3RD ANNUAL ENERGY STORAGE GRAND CHALLENGE SUMMIT

Manufacturing Activities Panel

ENERGY STORAGE GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY

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U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

U.S. DOE Initiatives Supercharging

Advanced Battery Manufacturing Innovation

Paul Syers

U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy,
Advanced Materials & Manufacturing Technologies Office (AMMTO)

ENERGY STORAGE GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY

Accelerating the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage.

FOUR INTEGRATED TRACKS

TECHNOLOGY DEVELOPMENT

Focuses DOE's ongoing and future energy storage R&D around user-centric goals and long-term leadership to maximize the pace of storage innovation.

MANUFACTURING & SUPPLY CHAIN INNOVATIONS, WORKFORCE

Develops technologies, approaches, and strategies for U.S. manufacturing that **support and strengthen U.S. leadership in innovation and continued at-scale manufacturing** while also educating members of the workforce, who can then research, develop, design, manufacture, and operate energy storage systems.

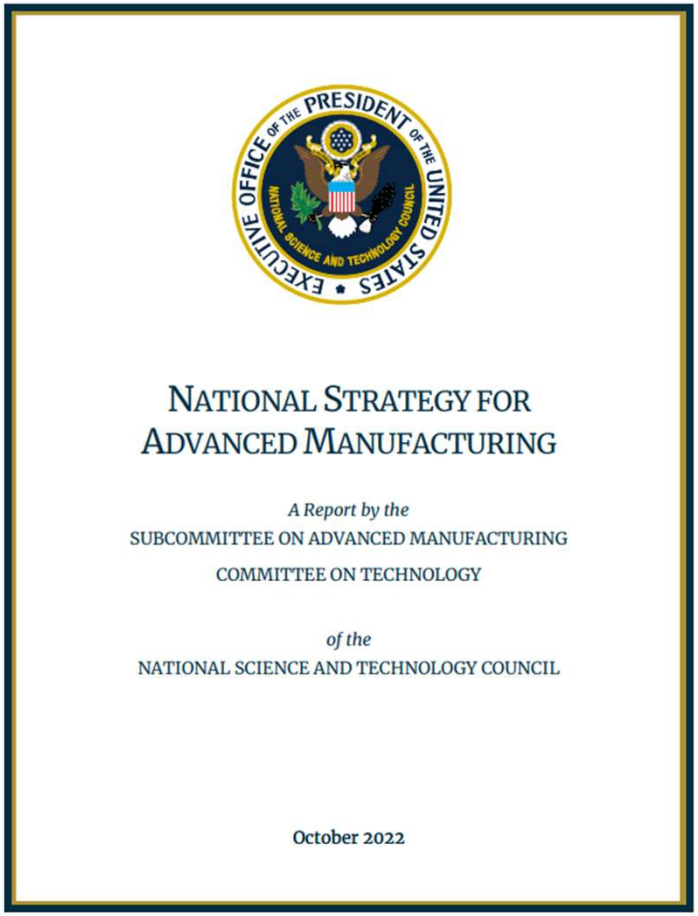
INVESTMENT, COMMERCIALIZATION, AND SCALE-UP

Ensures that **DOE's R&D investments transition to domestic markets** through field validation, demonstration projects, public private partnerships, bankable business model development, and the dissemination of high-quality market data.

POLICY & VALUATION

Provides data, tools, and analysis to support policy decisions and maximize the value of energy storage.

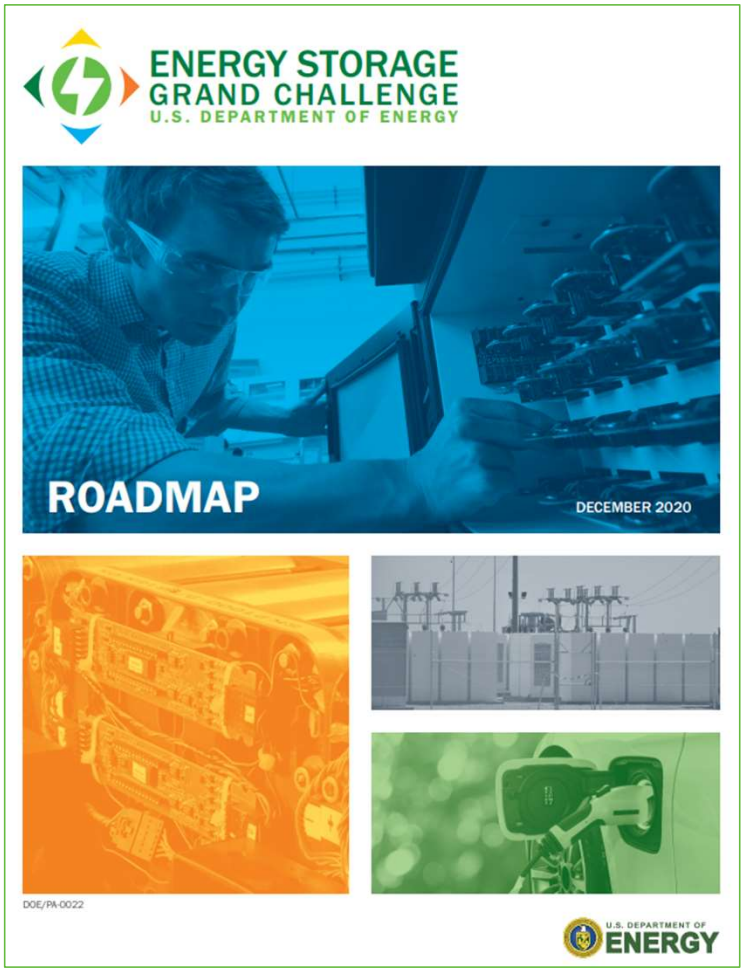
Energy Storage is Key to the National Strategy for Advanced Manufacturing



National strategy for ADVANCED MANUFACTURING (whitehouse.gov)

- "…Manufacturing advances that produce cost-competitive technologies for clean energy production, storage, and utilization domestically position the United States to lead the global energy transition…"
- "…A major enabling technology needed to achieve this is economical battery production for grid-scale energy storage…"
- "…Manufacturing process improvements are needed for increased energy densities enabled by next generation design and chemistries…"
- "…A domestic supply chain that includes recycling should enable high-performance low-cost energy storage devices to power the nation's electrified energy and transportation sectors…"

DOE's Initial Cost Targets



EV applications:

- **$80/kWh manufactured cost for a battery pack by 2030** for a 300-mile range electric vehicle, a 44% reduction from the current cost of $143 per rated kWh.*

Long-duration stationary applications:

- **¢5/kWh LCOS (levelized cost of storage) for long-duration stationary applications**, a 90% reduction from 2020 baseline costs by 2030.**

* Current performance is for Li ion cells based on BATPAC model and future targets may be met by other chemistries such as lithium metal.

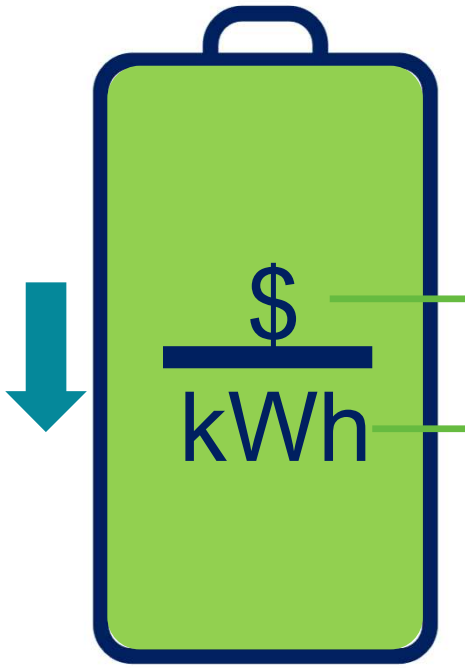
** Achieving this levelized cost target would facilitate commercial viability for storage across wide a range of uses including:

- Meeting load during periods of peak demand
- Grid preparation for fast charging of electric vehicles
- Applications to ensure reliability of critical infrastructures, including communications and information technology.

Source from Energy Storage Grand Challenge Roadmap, December 2020

How Do We Get There?

There Are Two Ways To Affect $/kWh.



