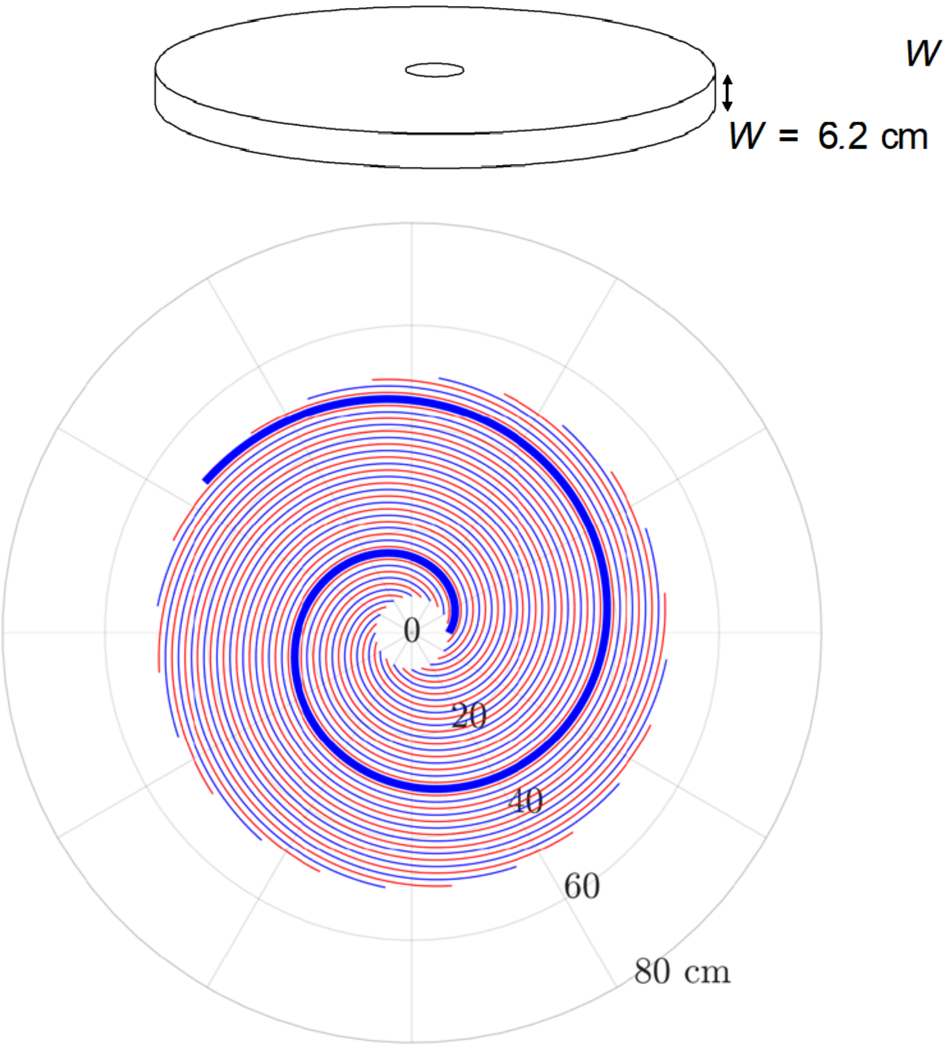




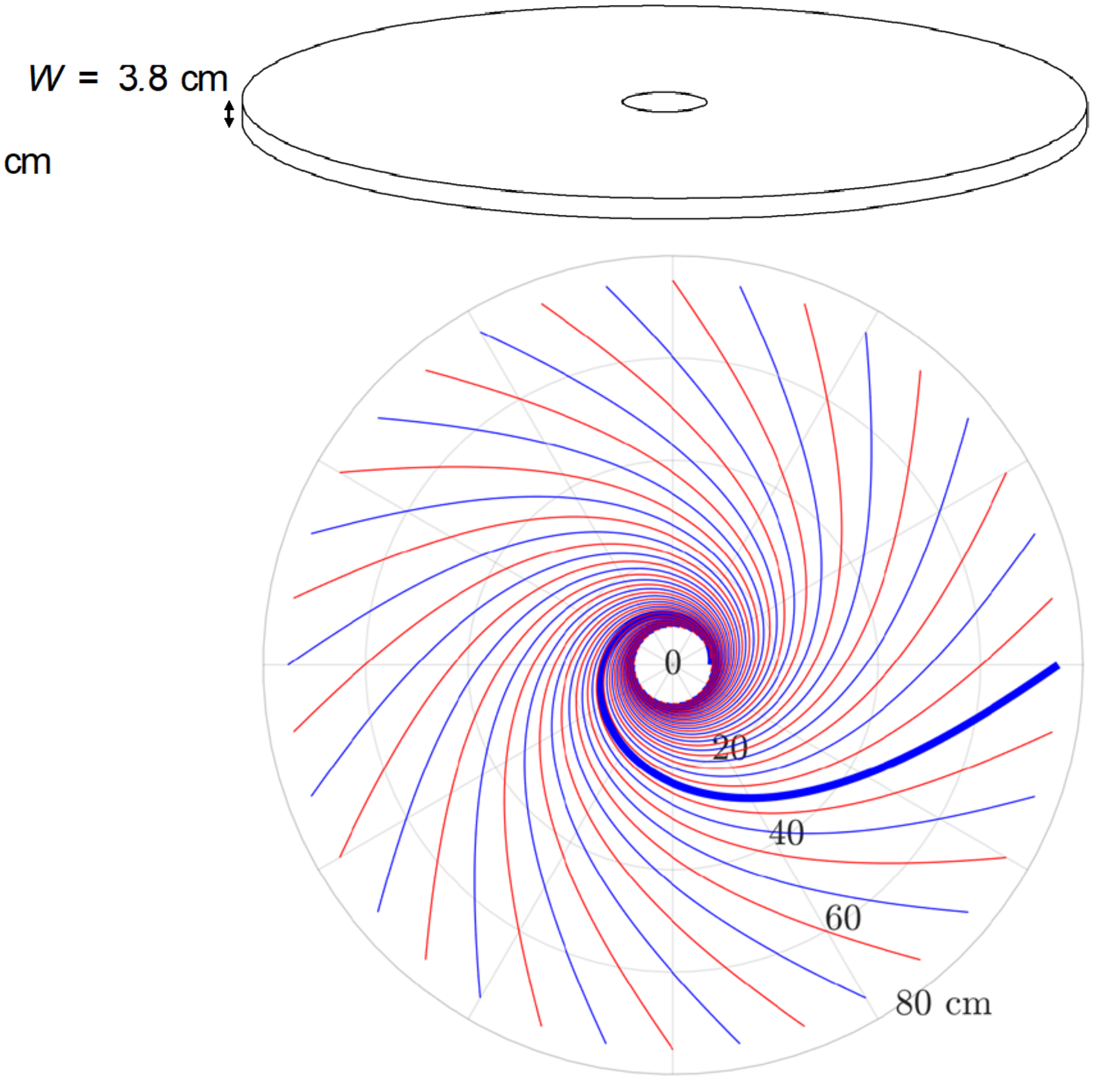
Concentration decreases linearly with turn number; applied current density does not.

N. C. Wright and A. G. Winter V., "Model and Experimental Validation of a Spiral-Wound Electrodialysis Module." *In Proceedings of the IDA World Congress* (October 2017).

Archimedean



Ideal



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

THE EFFECT OF CURRENT
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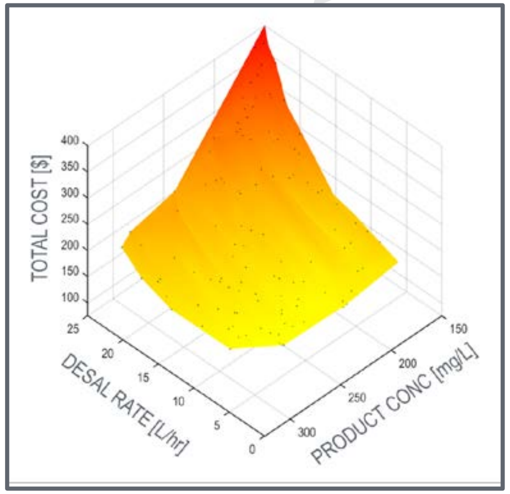
SPIRAL STACK
DESIGN

