Argonne
NATIONAL LABORATORY

FRONTIERS IN MATERIALS MANUFACTURING

THE FUTURE OF ENERGY STORAGE

U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

FRONTIERS IN MATERIALS MANUFACTURING

THE FUTURE OF ENERGY STORAGE

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ENERGY STORAGE GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY

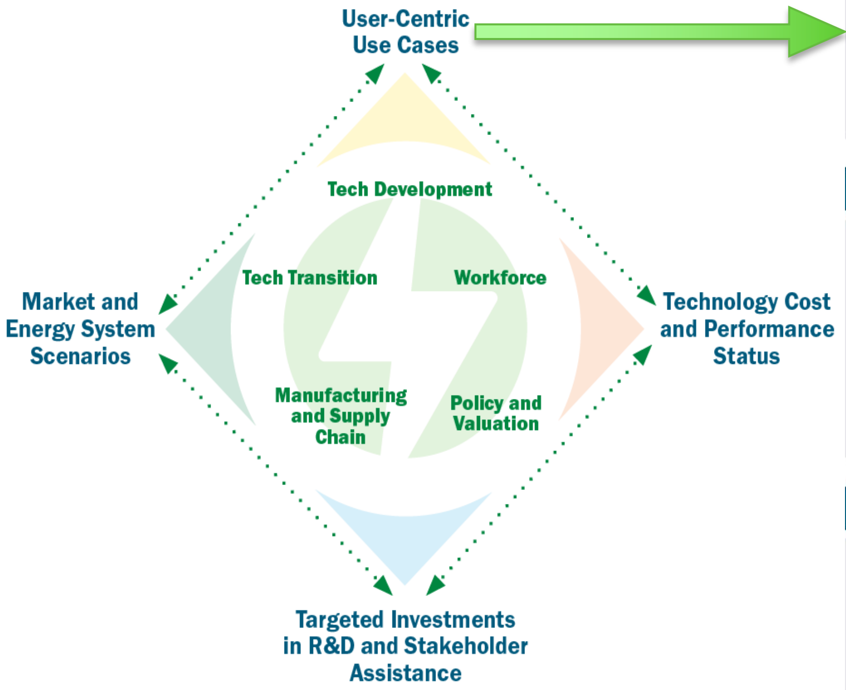
Accelerate the development, commercialization, and utilization of next-generation energy storage technologies and sustain American global leadership in energy storage.

How can DOE work to lower the cost and energy impact of manufacturing technologies, and strengthen domestic supply chains by reducing dependence on foreign sources of materials and components?

How can DOE enable the United States to lead in energy storage R&D and retain IP developed through DOE investment in the United States?

How can DOE work with relevant stakeholders to develop technologies that meet our domestic usage needs and enable the United States to not only successfully deploy technologies in domestic markets but also export technologies?

ENERGY STORAGE GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY



Facilitating an Evolving Grid

Drivers
- Increasing adoption of variable resources
- Dynamic changes in customer demand

Potential Price Target(s)
- $0.03-$0.05/kWh levelized cost of storage

Electrified Mobility

Drivers
- Distribution delivery capacity for fast charging
- Lower EV battery manufacturing costs and improved performance

Potential Price Target(s)
- $80/kWh manufactured cost for battery pack
- $104/kw-yr storage capex

Critical Services

Drivers
- Disaster-related and other power outages

Potential Price Target(s)
- $77/kw-yr for reliability applications
- $1392/kw-yr for backup generator offset

Serving Remote Communities

Drivers
- Electricity premium due to fuel logistics and maintenance
- Fuel supply disruptions

Potential Price Target(s)
- $65/mwh delivered energy

Interdependent Network Infrastructure

Drivers
- Grid interdependencies mean loss of function and service within these infrastructures can have far-reaching costs and impacts

Potential Price Target(s)
- $77/kw-yr storage capex

Facility Flexibility, Efficiency, and Value Enhancement

Drivers
- Enhance the overall facility value to the owner, operator, and the end consumer