Decreasing the Numerator

= Reducing the cost of batteries

- Cheaper materials
- Enhanced manufacturing processes
- Efficiencies of scale
- …

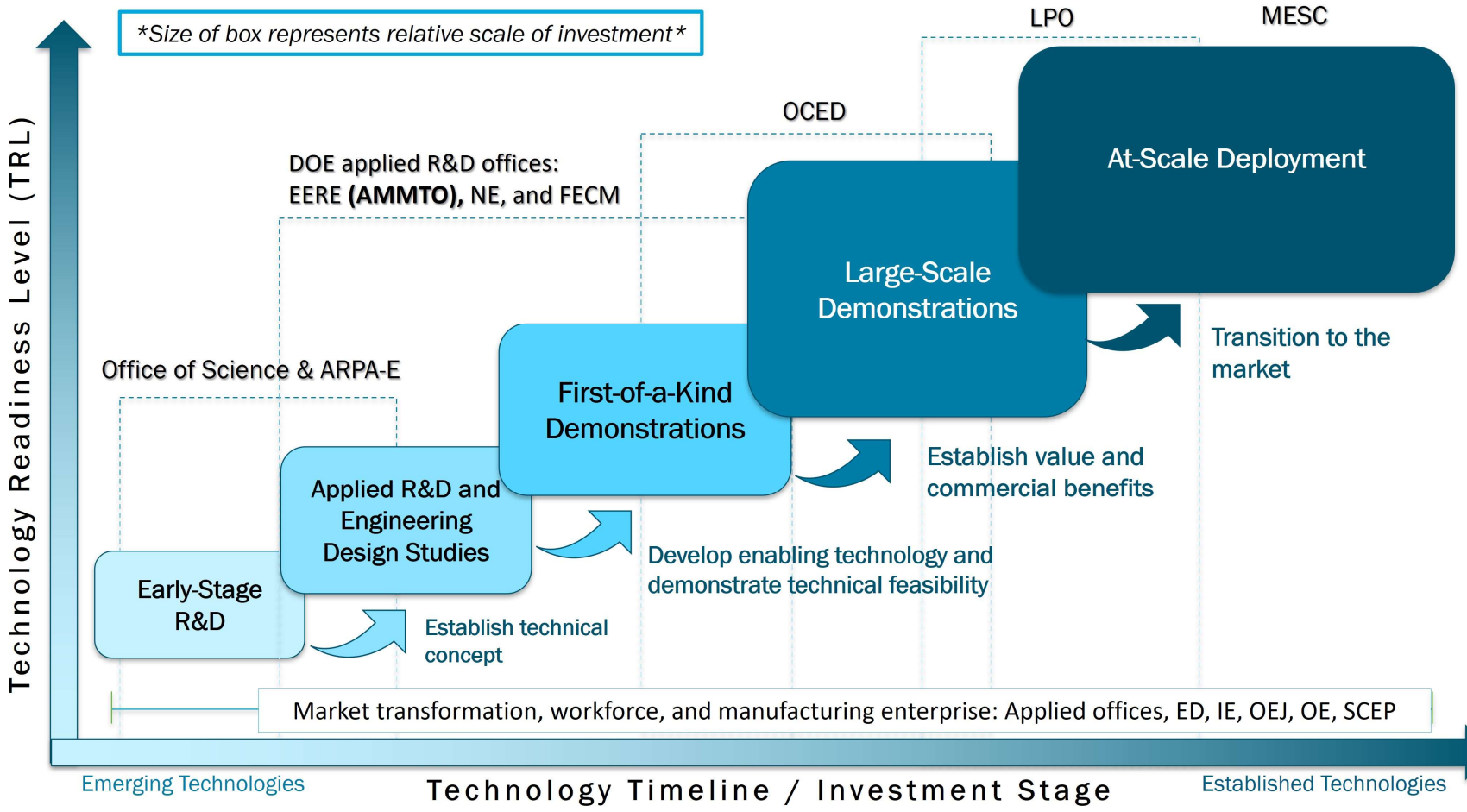
Increasing the Denominator

= Improving battery performance

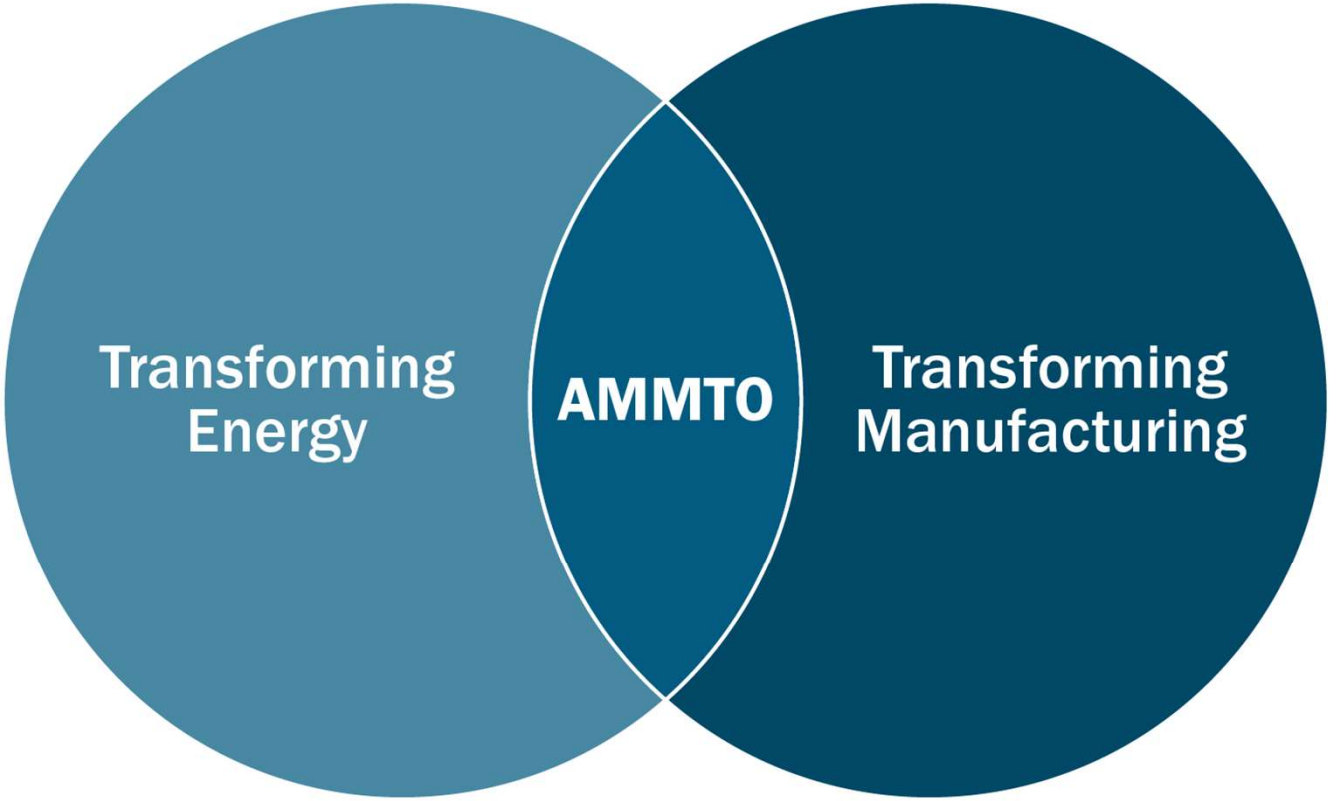
- Better materials
- Technological advances
- Better formulations
- …

From Visual Capitalist: https://www.visualcapitalist.com/cathode-advancing-lithium-ion/

DOE's Energy Storage Innovation, Demonstration, and Manufacturing Landscape



DOE's Energy Storage Innovation, Demonstration, and Manufacturing Landscape: AMMTO's Place



AMMTO Energy Storage Manufacturing — Core Values

Accelerate innovation to manufacture novel energy storage technologies in support of economy-wide decarbonization.

1. Scale up manufacturing processes
2. Lower lifecycle cost to manufacture energy storage system

AMMTO's objectives

Domestic suppliers – AMMTO strengthens domestic material supply chains and improves manufacturing capabilities for energy storage technologies.

Domestic manufacturers – AMMTO helps manufacturers integrate energy storage technologies into their processes to improve resiliency and productivity.