OPTIMAL FLOW-PATH
GEOMETRIES

TIME-VARIANT
PV-ED OPERATION



CONVENTIONAL PV-EDR SYSTEM DESIGN

Size water production rate
Define daily volume

ED desalination sub-system design

Solar power sub-system design

Water consumption behavior

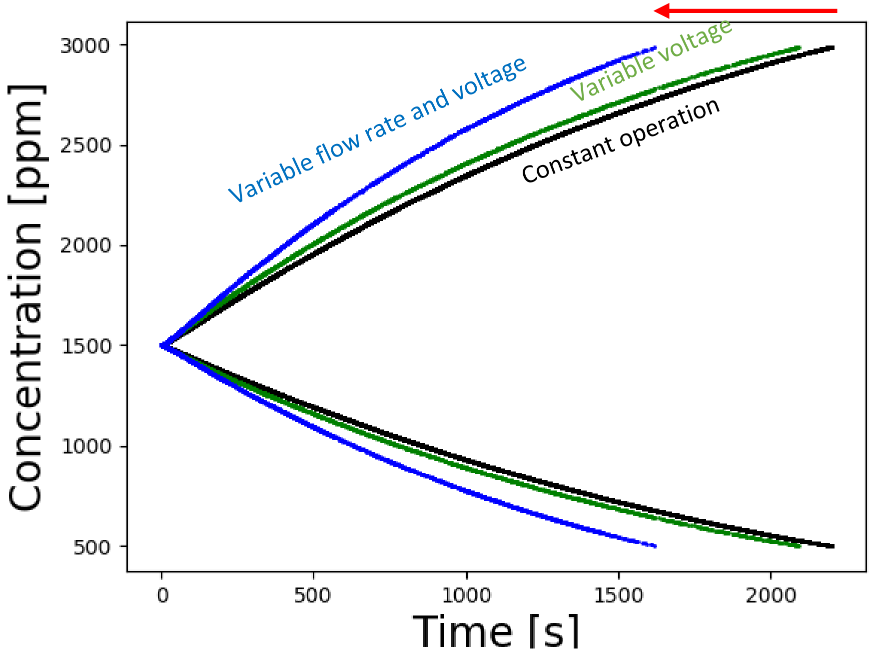
Solar intermittence

The conventional design sequentially design desalination sub-system and solar power sub-system, without considering connection between solar power and ED behaviors.

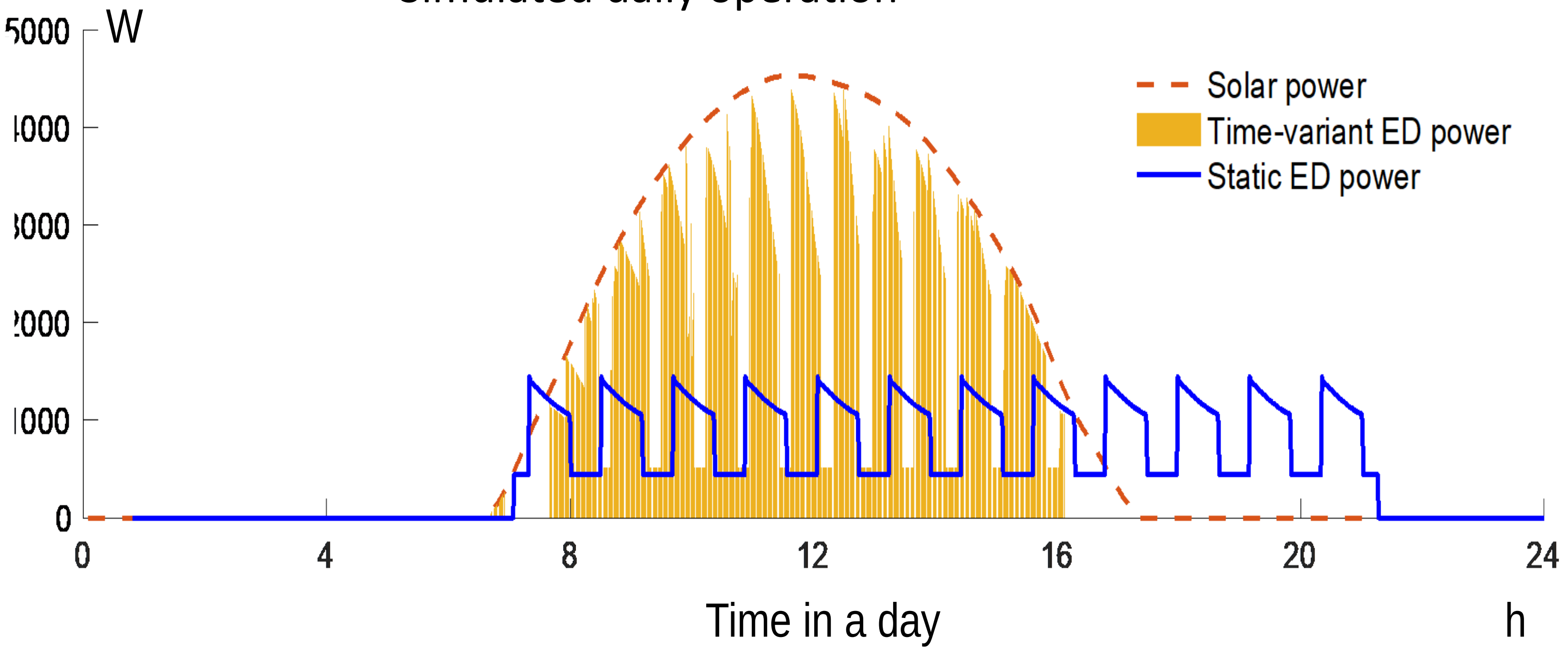
DESIGN TO UTILIZE SOLAR INTERMITTANCE

Simulated single-batch

26.5 % Batch time reduction



Simulated daily operation



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 m^3 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