Potential Price Target(s)
- $85/kwh, $52/kw-yr for commercial and residential buildings
- $20-$52/kw-yr for energy intensive facilities

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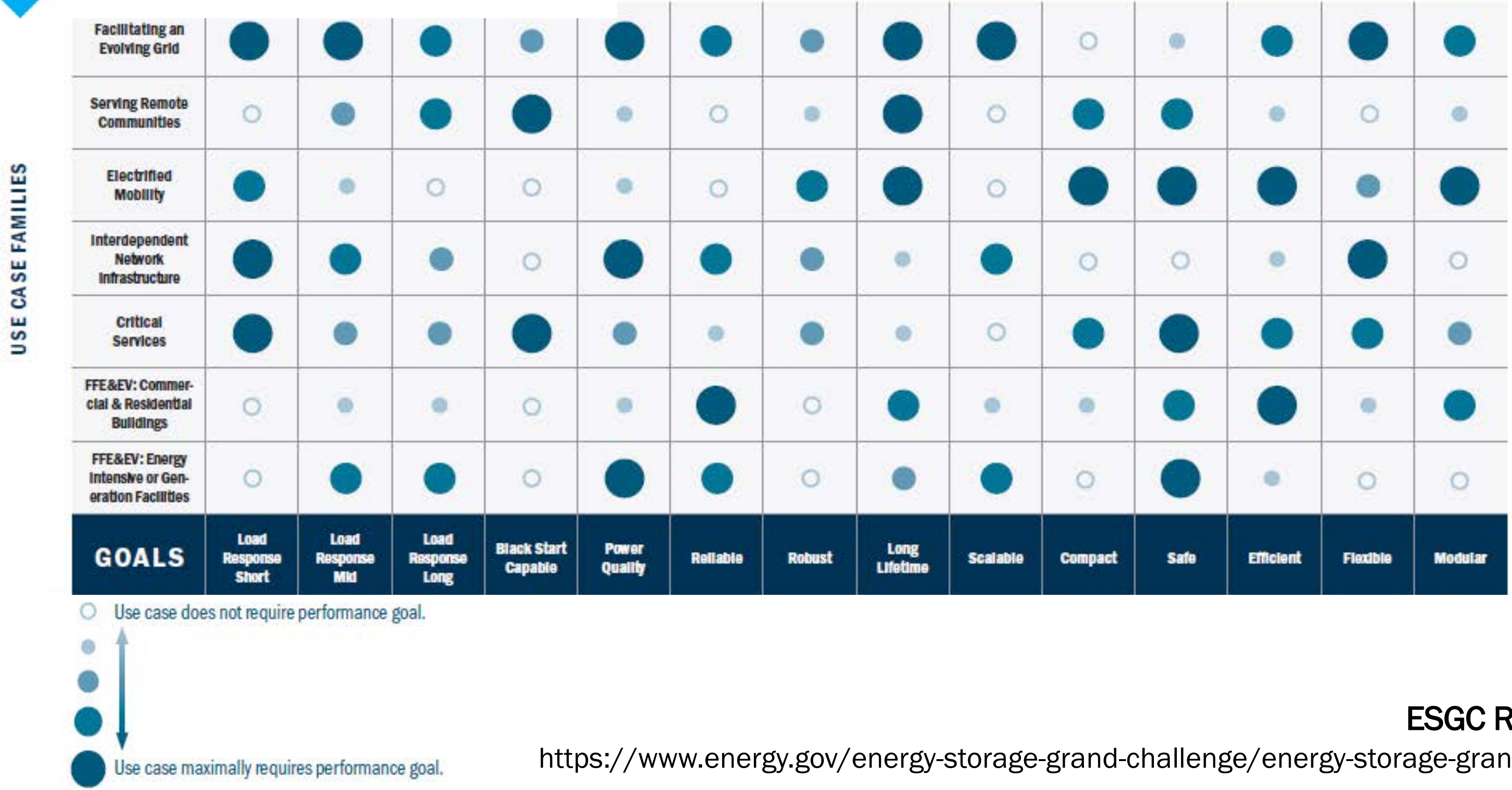
Opportunity space for use cases, and …