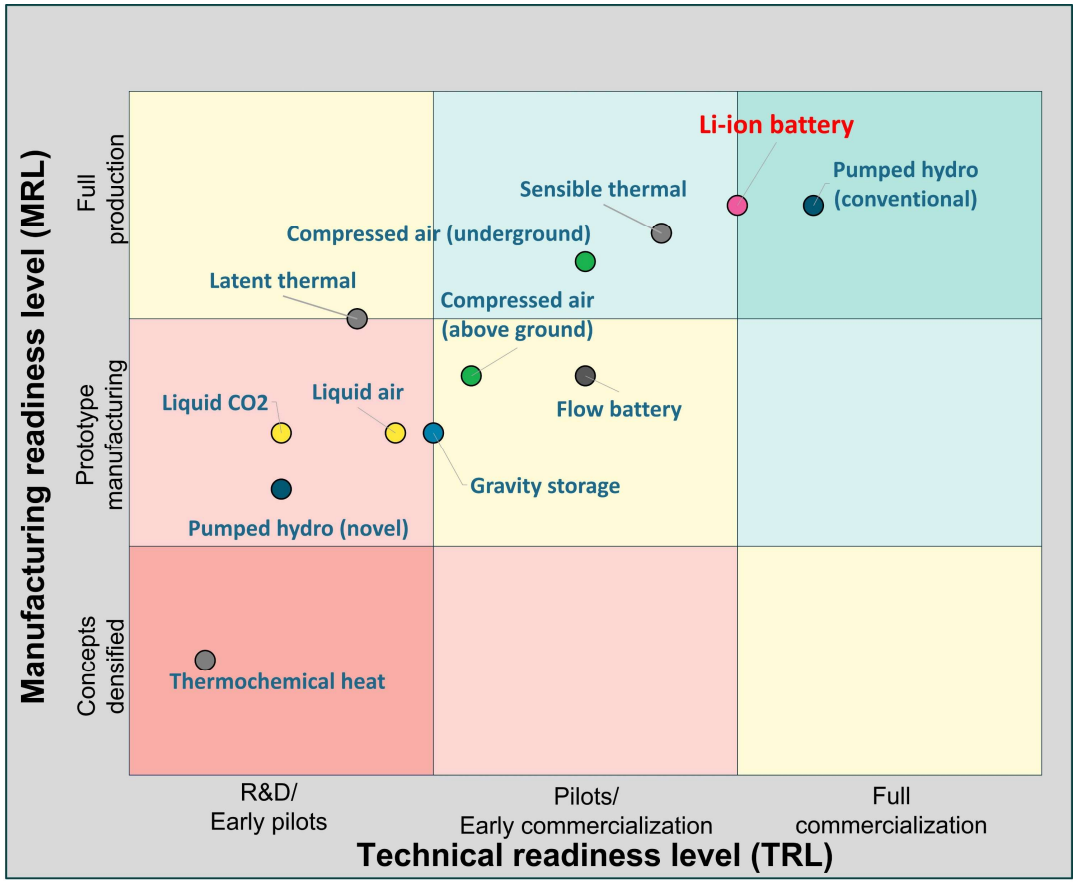
Who benefits from manufacturing innovation?

AMMTO focuses on:

- Improving the productivity, competitiveness, energy efficiency, and security of U.S. energy storage manufacturing
- Leveraging diverse platform manufacturing technologies for U.S. energy storage manufacturing
- Transitioning DOE-supported innovative storage technologies and practices into U.S. manufacturing capabilities

Why AMMTO?

Energy Storage Technology and Manufacturing Maturity Comparison

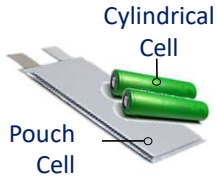


Source: Y. Zhou, "Beyond Lithium-Ion: Long-Duration Storage Technologies, Technology Deep Dive, BloombergNEF, Department of Energy, and International Energy Agency.

- Li-ion and Pumped Hydro most mature. Significant opportunities for manufacturing innovations that lower cost.
- Flow batteries, above ground, latent thermal energy at the cusp of realizing scale-up. Advancement here is key.
- Novel pumped hydro & thermochemical heat still nascent.

Note that different studies might place technical, manufacturing, and market maturity at different places.

DOE Manufacturing Innovation: Li-ion Batteries

	Upstream		Midstream		Downstream			
	Raw Materials Production		Materials Processing	Cell Manufacturing	Pack Manufacturing	Electric Vehicles Stationary Storage National Defense Aviation	End-of-Life Recycling and Reuse	
	Mining and extraction of materials including Lithium Cobalt Nickel Graphite		Cathode powder production Anode powder production Separator production Electrolyte production	*Electrode/cell manufacturing* 	*EV Battery Pack* 			
AMMTO	• Bolster domestic supply chain		•Support scale up •Develop revolutionary processes	•Develop and scale disruptive cell manufacturing methods • Electrode quality control				•Processes to reintroduce materials into supply chain
Joint	• Eliminate or reduce the use critical materials • Recover and reuse							•Battery recycling prize •Strategies to collect, sort, storge and transport spent Li-ion batteries
VTO			•Develop disruptive active materials	• Novel cell designs to enable faster cell assembly • Enable production to leap-frog technologies	• Foster automation • Quality control & diagnostic testing • Design for recyclability			•Reduce recycling costs •Increase material recovery rates

Key Actions Towards Li-ion Battery Technology Advances. Collaboration is key to success.

DOE Manufacturing Innovation: Flow Batteries

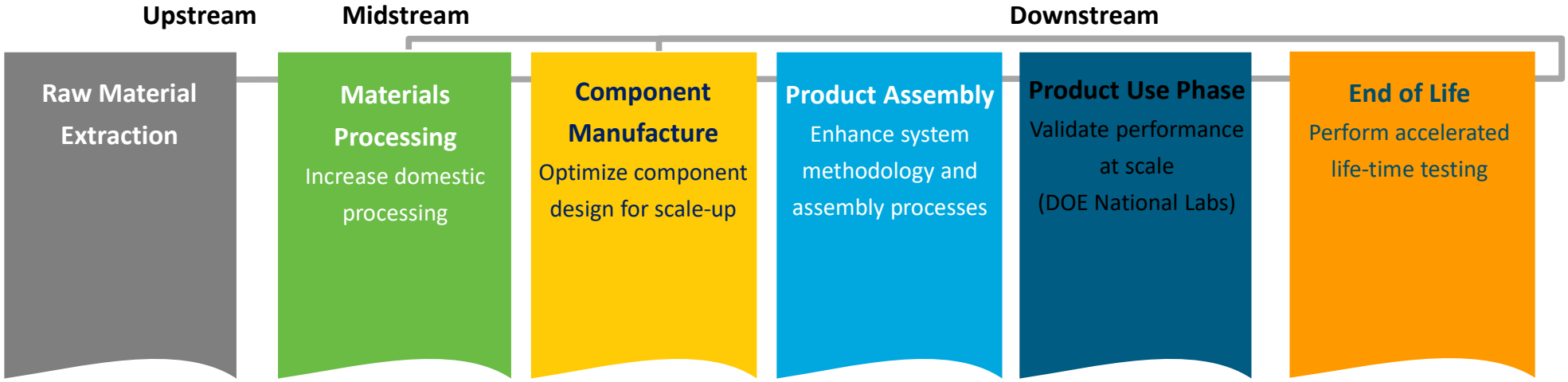
AMMTO

- New chemistries and designs
- Innovative mfg. capabilities, technologies, and practices
- Accelerated, cost effective scale-up
- Streamlined & secure domestic supply chains

OE

- Predictable and robust systems and components
- Grid use cases and testing protocols
- Safe and reliable large-scale deployment
- Enable systems integration

AMO/OE Flow Battery FOA projects
Goal: accelerate innovation & deployment by addressing the entire ecosystem:



Technology advances for large scale energy storage. Collaboration is key to success.

Lab Embedded Entrepreneurship Program

INNOVATION CROSSROADS | CHAIN REACTION INNOVATIONS | WEST GATE | cyclotronroad

Recruit the best energy technology innovators

2 Years Stipend & Benefits

Allows innovators to focus on technology & business full-time.

Access to National Lab Resources

CRADA* provides funds for resources

Mentorship & Business Training

Leads to networking, community building, and improved outcomes.

Market

Position people and technology for market

**CRADA – Cooperative research & development agreement*

Leverage expert mentorship and world-class facilities at the national labs on a win-win basis

Bottom Lines

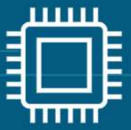


Transformation of
the energy system and
the manufacturing sector
is our future.

Collaboration is essential to meet the moment.

Changing the world together will be fun!