FIELD EVALUATION OF TIME-VARIANT PV-ED OPERATION

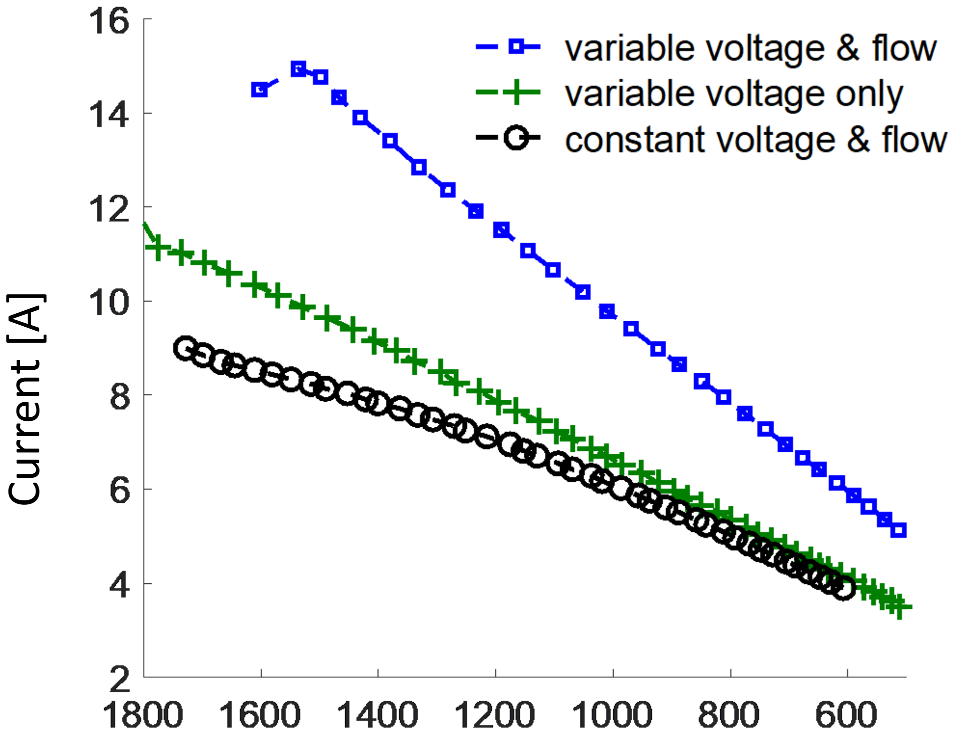
AT BGNDRF IN NEW MEXICO, USA

Experimental assessment of the time-variant PV-ED system's benefits is on-going

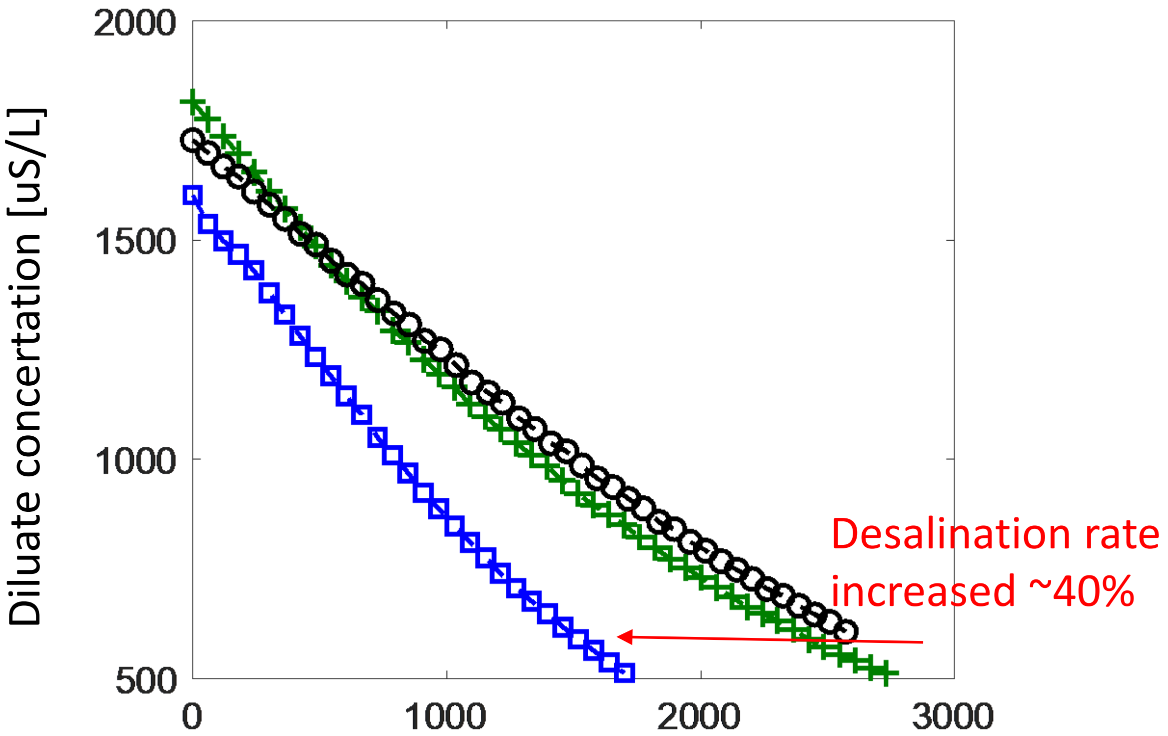
FIELD EVALUATION OF TIME-VARIANT PV-ED OPERATION

FIRST EXPERIMENTAL RESULTS AND NEXT STEPS

Experimental batch operation – Current profile



Experimental batch operation – diluate concentration profile



- 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.

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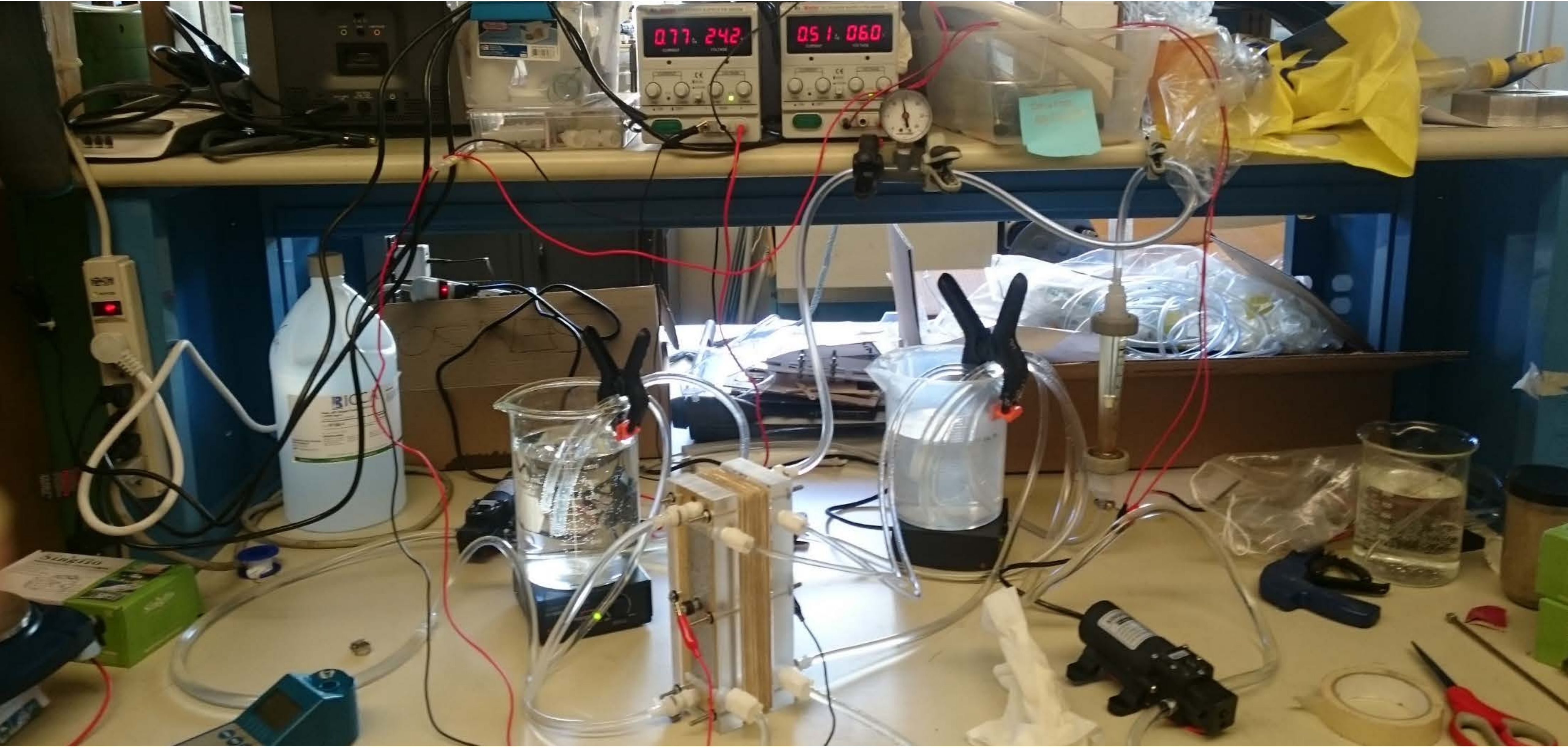


jcostello@mit.edu ncwright@mit.edu gear.mit.edu

Thank you!

