U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

AMMTO & IEDO JOINT PEER REVIEW

May 16th-18th, 2023

Washington, D.C.

Innovative Manufacturing Processes to Enable Flow Batteries with Unmatched Capital Costs

AMMTO

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Project Overview

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- **Primary innovation**: Advanced Manufacturing Process for RFB Systems
  - ➢ Currently, the majority of RFB CapEx are manufacturing cost, *not* material costs
    - LCE is focused on five new manufacturing processes to produce RFB Cell Stacks and RFB Electrolyte in our factory in Wilmington, MA.
    - LCE is focused on all-vanadium RFBs (VRFBs), but these production processes can potentially be used with any RFB chemistry.
  - ➢ **Impact:** Enable commercially-viable Long Duration Energy Storage (LDES)
    - Substantial LDES is required to enable large penetration of stochastic renewable electricity sources (*e.g.*, wind & solar).
  - ➢ **RFBs have inherent attributes that make them highly attractive for LDES apps**
    - These attributes include:
      - Power & Energy independence; long cycle life; superior safety
    - This project can help enable complete RFB systems with capital costs that are significantly lower than other LDES solutions
      - RFBs are ideal for systems with 6- to 10-h discharge cycles at rated power

Project Outline

Innovation: Multiple advanced manufacturing process to produce RFB systems
Project Lead: Largo Clean Energy
Project Partners: IRD Fuel Cells (sub-contractor); University of Kansas

Timeline: Start Date = 07/01/2022; End Date = 09/30/2025; 3.25 years (23%, as of 3/31/22)
Budget: Total = $5.99M; Federal = $4.19M; Cost Share = $1.80M (30%)

	BP-1 (FY-22/23)	BP-2 (FY-24)	BP-3 (FY-25)	Total Planned Funding
DOE Funded	$1,425,226	$1,416,878	$1,349,856	$4,191,960
Project Cost Share (30%)	$756,937	$590,156	$449,039	$1,796,132

Spent to Date (as of 3/31/22): Total = $599,901 (Federal = $422,031; CS = $177, 870)
Received from DOE to Date (as of 3/31/23): $0 (LCE did not submit any invoices until 2023)

End Project Goal: Demonstrate DOE test protocols for RFB systems (TBD) in an Advanced Prototype System (APS), which shall consist of a VRFB cell stack with ≥ 10 full-size cells and shall comprise an important part of LCE's V&V plan for these new production processes.

Background: RFB Systems

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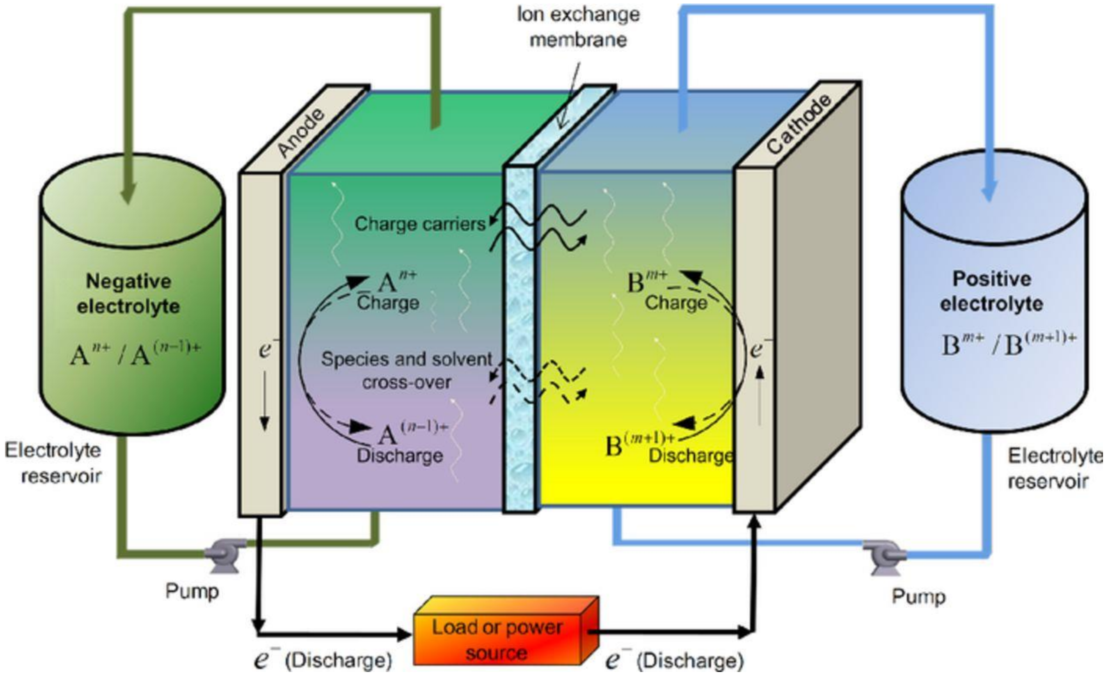
<u>RFB System = Stack, Electrolyte, & BOP</u>