Prototype Cell Manufacturing for Lithium-ion Batteries

Andrew N. Jansen
Senior Chemical Engineer, Group Leader
Electrochemical Energy Storage
Chemical Sciences & Engineering Division

2023 Energy Storage Grand Challenge Summit
July 25-27, 2023
Atlanta, Georgia

THREE MAJOR DOE/VTO POUCH CELL MAKING LABS
IN DRY ROOMS

Argonne CAMP Facility

ORNL Battery Manufacturing Facility

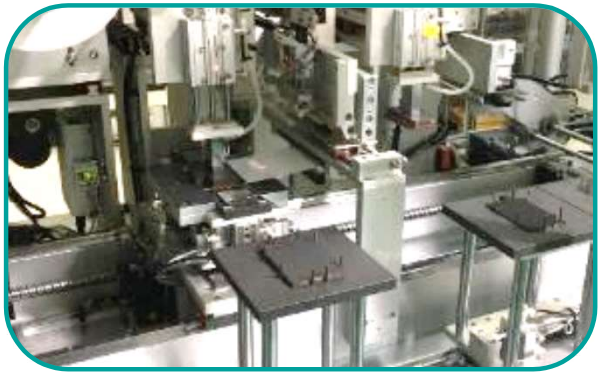
PNNL Advanced Battery Facility

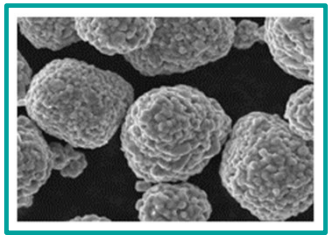
Please visit their websites for more information.

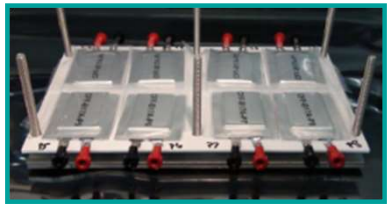
CAMP FACILITY

(Cell Analysis, Modeling, and Prototyping Facility)

- Researchers are often not able to provide the quantities of novel materials needed to make a full-size EV cell to demonstrate the merits of their discoveries.
- The CAMP Facility is specifically designed to explore new materials with quantities as small as 10 g and up to 2 kg (longer lengths of electrode made from materials scaled from MERF, commercial partnerships, *etc*.)
- Electrodes and pouch cells are made and tested; using extensive diagnostics & electrochemical modeling on promising technologies

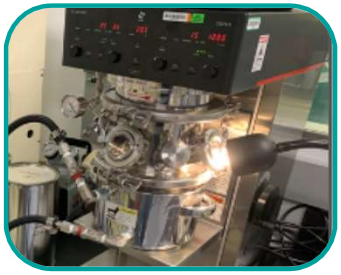






DOE-EERE-Vehicle Technologies Office Program

CAMP FACILITY'S CAPABILITIES CONSIST OF:



- **Equipment located in a dry room (area of ~160 m²) that is capable of maintaining <100 PPMv (-42°C dew point) with 8 people & 1200 SCFM of exhaust ventilation.**

	Planetary Centrifugal Mixers	Acoustic Mixer	Immersion Disperser	Thin-Film Spin Syst. High-Speed Mixer	High-Speed Planetary Mixer	Mixing & Kneading Disperser
Blade Description	No blade	No blade	Rotor/ Stator	High speed rotor	High speed disperser, stirrer, & side scraper	Twisted blades (planetary) & homogenizing disperser
Working Capacity	10 - 500 mL	5 - 500 grams	20 - 2000 mL	50 - 90 mL (batch), 180 mL / min (continuous)	200 mL - 2000 mL	1000 mL - 2000 mL

- **A wide range of mixing equipment that can work with slurry volumes from 10 mL to 2 L and includes cooling capabilities**
- **Two high precision electrode coaters with 2-3 drying zones**
  - One Coater with Reverse Comma Coater Head
  - New Coater with multi-functional capabilities
- **A heated roll press for calendering capabilities**
- **Semi-automated equipment used to make various sized high-quality Li-ion & Li metal pouch cells:** ultrasonic welder, Z-fold winder, vacuum sealers, electrode punch, heated tab sealer, *etc*

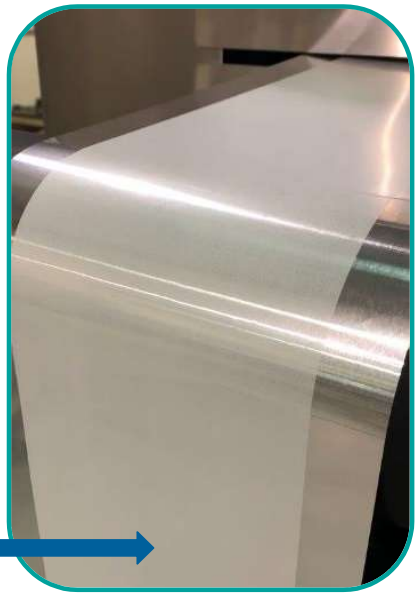
MULTI-FUNCTIONAL COATER INSTALLED IN DRY ROOM

Advanced interchangeable coating head system designed for utilization flexibility

- **State-of-the-art features:**
  - Interchangeable coating heads (Gravure & Slot Die, can get others)
  - Progressive cavity pump
  - Corona treatment
  - IR drying system
- **Coating system greatly enhances adaptability for coating various materials:**
  - Hybrid ceramic polymer electrolyte composite membrane
  - Promising next-gen anodes & cathodes
  - Polymer electrolyte material
  - Thin to thick coatings
  - Structured layered coatings
  - Traditional energy storage materials

FRONTIER
A Delta ModTech Company

Uniform thin coatings were achieved using the gravure coating head.



Al_2O_3 w/ PVDF on substrate

EXAMPLES OF CAMP FACILITY EXPERIENCE:

SOME DOE PROJECTS CAMP IS INVOLVED IN

- **ReCell:** Focus on Recycling
  - Validating methods of material recovery & rejuvenating harvested cathodes
  - Recycling Impurity Studies
- **XCEL:** Focus on Fast Charging
  - Improve fast charging through electrode structural changes & system optimization
- **SCP:** Focus on Silicon in Anodes
  - Prelithiation & annealing studies
  - Binder, Si particle size, & low-to-no graphite studies
- **EaCAM:** Focus on Earth-abundant Cathode Active Materials
  - Experimental low-to-no cobalt / EAM cathode coatings & validation
- **BTMS:** Focus on Battery Storage in Commercial Buildings
  - LTO | LMO & LTO | LFP Builds (lower energy, long life, EAM goal)
  - Electrolyte, separator wetting, & n:p ratio studies

ADDITIONAL EXPERIENCE

- **Solid Polymer Electrolyte (SPE) preparation & characterization**
- **Imaging Analysis**
  - Cell optimization *via* X-ray imaging at the APS
  - Visualizing “breathing” in NMC811/Li coin cells

CHEMISTRIES CAMP HAS WORKED WITH

- **Cathodes**: NMCs, LFP, LMO, LCO, LMR-NM, LNO, HE5050, NCA, NMA, spinels, single-wall carbon nanotubes, & other low-to-no cobalt cathodes
- **Anodes:** natural & artificial graphite systems, silicon systems of varying particle sizes, LTO
- **Separators:** PP, PE, PP:PE:PP, ceramic coated polymers, PVDF, polyester fiber, *etc*
- **Binders:** PVDF, CMC, SBR, LiPAA, PAA, Polyimide, *etc*
- **Solid State Systems**
- **Various Electrolytes & Additives**

Argonne NATIONAL LABORATORY

CAMP FACILITY COLLABORATIONS:

Majority of these collaborations over the past several years are centered on the CAMP Facility providing electrodes, cells, and data

Support from Haiyan Croft and Brian Cunningham of the Department of Energy's Vehicle Technologies Office is gratefully acknowledged.

Thank you!
Any Questions?

ANDREW JANSEN - CAMP Facility, Jansen@anl.gov
Steve Trask, Alison Dunlop, Marco Rodrigues, Daniel Abraham, Wenquan Lu

Energy Storage Grand Challenge
Battery Manufacturing Panel
July 26, 2023

otoro energy

affordable grid scale energy storage

www.OtoroEnergy.com

mike@OtoroEnergy.com

otoro

New Flow Battery Chemistry

Engineered from the ground up

- *Iron* and *Chromium* with a twist: organic chelating agents, like EDTA
- Materials leverage *domestic* steel and chemical manufacturing infrastructure
- Discovered in my chemistry lab at the *University of Colorado Boulder*
- Partnered with Raytheon Technologies Research Center in *ARPA-e DAYS Program*
- *Otoro Energy* founded for commercialization
- Support from *AMMTO* for battery electrolyte manufacturing and prototype demonstration, RTRC as a partner

RTRC
Raytheon Technologies Research Center

arpa·e

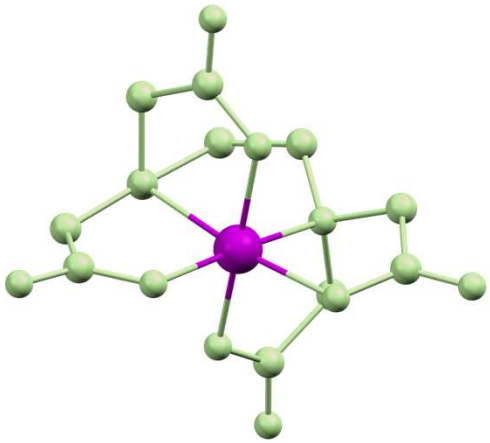
otoro energy

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
ADVANCED MANUFACTURING OFFICE

otoro

Material Advantages for LDES

Better in every way



- **All-liquid:** fully decoupled power and energy
- **Safe:** pH-neutral, non-flammable, non-corrosive, non-toxic; enables non-fluorinated materials
- **High-performance:** 1.62 V cell voltage drives 80-90% round trip efficiency at power comparable with vanadium systems.
- **Soluble:** Same energy density as Vanadium battery. Chelates change metal ion charge from positive to negative.
- **Stability:** Chelates considered “extremely persistent” by EPA. No degradation observed during extended battery operation.