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

Size water production rate
Define daily volume

ED desalination sub-system design

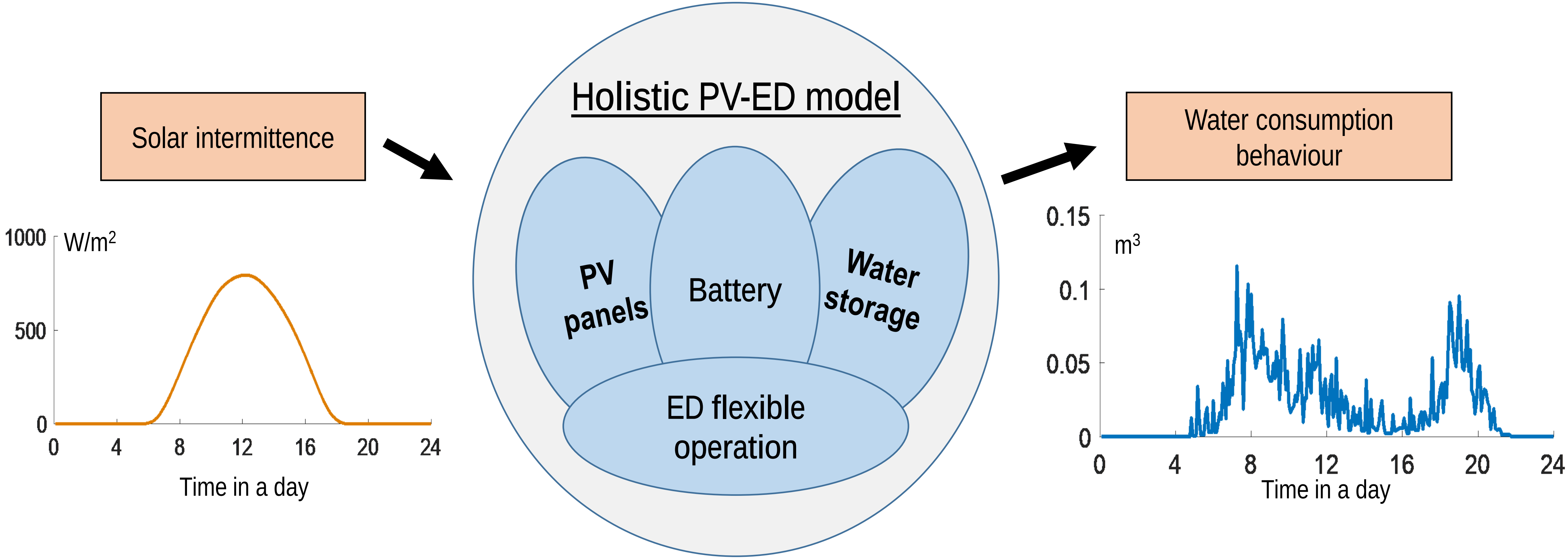
Solar power sub-system design

Water consumption behavior

Solar intermittence

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

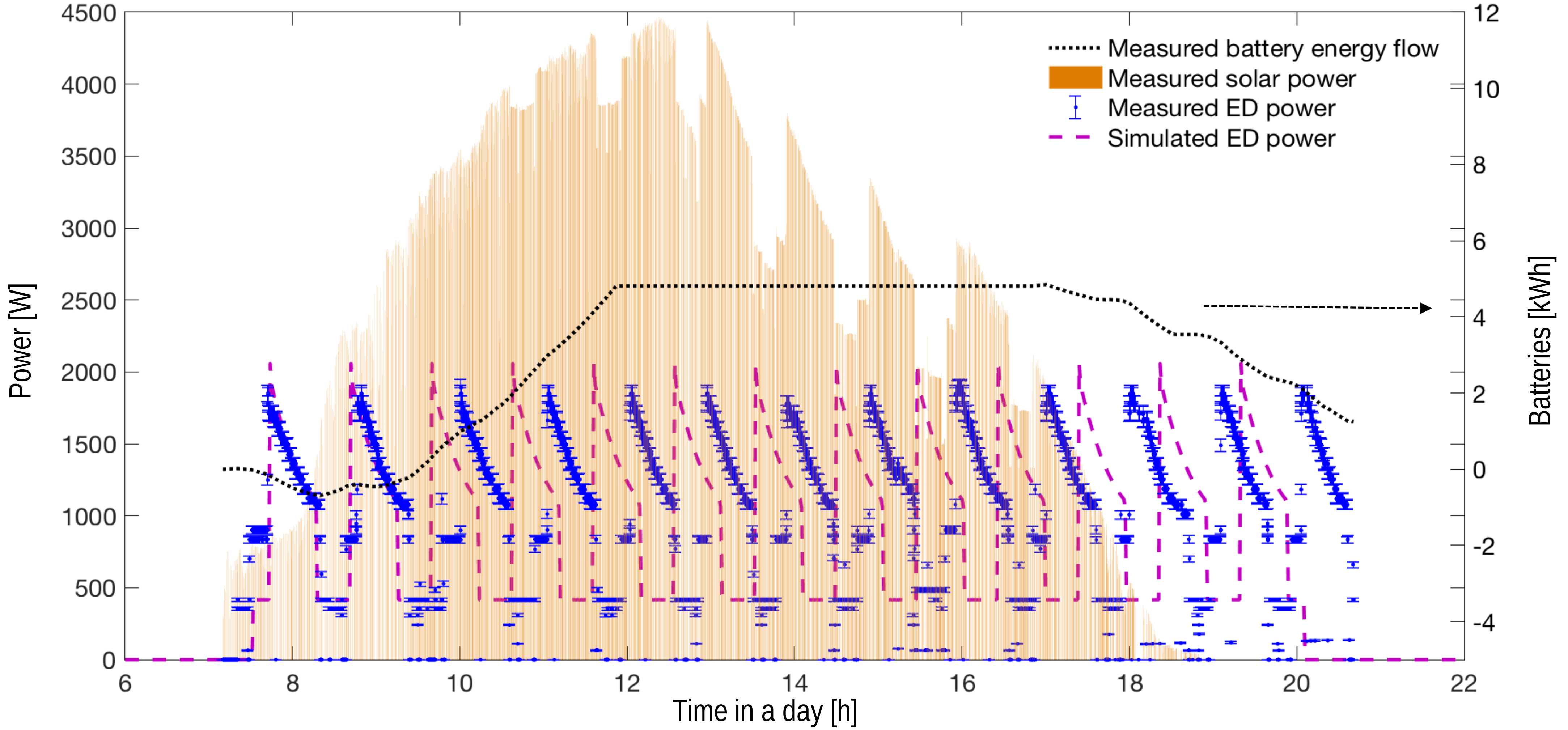
PV panels

Batteries and inverter

ED stack, hydraulics, control panel, etc.

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

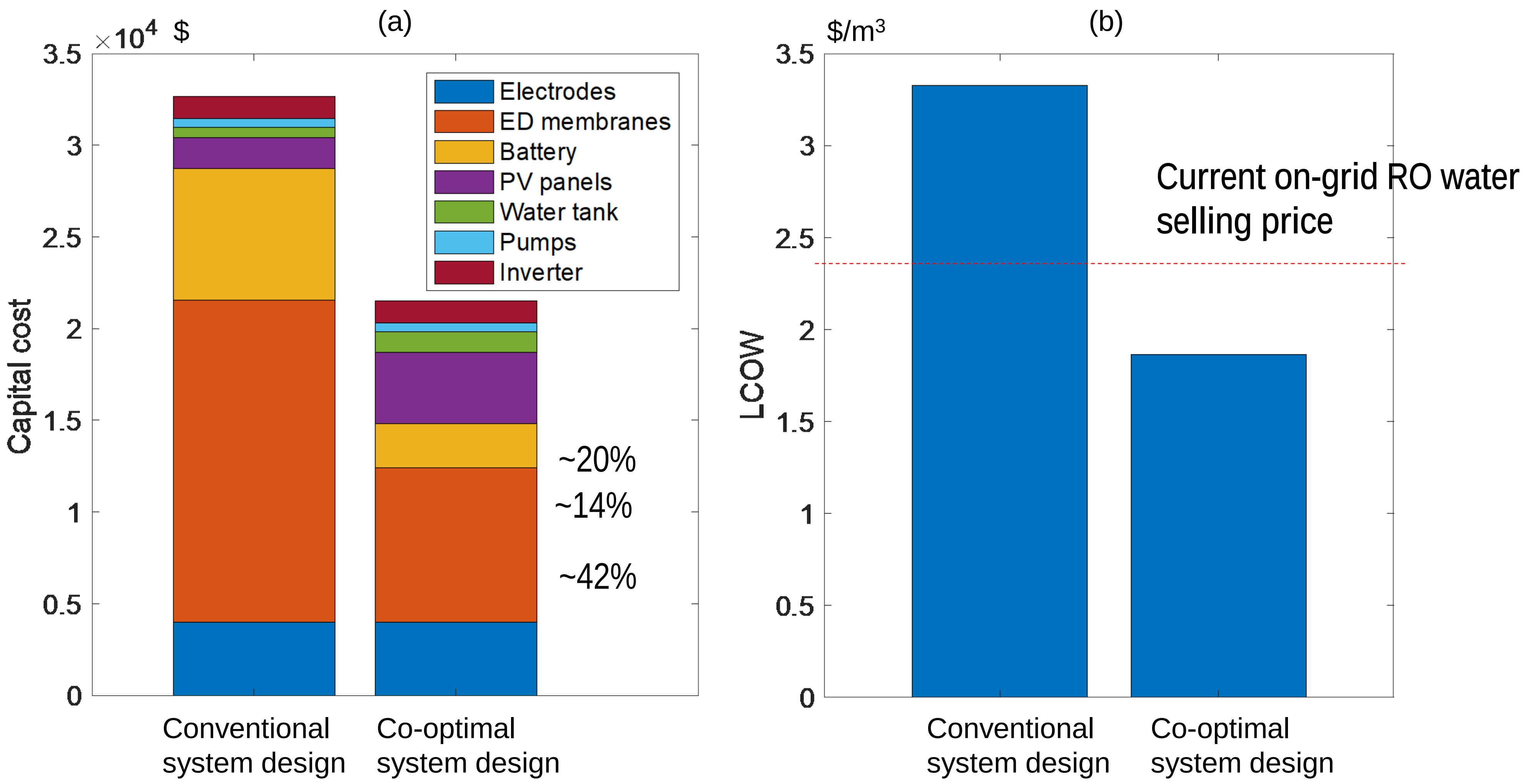
Results and water cost of the field pilot in India



- ➢ 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

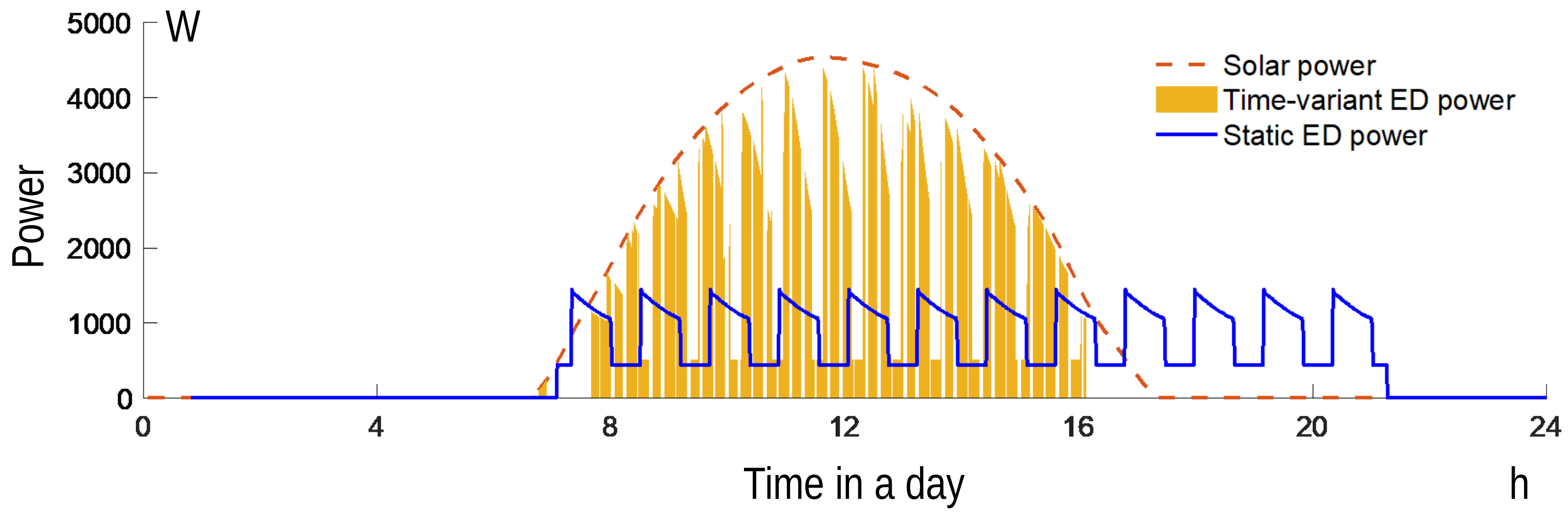
Results and water cost of the field pilot in India