(Figure from: M. Perry & A. Weber,

J. Electrochem. Soc., **163,** 2016)



Stack & BOP = Power (kW)

Electrolyte & Tanks = Energy (kWh)

<u>LCE's current VRFB Product</u>

Rated Power = 1.2-MW

With 6-, 8-, or 10-h discharge cycle

Fully-containerized system requires only footings on-site

Containers also serve as Secondary Containment

Background: Key LCE Differentiations

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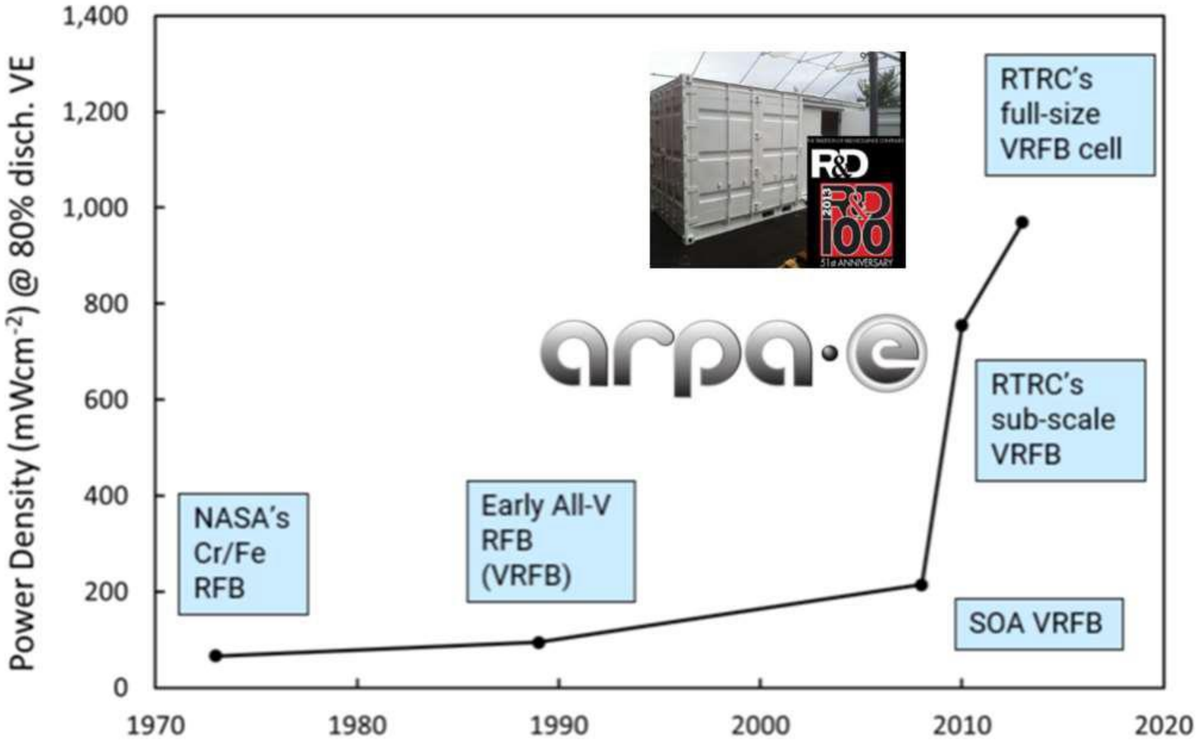
High-performance Cells = Reduce Stack Cost ($/kW)

ARPA-E describes LCE's licensed technology as "*breakthrough flow battery stack*"



Simple Purification = Reduce Electrolyte Cost ($/kWh)

Electrochemical process effectively removes key impurities (Figure from US Patent 11,233,260)