ARPA-e DAYS Validation

Multi-month Torture Test

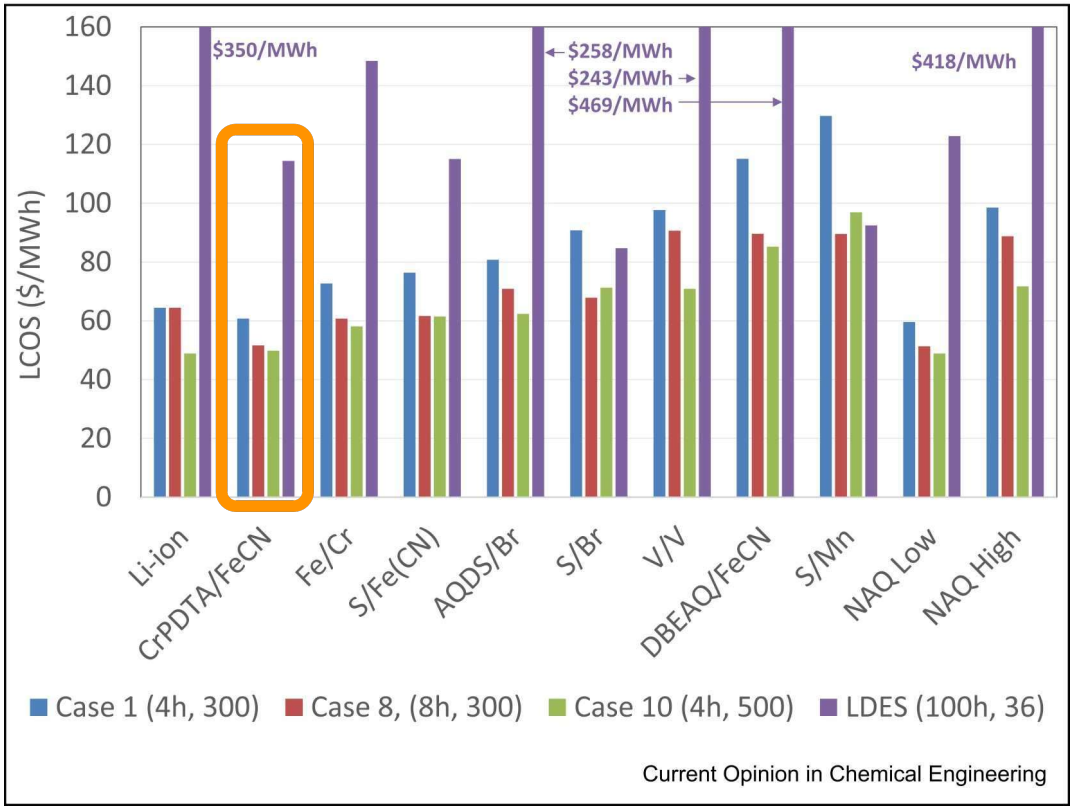
Zero loss in capacity or performance

RTRC
Raytheon Technologies Research Center

Flow Battery Techno-economics

JCESR Analysis

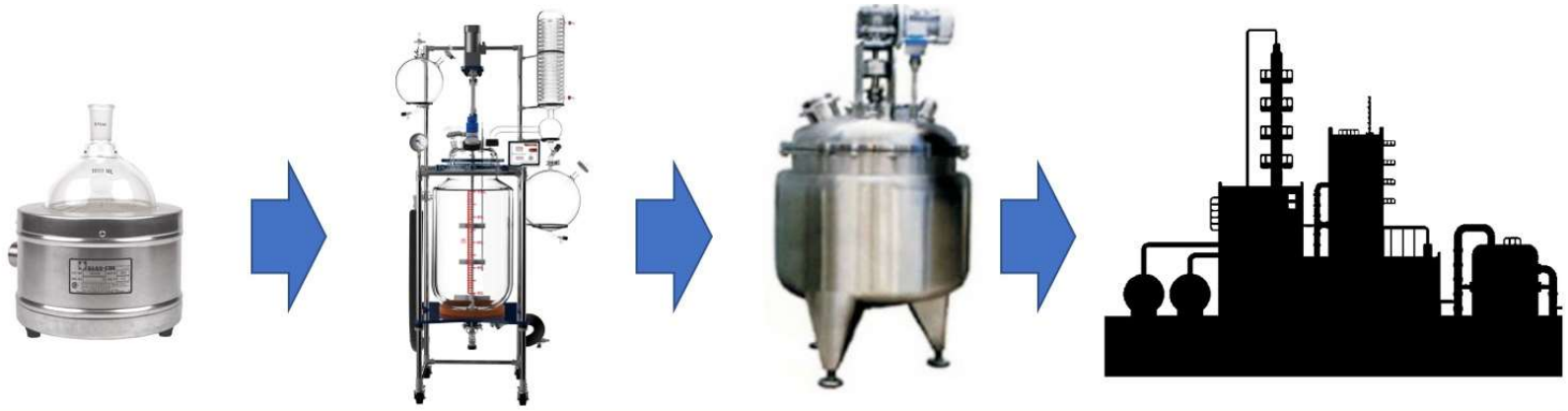
- Meets $0.05/kWh LCOS at 10 h discharge
- Cost-parity with LFP at 4-hour discharge duration
- *"The higher open-circuit voltage of ligand-modified Fe/Cr essentially pays for the ligands and negates the impact of higher impedance."*



Darling, R. M. *Curr. Opin. Chem.* **2022**, *37*, 100855.

1. Metric ton scale electrolyte manufacturing, optimizing

- Raw materials costs, lower grade ores
- Time-space-yield of mfg. process
- Optimized purification and waste



2. Environmental and Toxicology Analysis

How safe is it?

When scaled, the electrolyte will become an EPA-defined “high production volume” material.

- Can this deliver on safety?
- Pass environmental and regulatory
- How will safety enable new locations for distributed storage systems?

Chromium chelate is used in humans and animals to measure GFR.

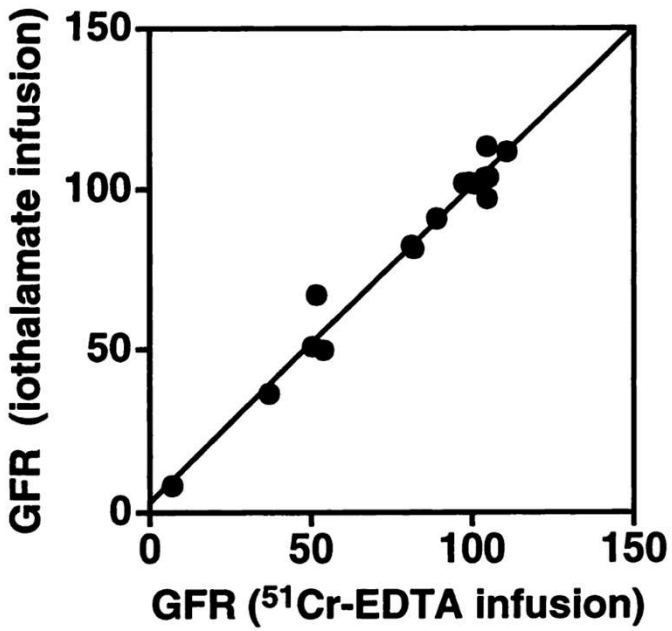
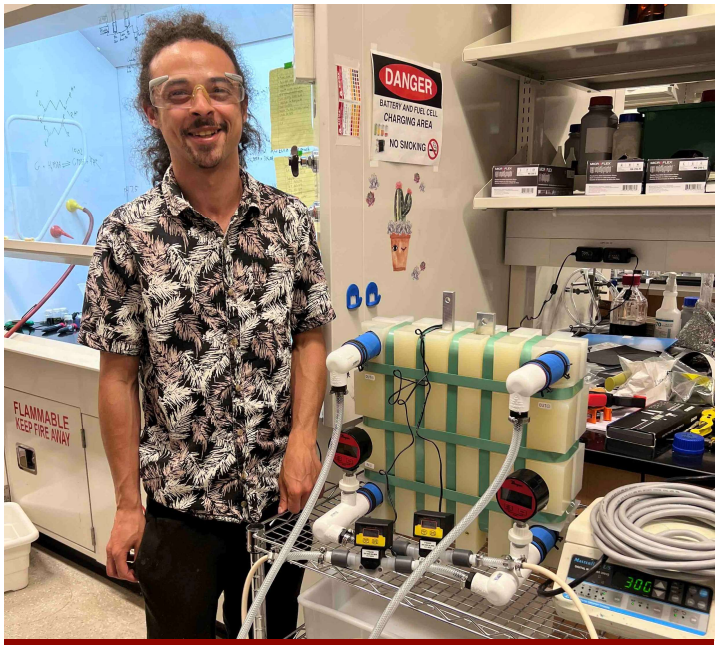