TATA PROJECTS
Simplify.Create



- The PV-ED field pilot has a potential to achieve the cost affordability

Benefits of time-variant PV-ED system



The time-variant PV-ED system can significantly:

- Increase the instantaneous solar energy utilization rate
- Increase desalination rate
- Increase membrane effectiveness in m^3 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

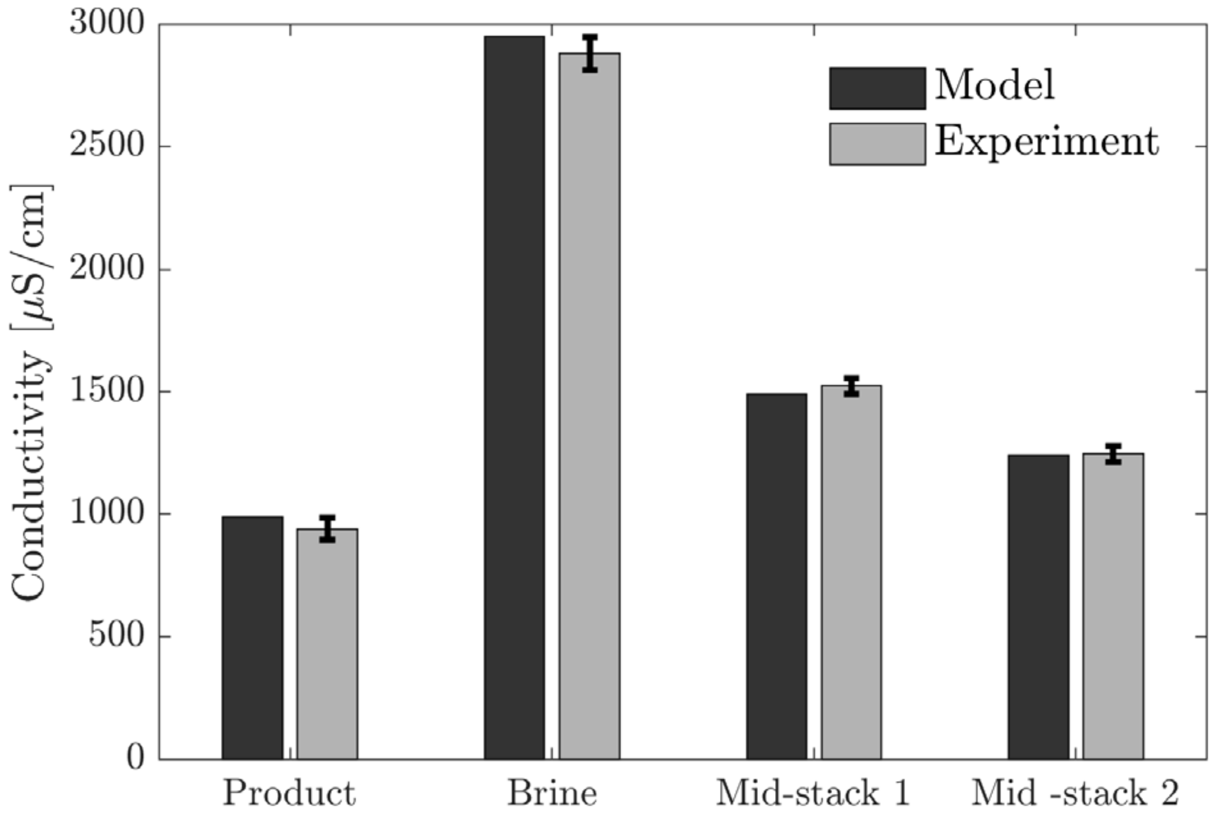
Field pilot of time-variant PV-ED prototype in New Mexico

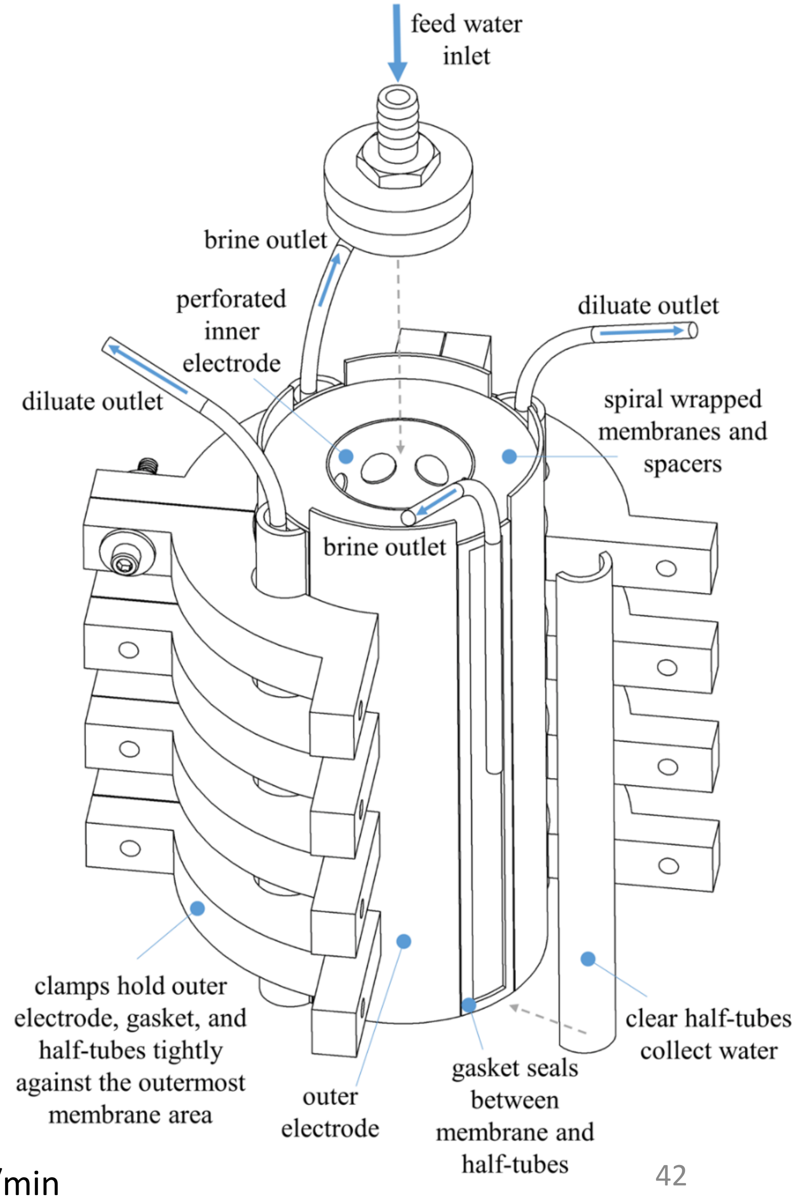
The field pilot being built at BGNDRF, New Mexico, USA