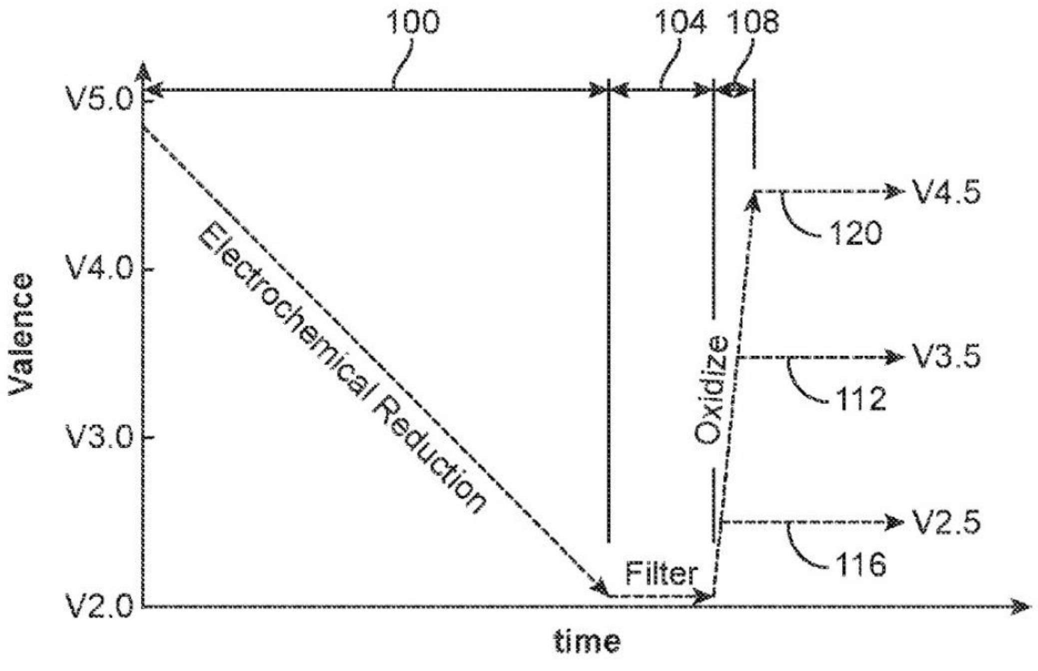


FIG. 1

Largo also has innovative business model that enables "almost-free vanadium"

Vanadium assets are owned by investors in Largo Physical Vanadium (LPV); TSX.V = VAND

Strategic Approach

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Focused on developing five new manufacturing processes for Stacks & Electrolyte

- Three new RFB Stack-assembly processes (both stack components, and complete cell stacks)
- Two new RFB Electrolyte-production processes

	Process	Current SOA	Key Innovations	Major Benefits
Cell Stack	Unitized Electrode Assembly (UEA)	Manual lamination of discrete sheets	High-volume conversion process w/ more automation	Reduce UEA cost; improve quality
Cell Stack	Bipolar Plate & Frame Assembly (BPFA)	Manual integration of seal and plastic frame	Overmolding of seal onto the plastic picture frames	Reduce BPFA cost; improve integration
Cell Stack	Cell Stack Assembly (CSA)	Manual layering of UEAs and BPFAs	Automation of key stack assembly processes	Reduce cost and improve quality
Electrolyte	Electrolyte Purification Process (EPP)	Complex processes that are not effective	Novel and simple electro-chemical process	Reduce cost & waste; improve quality
Electrolyte	Electrolyte Densification for Shipping Process (EDSP)	Liquid electrolyte is shipped in totes	Novel processes to form gel and ship inside tanks	Reduce shipping costs & required onsite work

All of these improved processes could also potentially be used to produce non-V RFB Systems

Results & Achievements: Electrolyte Purification

- **LCE's Beta EPP System:**
  - Used to purify electrolyte used in LCE's VRFB for Enel Green Power in Spain
    - 1.2-MW / 6-MWh System
    - Proven run time of 9.5-h/day and 47.5-h/week (5 days/week)
  - Nameplate Capacity
    - > 58-MWh/y with 3 shifts/day and 7 days/week (22-h/day)

- **This task is ahead of DOE project schedule**
  - Started early, and all of the EPP equipment was purchased by LCE (not included in DOE project budget)
  - Current focus is primarily on developing QC methods and metrics

A picture of LCE's electrolyte-purification process (EPP) system housed inside a 53-foot shipping container in LCE's facility in Wilmington, MA

Results: Electrolyte Densification CONCEPT

- **With conventional VRFB electrolyte and system-build process:**
  - Electrolyte is comprised mostly of water and electrolyte-shipping costs are high
    - For example, with 1.5M V salts in 2M H_2SO_4, then 66 wt.% of electrolyte is water
  - Electrolyte tanks are shipped empty and filled on-site from IBC totes
- **New approach is to densify and precipitate electrolyte in gel form [1]**
  - Allows the electrolyte to be quickly reconstituted onsite by adding deionized water
  - Approach was based on nucleation/precipitation work in solid-liquid electrolyte storage study [2]
  - Goal is to reduce electrolyte volume by half, precipitate it in < 24 hours, & reconstitute it in < 24 hours

Electrolyte Containers

Fill Electrolyte Containers in factory with Densified Electrolyte

Ship partially-filled Containers with Electrolyte in Gel form

Add DI water on-site to Electrolyte Containers

[1] M. L. Perry, Provisional U.S. Patent Application 63/312,999 filed on Feb. 2, 2022.
[2] Yuanchao Li and Trung Van Nguyen, "A Solid/Liquid High-Energy-Density Storage Concept for Redox Flow Batteries and Its Demonstration in an H2-V System," *J. Electrochem. Soc.*, **169** (2022). 10.1149/1945-7111/ac97c6