Figure 1. Comparison between the measurements of GFR by renal clearance during continuous infusions of iothalamate and ^{51}Cr-EDTA in 17 diabetic patients with different degrees of renal function. Units are mL·min^{-1}·1.73 m^{-2}. Slope = 0.979, r^2 = 0.973, $P < 0.0001$.

3. Inclusive Workforce Development

Critical Need for US Competitiveness

- Summer student internships give undergraduates an immersive introduction to battery research.
- Motivates students to pursue PhD's and careers in energy storage research.
- Former program participants include a founder of a robotics company, and a current intern at Form Energy

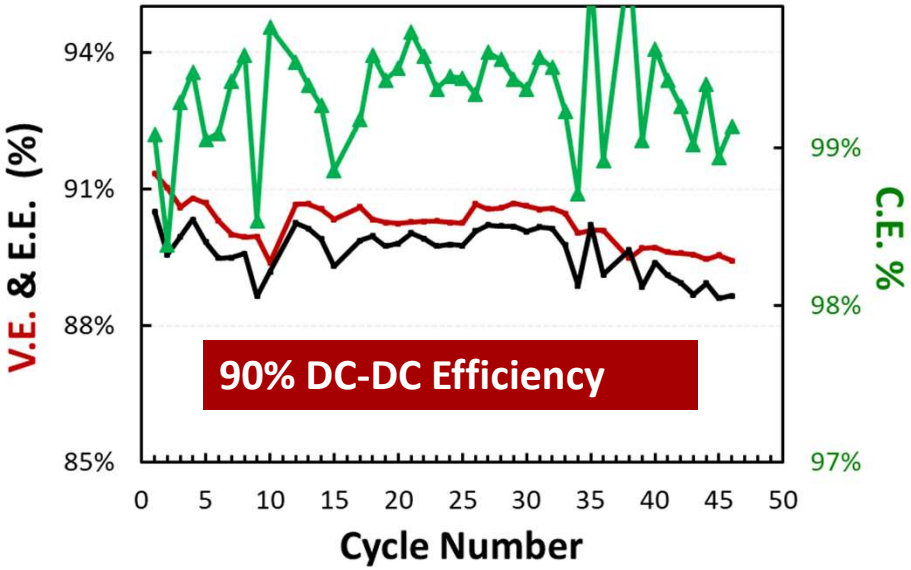


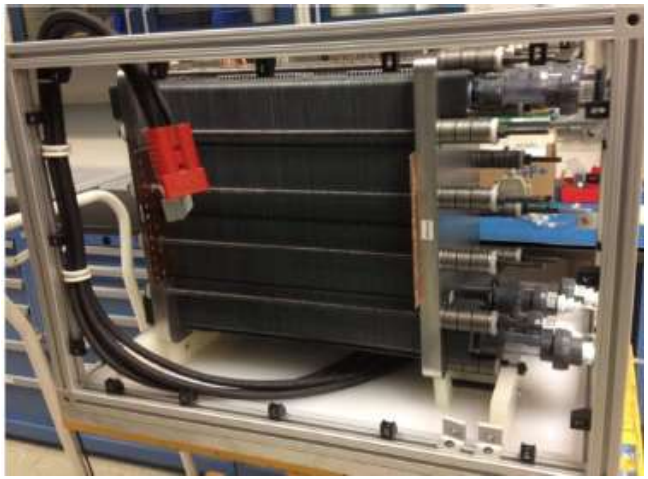
Jordan Marshall, 2023 Summer Intern

4. System Scale-up and Demonstration

5 kW / 20 kWh Prototype

- Based on RTRC's patented stack design and experience in Vanadium flow battery prototypes
- Using Otoro-manufactured electrolyte





RTRC
Raytheon Technologies Research Center

Raytheon Technologies

Thank You

otörö energy

Michael Marshak, PhD
Founder & CEO
mike@OtoroEnergy.com

2023 Energy Storage Grand Challenge Summit -

Manufacturing Activities Panel

Form Energy

Nidhi Thakar, VP, Policy and Regulatory

Wednesday, July 26, 2023, Atlanta, GA

Rising to the challenge of climate change with a team that will deliver

OUR INVESTORS: LONG-TERM AND IMPACT-FOCUSED

$820M+ in venture capital from top investors including: Breakthrough Energy Ventures (BEV), TPG's Climate Rise Fund, Coatue Management, GIP, NGP Energy Technology Partners III, ArcelorMittal, Temasek, Energy Impact Partners, Prelude Ventures, MIT's The Engine, Capricorn Investment Group, Eni Next, Macquarie Capital, Canada Pension Plan Investment Board, and other long-term, impact oriented investors

LED BY ENERGY STORAGE VETERANS

Decades of cumulative experience in energy storage

- 100's of MW of storage deployed

TESLA ENERGY

A123 SYSTEMS

SUNPOWER FROM MAXEON SOLAR TECHNOLOGIES

24M

NEXTera ENERGY

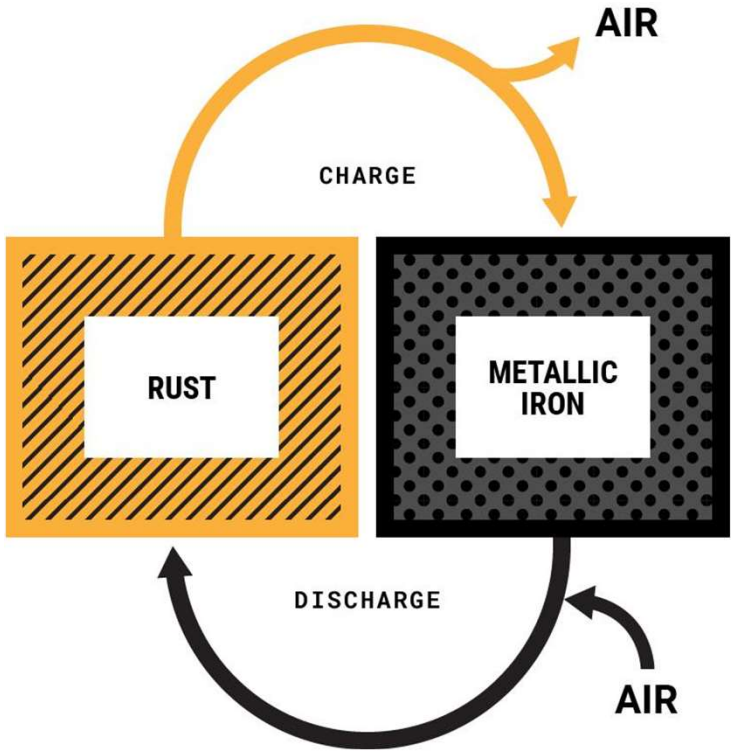
amsc

Massachusetts Institute of Technology

AQUION ENERGY

Rechargeable iron-air is the best technology for multi-day storage

Form's 100-Hour Reversible Rust Battery



COST

Lowest cost rechargeable battery chemistry.
Chemistry entitlement <$1.00/kWh

SAFETY

No thermal runaway (unlike li-ion)
Non-flammable aqueous electrolyte

SCALE

Iron is the most globally abundant metal
Easily scalable to meet TW demand for storage

DURABILITY

Iron electrode durability proven through decades of life and 1000's of cycles (Fe-Ni)

Form Factory 1: commercial-scale manufacturing

Transforming Weirton Steel land for battery manufacturing in West Virginia

Building rendering

- **Total Local Investment:** $760 million
- **Construction Start:** Early 2023
- **Production Start:** Late 2024
- **Jobs:** Minimum of 750 full-time jobs

Location Benefits

- Close to our existing pilot manufacturing facility in PA
- Strong natural infrastructure
- Local manufacturing know-how

Factory Function

- Semi-to-fully automated cell, module, & enclosure assembly
- Ability to scale production in modular blocks

Construction on Form Factory 1 underway

2024

Over 3 GWh of commercial engagements

Georgia Power

Partnering with Georgia Power to deploy a **15 MW / 1500 MWh** iron-air battery system in Georgia to come online as early as 2026

"At Georgia Power, we know that we must make smart investments and embrace new technologies now to continue to prepare for our state's future energy landscape," said **Chris Womack, President and CEO of Southern Company.** "We're excited to have Form Energy as a partner to help us build on Georgia's solid energy foundation."