ESGC Roadmap – https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge

ENERGY STORAGE GRAND CHALLENGE
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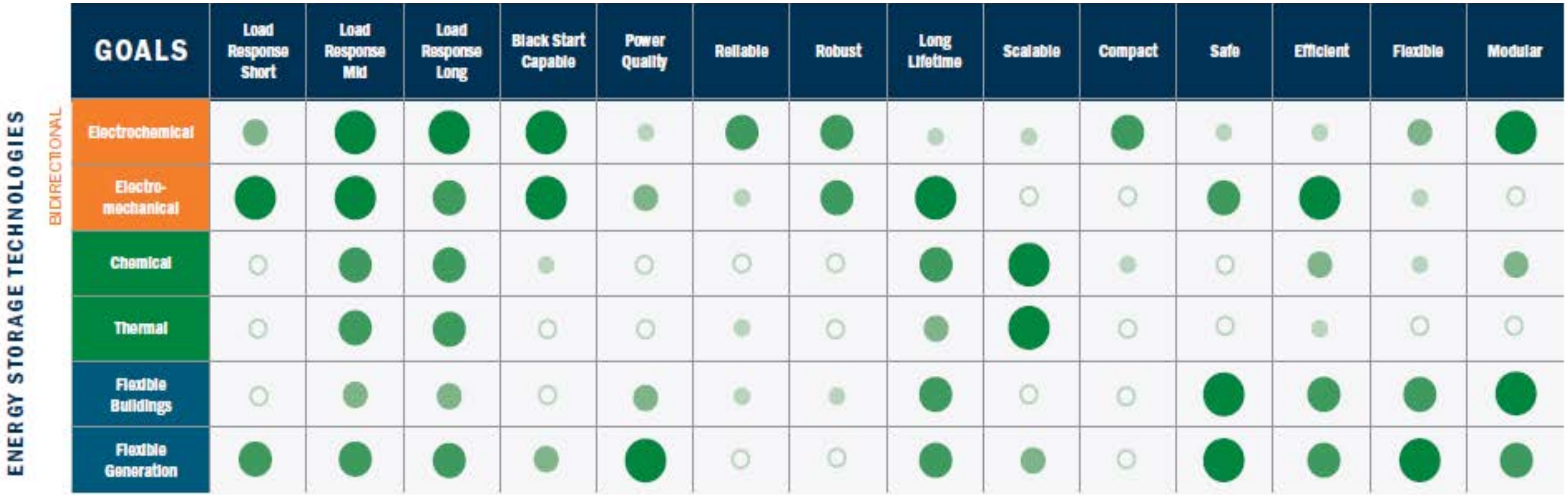
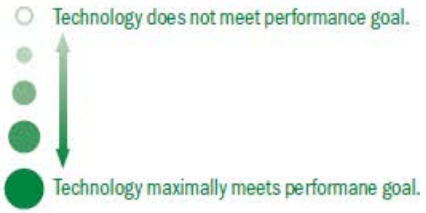
… opportunity space for energy storage systems.