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



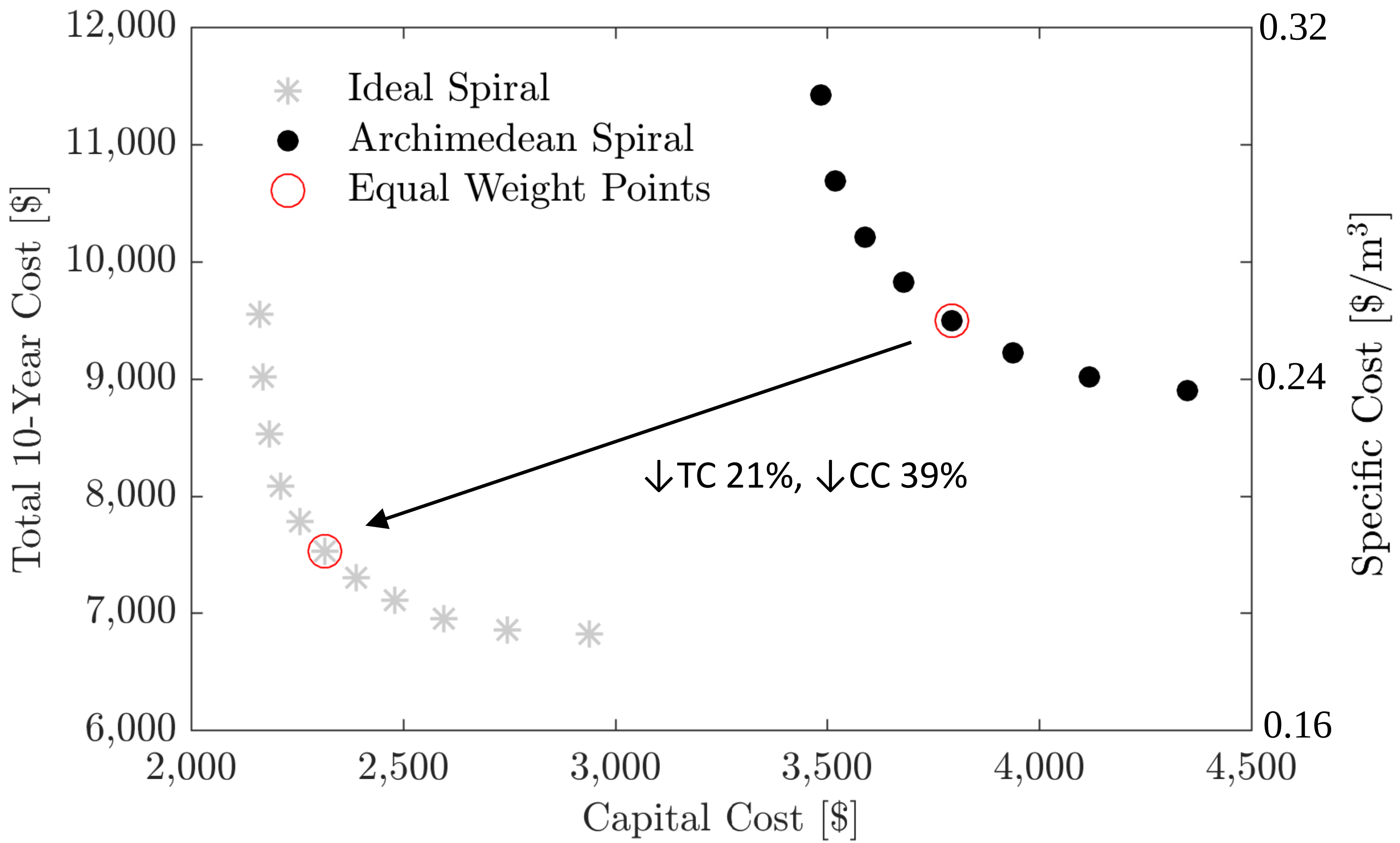


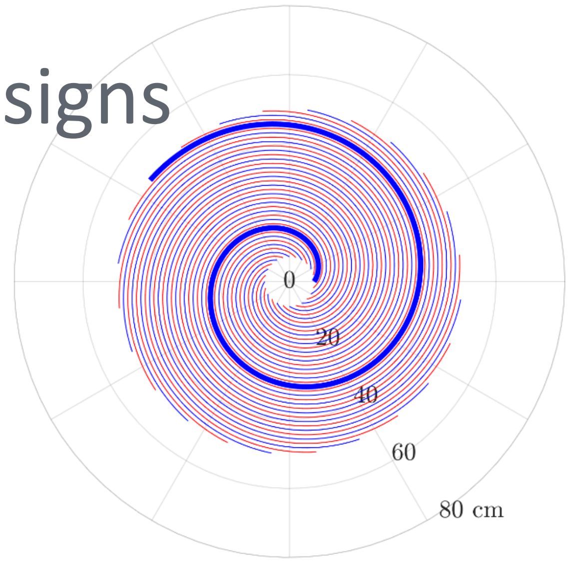
Measured energy consumption within 1-15% of modeled values (average 7%)

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

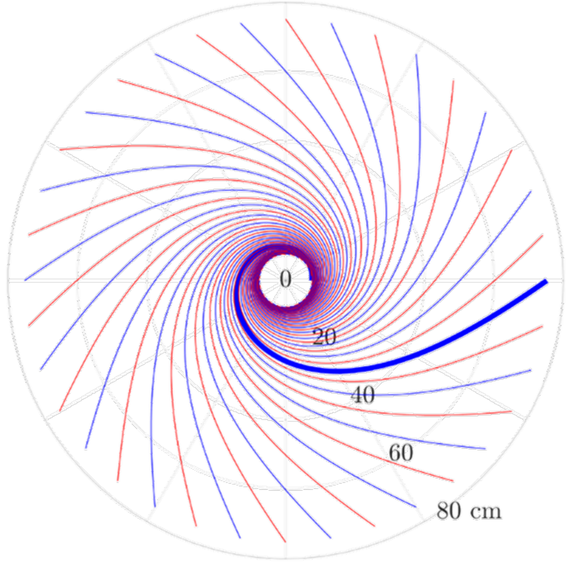
Sample data here shown for: Feed concentration - 1060 mg/L   Applied voltage - 14 V   Flow Rate - 1.5 L/min

Cost Optimal Archimedean Spiral vs. Ideal Spiral Designs





Archimedean



Ideal

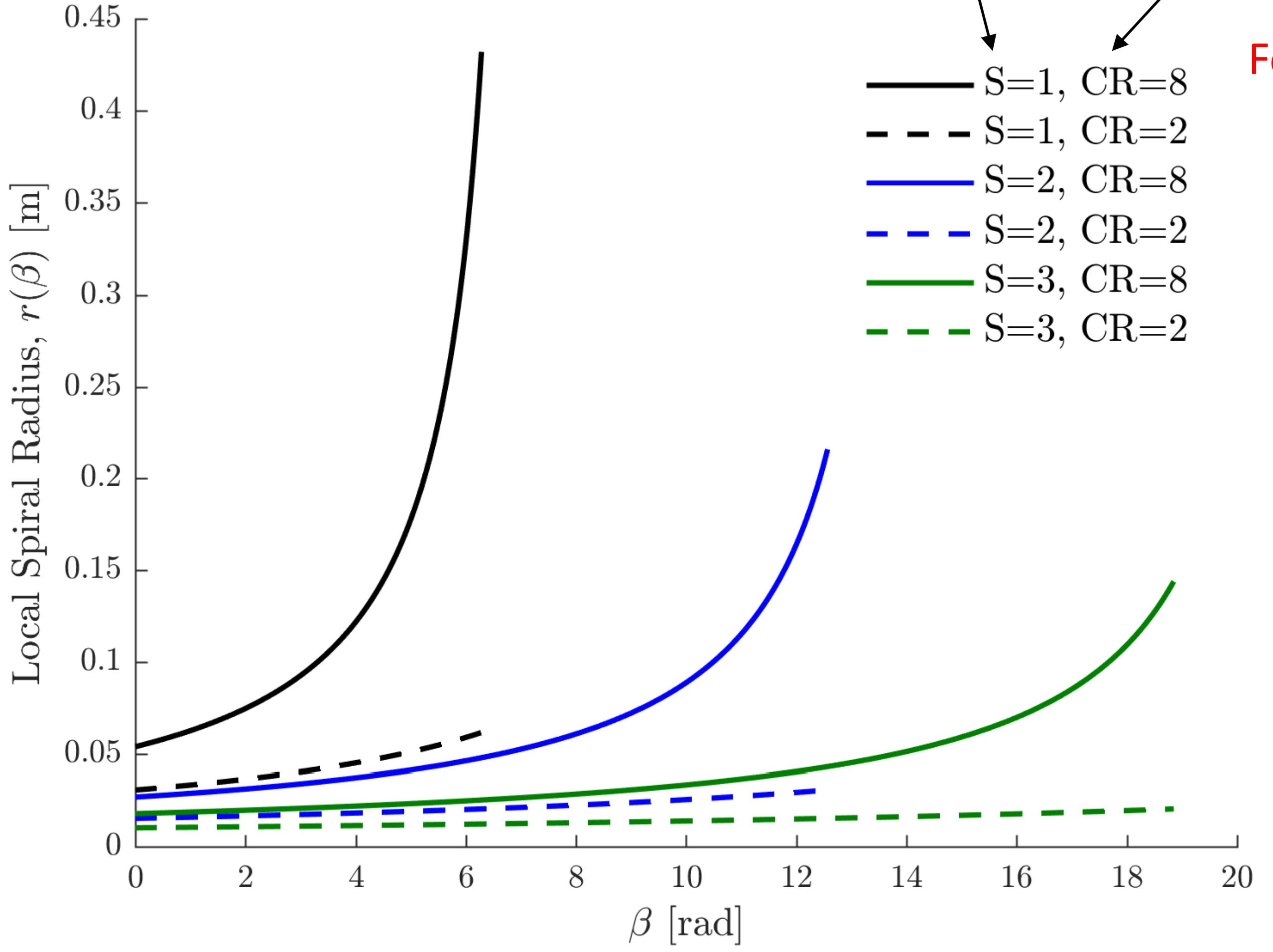
*from 57m^2 to 30 m^2 total membrane area