GREAT RIVER ENERGY™

Partnering with Great River Energy to deploy a first-of-its-kind **1.5 MW / 150 MWh** multi-day energy storage project in Cambridge, Minnesota in 2024

"Great River Energy is excited to partner with Form Energy on this important project. Commercially viable long-duration storage could increase reliability by ensuring that the power generated by renewable energy is available at all hours to serve our membership," said **Great River Energy Vice President and Chief Power Supply Officer Jon Brekke.**

Xcel Energy®

Partnering with Xcel Energy to deploy **two 10 MW / 1,000 MWh** multi-day storage systems; one in Becker, MN and one in Pueblo, CO. Both projects are expected to come online as early as 2025

"As we build more renewable energy into our systems, our partnership with Form Energy opens the door to significantly improve how we deliver carbon-free energy so that we can continue to provide reliable and affordable electric service to our customers well into the future." said **Bob Frenzel, Xcel Energy President and CEO.**

Scaling multi-day energy storage for mass deployment

- Building the Alpha production line in Eighty-Four, PA
- Completing 500MW of manufacturing capacity at Weirton, WV
- Ensuring robust supply chains
- Growth and scale to attain Energy Storage Grand Challenge Goals goal of $0.05/kWh and Long Duration Earthshot Goal of lowering LDES costs 90% in 10 years

ESS INC

Catalyzing a Clean Future. Every Day.

July 2023

Company Overview

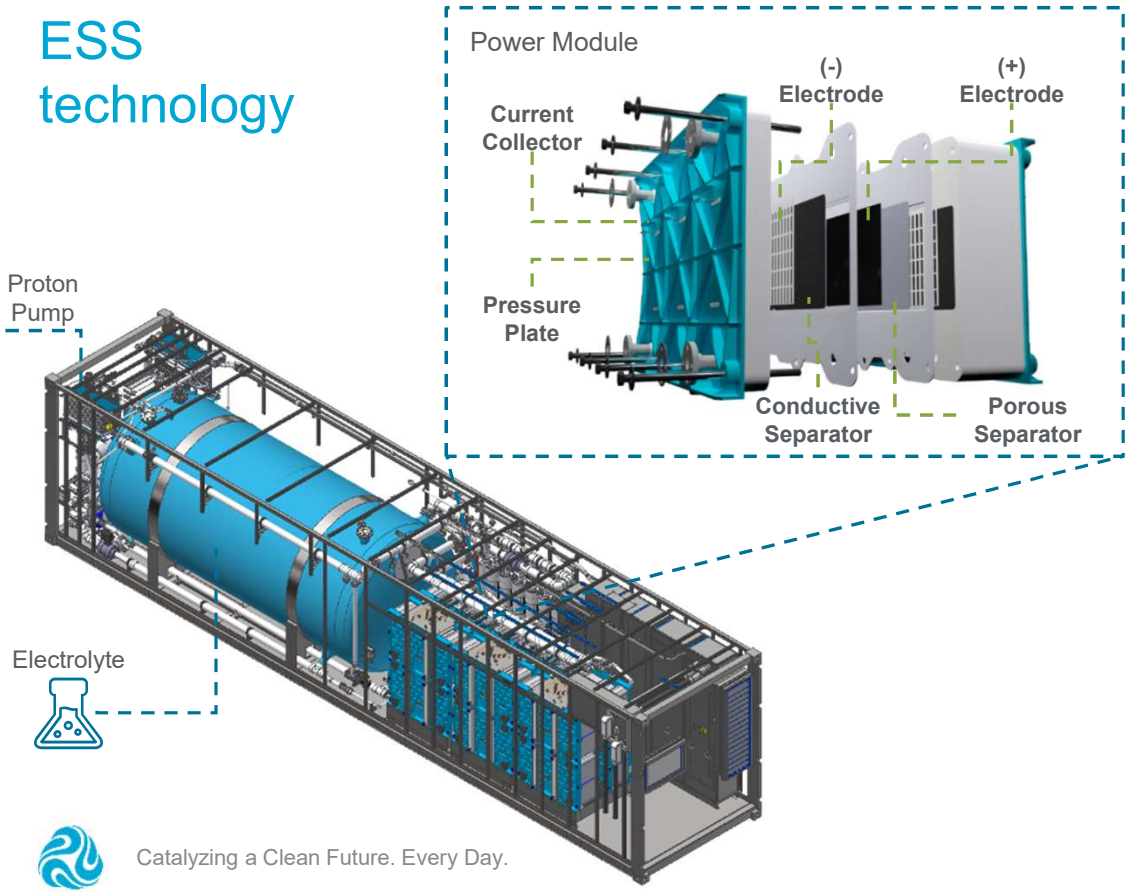
Company profile

ESS	Founded in 2011 with mission to develop lowest cost long-duration energy storage technology
Headquarters	Wilsonville, OR
Facilities	250,000 ft^2 manufacturing plant Automated production line currently scaling to 2GWh annual production
Employees	300+
Technology	Iron flow battery for utility-scale and commercial applications
Publicly traded	NYSE: GWH

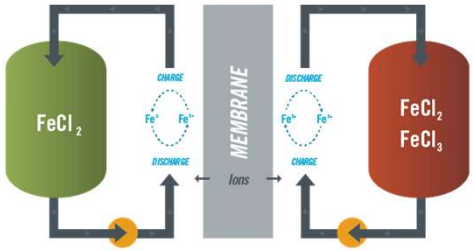
Manufacturing facility in Oregon

ESS Battery Technology

ESS technology



Electrochemistry

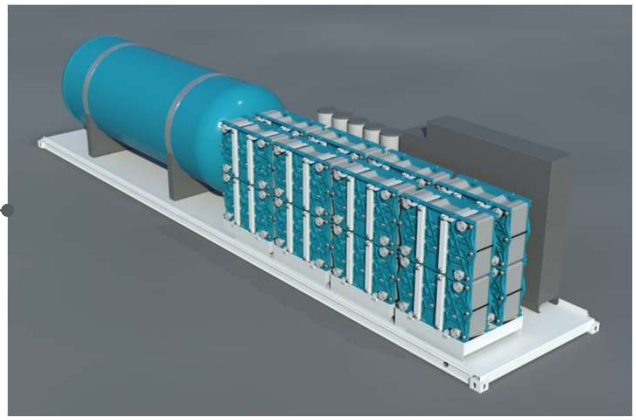


$$Fe^{2+} + 2e \underset{discharging}{\overset{charging}{\longleftrightarrow}} Fe^{0} \qquad E^{0}=-0.44V$$

$$2Fe^{2+} - 2e \underset{discharging}{\overset{charging}{\longleftrightarrow}} 2Fe^{3+} \qquad E^{0}=+0.77V$$

- During charging iron collects (electroplates) on the negative electrode
- During discharging iron dissolves back into solution
- Passive design proton pump continuously refreshes electrolyte in closed-loop system

Four Major Technologies of the EW



Battery Modules (Stacks)

- Intellectual property that differentiates ESS
- Generates the electricity
- More complex build processes

Proton Pumps

- Intellectual property that differentiates ESS
- Keeps the iron flow battery electrically balanced
- Moderate build complexity

Electrolyte

- High-grade iron, salt, and water
- Mixture simple to combine

Balance of System (BoS)

- Necessary componentry to make the other three work together
- Low build complexity, many parts – like a giant washing machine
- Great benefits in streamlining assembly

Orchestrating these four technologies into a single system

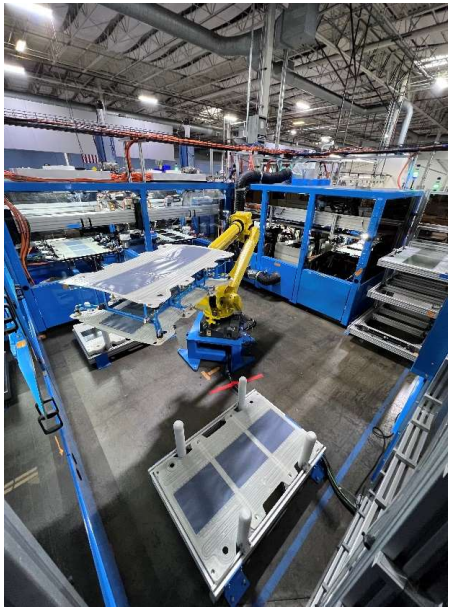
Transitioning to Mass Production with Automation