Results & Achievements: : Electrolyte Densification

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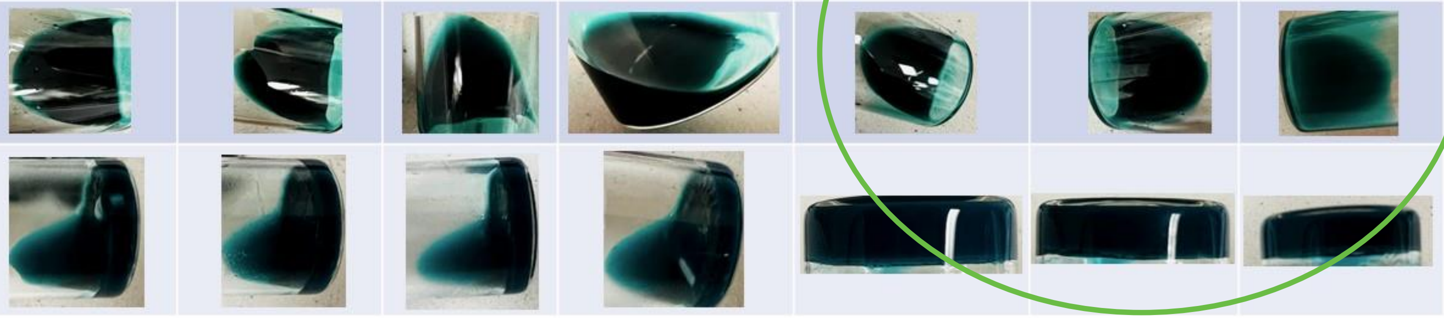
➢ Key results for Precipitation Process (dissolution process is more facile)

- In addition to the nucleation material types identified in KU's previous work, we found key controlling variables to be:
  1) densified or oversaturation level, 2) concentration or density of nucleation materials, 3) mixing time
- Since mixing is inconvenient and most likely achieved by bubbling air or nitrogen gas through the solution, it is desirable to minimize the mixing time required for the precipitation process.

➢ **Low-crystallinity gel-like precipitate can be achieved with ~50% densification level and 1-hr mixing time**

Densification Level	51. ≈ 50%						
Nucleation Density (mg/mL)	1	1	1	10	10	10	10
Mixing Time (hr)	1	1.5	2	0.5	1	1.5	2
After Stirring							
Overnight Storage							



← Partial Gel → ← Full Gel →

These results will be presented in more detail by KU at next ECS meeting on 5/29/23 in Boston

Future Work, Technology Transfer, & Impact

Future Work: Focus on production trials & scale-up in the next ≈ 1.5 y; then build APS and demo

	Process	Current Status	Next Steps
Cell Stack	Unitized Electrode Assembly	High-volume UEA design is 90% complete	Run production trials
	Bipolar Plate & Frame Assembly	New design is 90% complete; mat'ls selected	Run production trials
	Cell Stack Assembly	Selecting the appropriate mfg equipment	Run production trials
Electro-lyte	Electrolyte Purification Process	Process successfully scaled-up	Refining QC techniques
	Electrolyte Densification Process	Process steps demonstrated on lab-scale	Scale-up complete process

Technology Transfer:

- LCE plans to continue producing both RFB stacks and VRFB electrolyte
- LCE has discussed potentially providing short stacks to two other AMMTO projects focused on developing new RFB chemistries (U. of Colorado and Quino Energy)

Impact:

- Enable commercially-viable Long Duration Energy Storage (LDES) solutions that are suitable for applications that require 6- to 10-h discharge at rated power (projected to be multi-$B market)

Questions?

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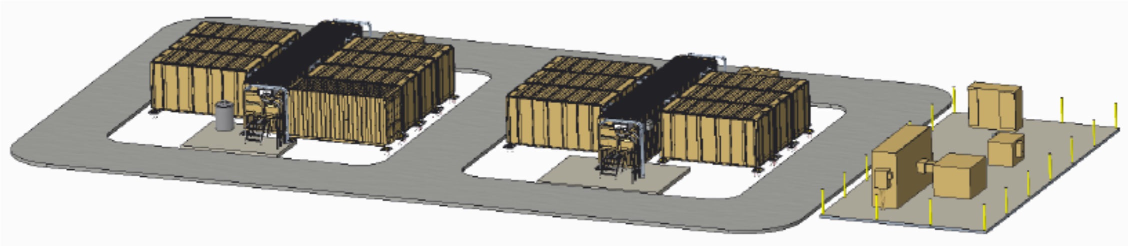
Thanks for your attention!

ENEL Site Layout



- LCE's first commercial deployment
- Being installed in Majorca, Spain
- 1.2-MW / 6-MWh VRFB System
- Paired with solar to provide island grid support

enel Green Power