Staging for more reasonable electrode radii

of turns

Concentration ratio ($\frac{C_{feed}}{C_{product}}$)

For example: CR=8 could be 2000 mg/L to 250 mg/L

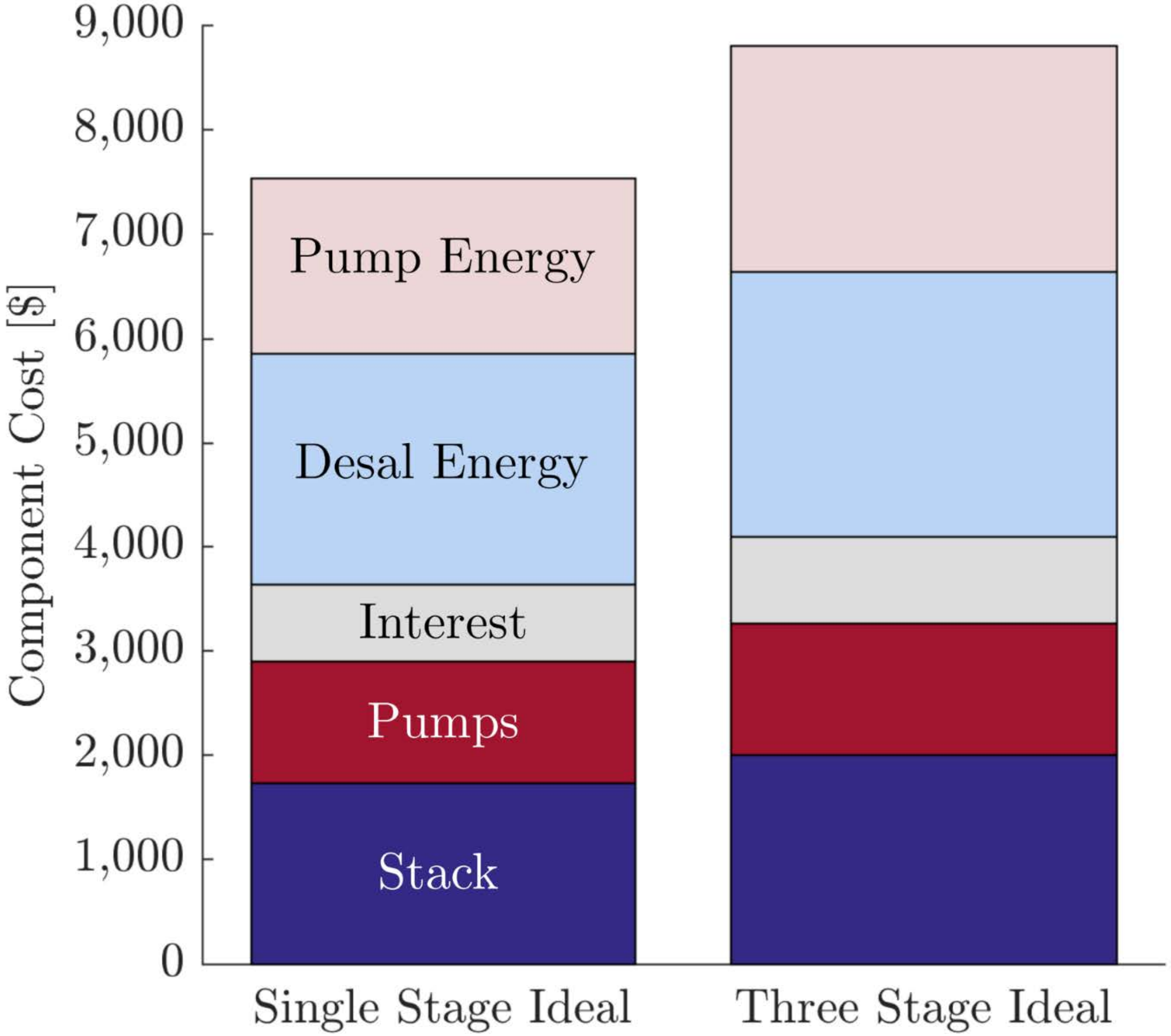


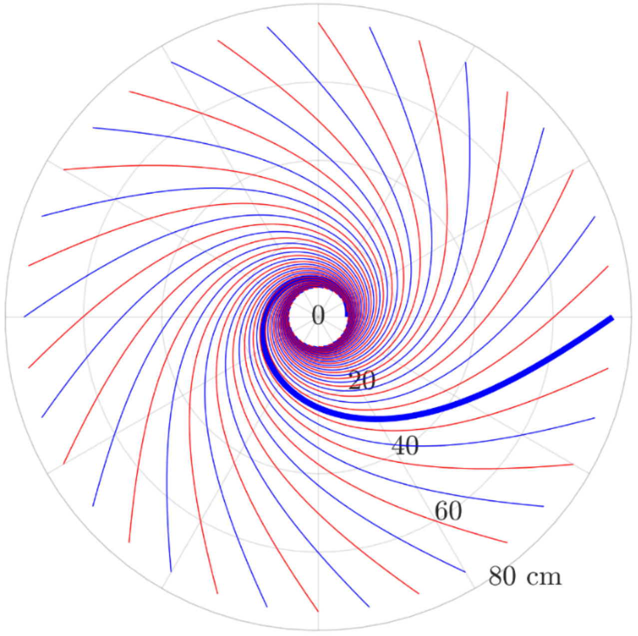
Radii decrease if use more turns of the spiral.

But this increases the amount of membrane area required.

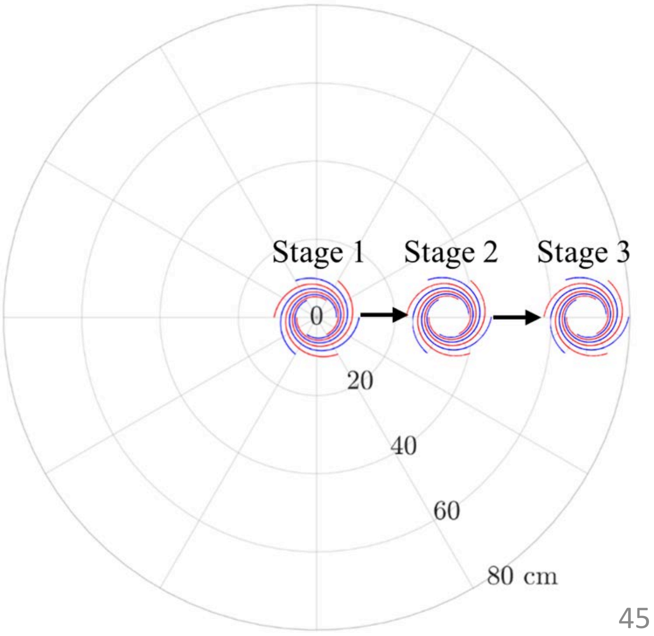
What happens if we stick to one turn, but put 3 spirals in series, each with CR = 2?