Power Module Production

Automation line optimizing
- Process recipe / control
- Preventative maintenance
- Quality & yield
- OEE and output

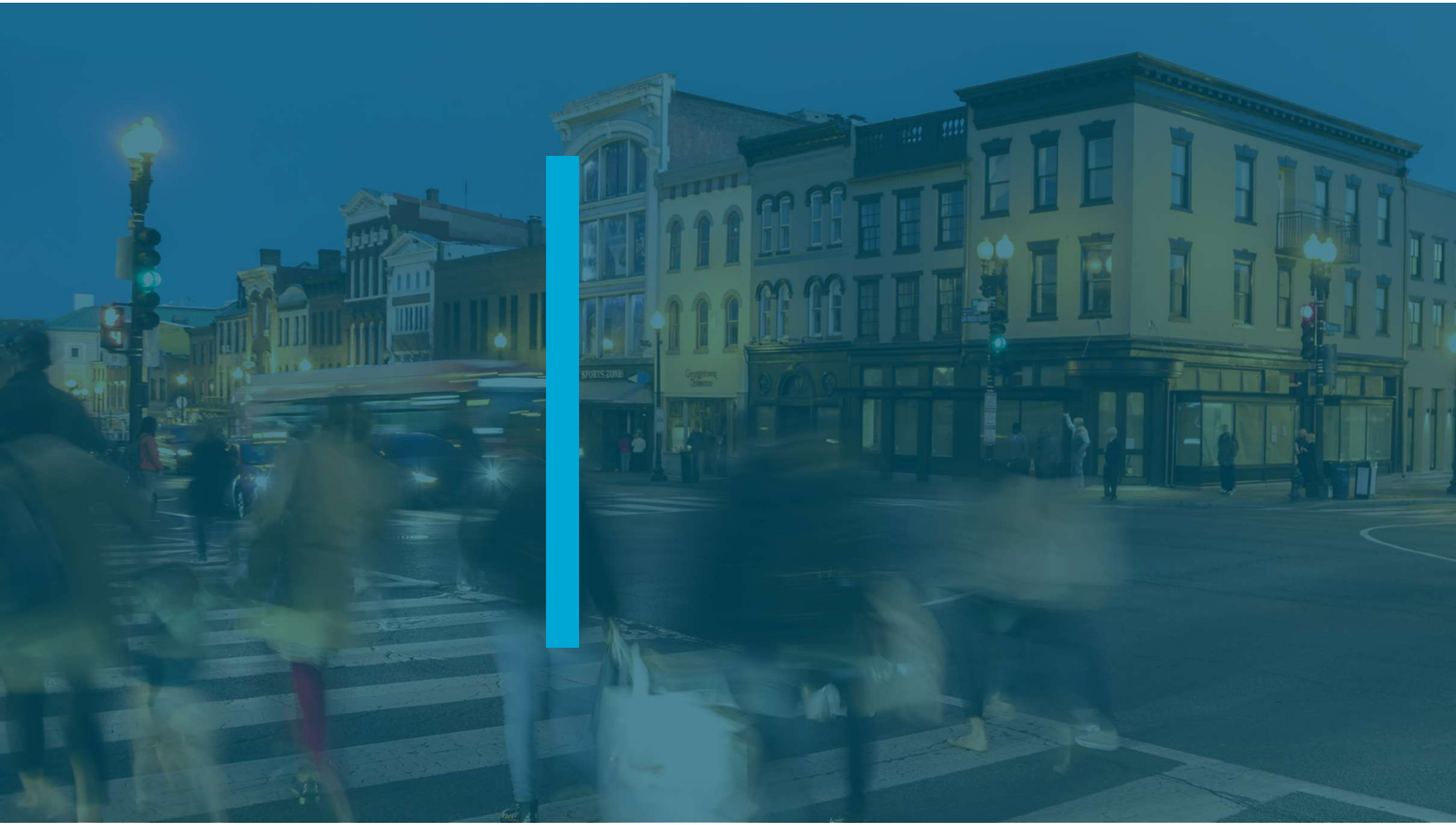
Achieving economies of scale
- Labor cost reduction: 75%
- Cycle time reduction: 60%
- Manufacturing footprint reduction: 75%

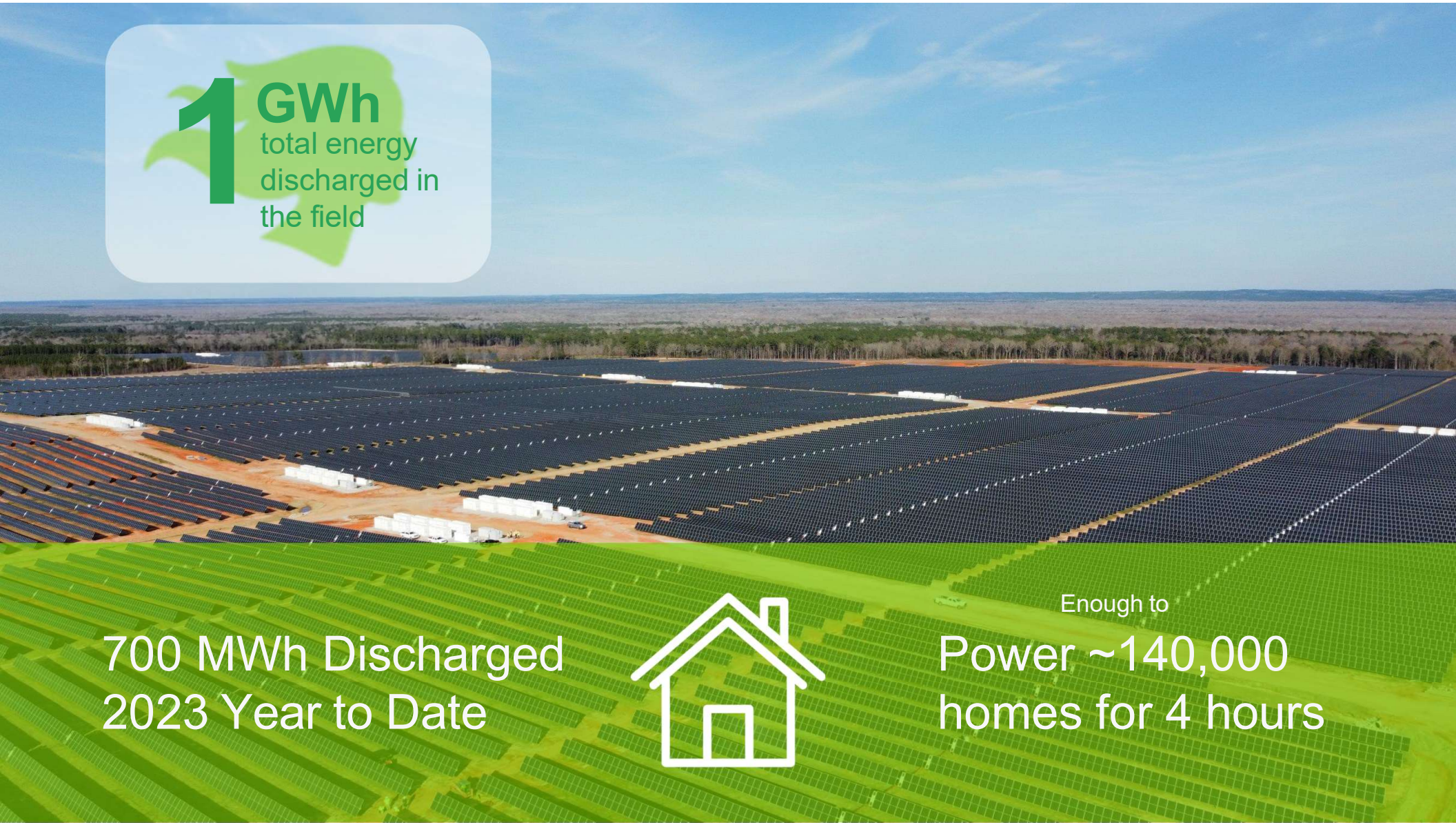
Frame Preparation & Test Stations



Frame Attachment Stations

Frame Stack Station


SPORTS ZONE


1 GWh
total energy discharged in the field
700 MWh Discharged
2023 Year to Date
Enough to
Power ~140,000
homes for 4 hours