Staging for more reasonable electrode radii





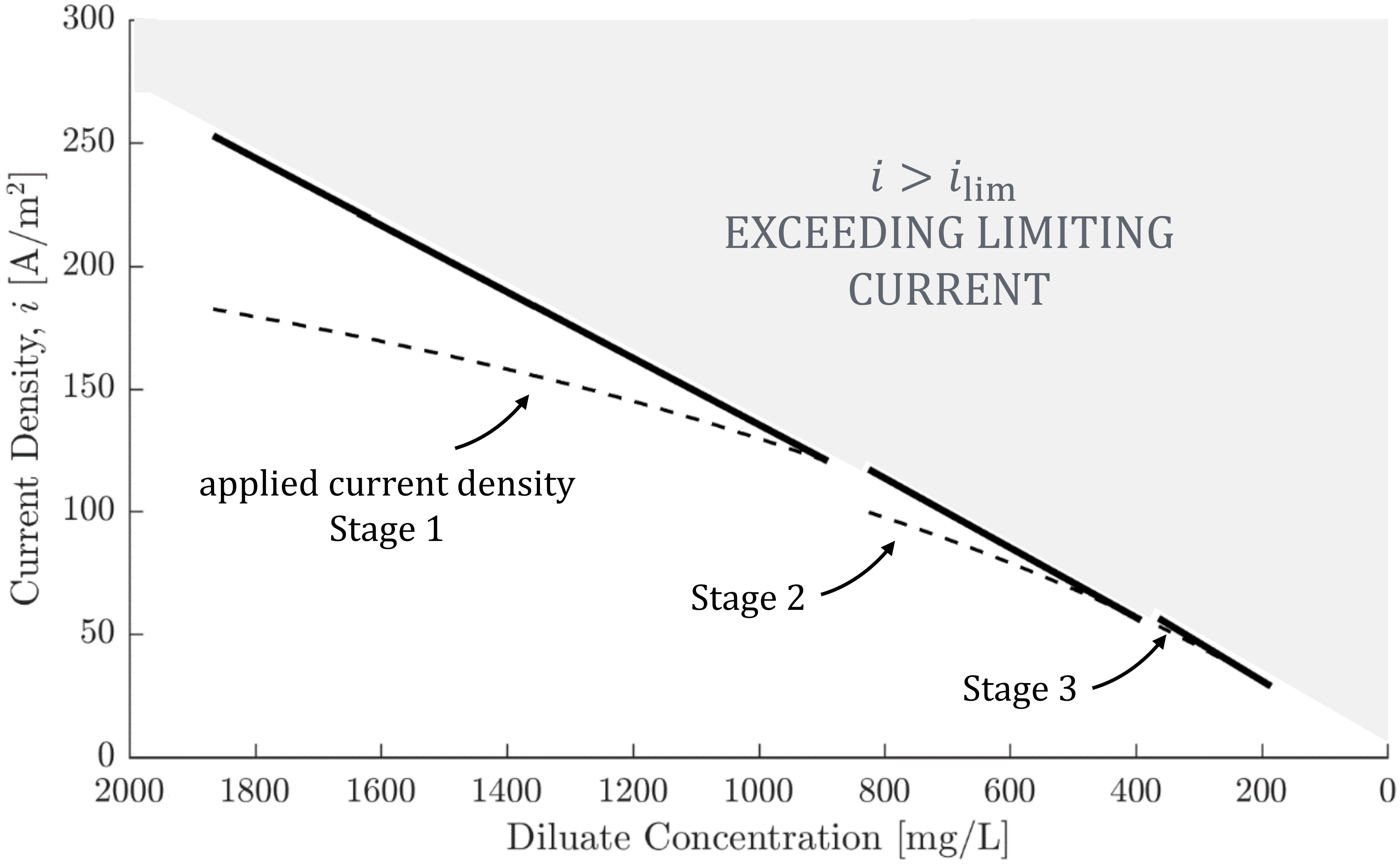
Single Stage Ideal



Three Stage Ideal

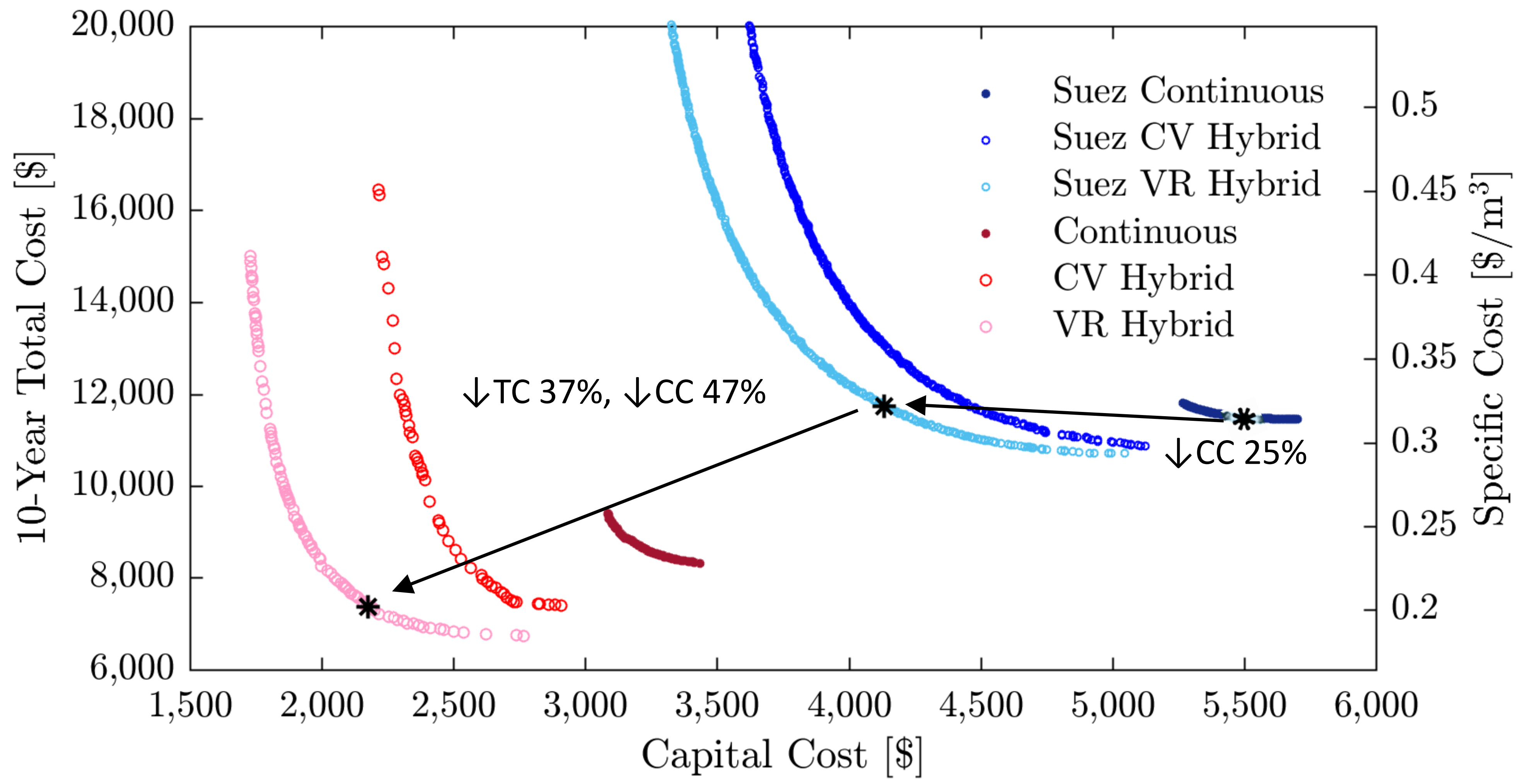
Relationship between limiting and applied current density

Three electrical stage continuous operation

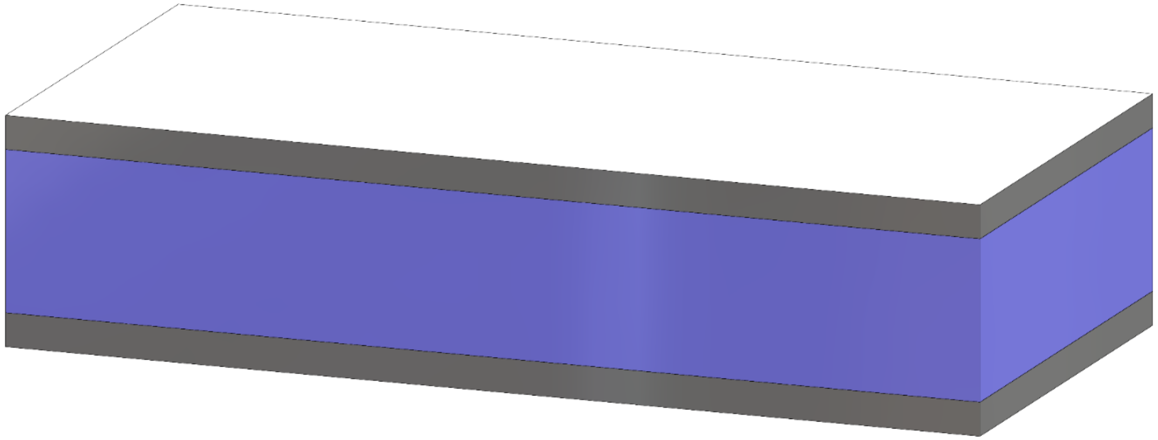


Fully Optimized vs. Optimized within Commercial Constraints

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.

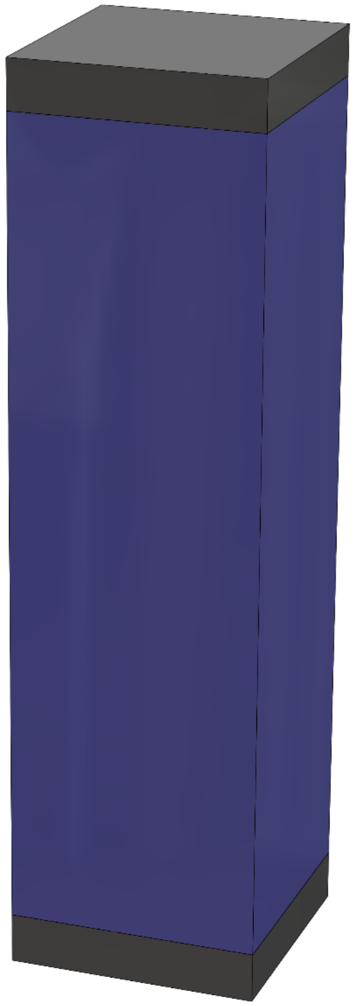


Optimized **Utilizing Suez Components, Operating in** Voltage-Regulated Hybrid



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

Fully Optimized Stack, Operating in Voltage-Regulated Hybrid



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

Stack cost reduction of ~55%