ESGC Roadmap –
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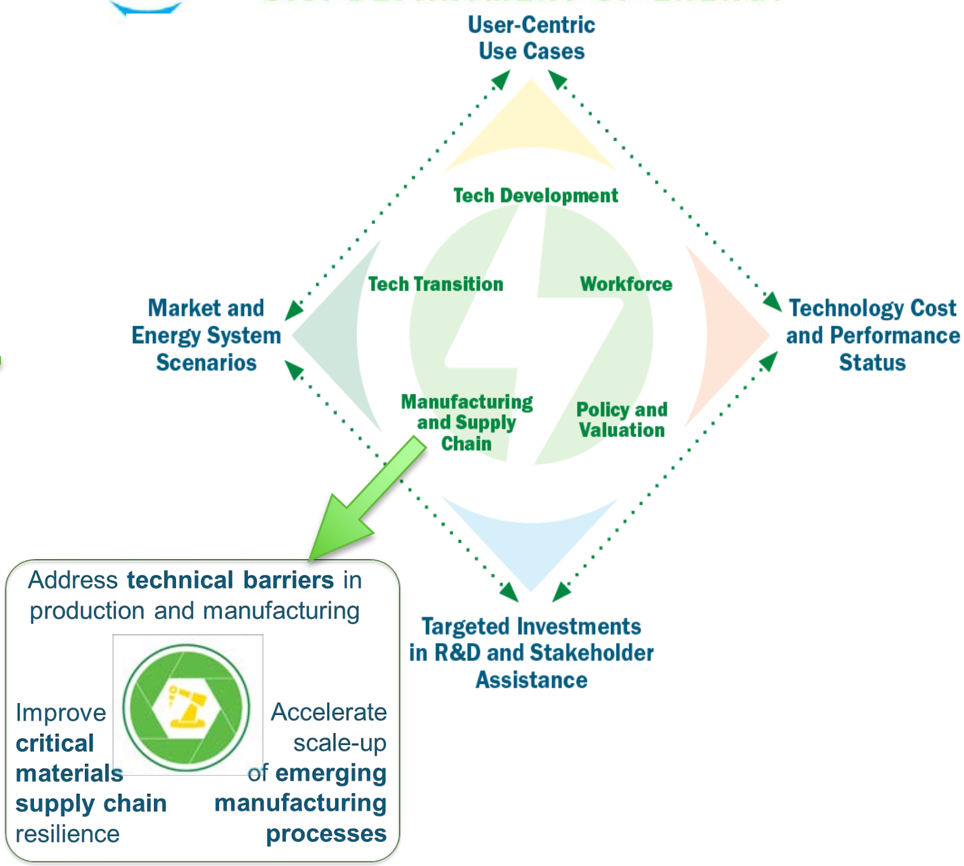

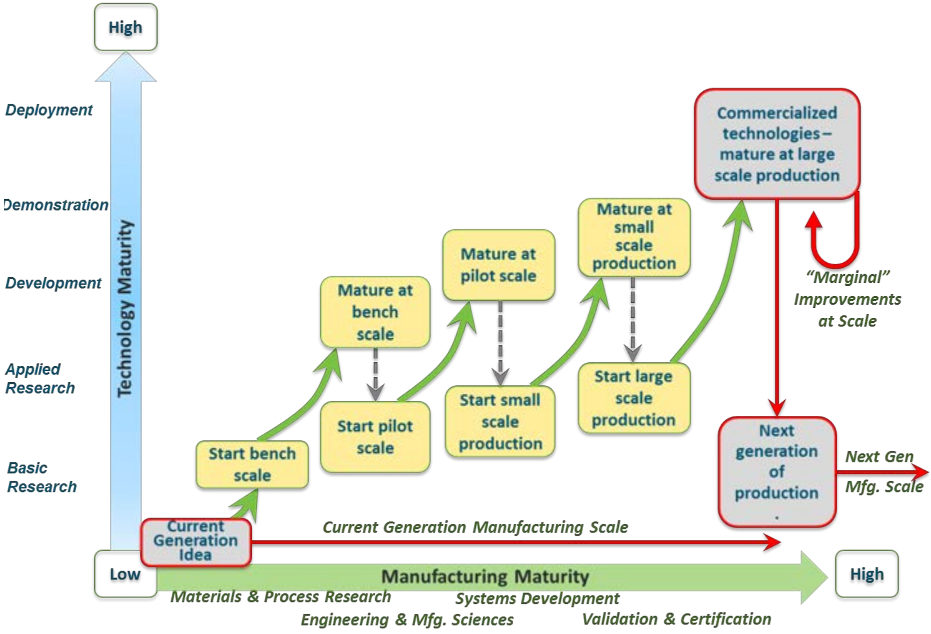

Technology challenges arise at all manufacturing scales

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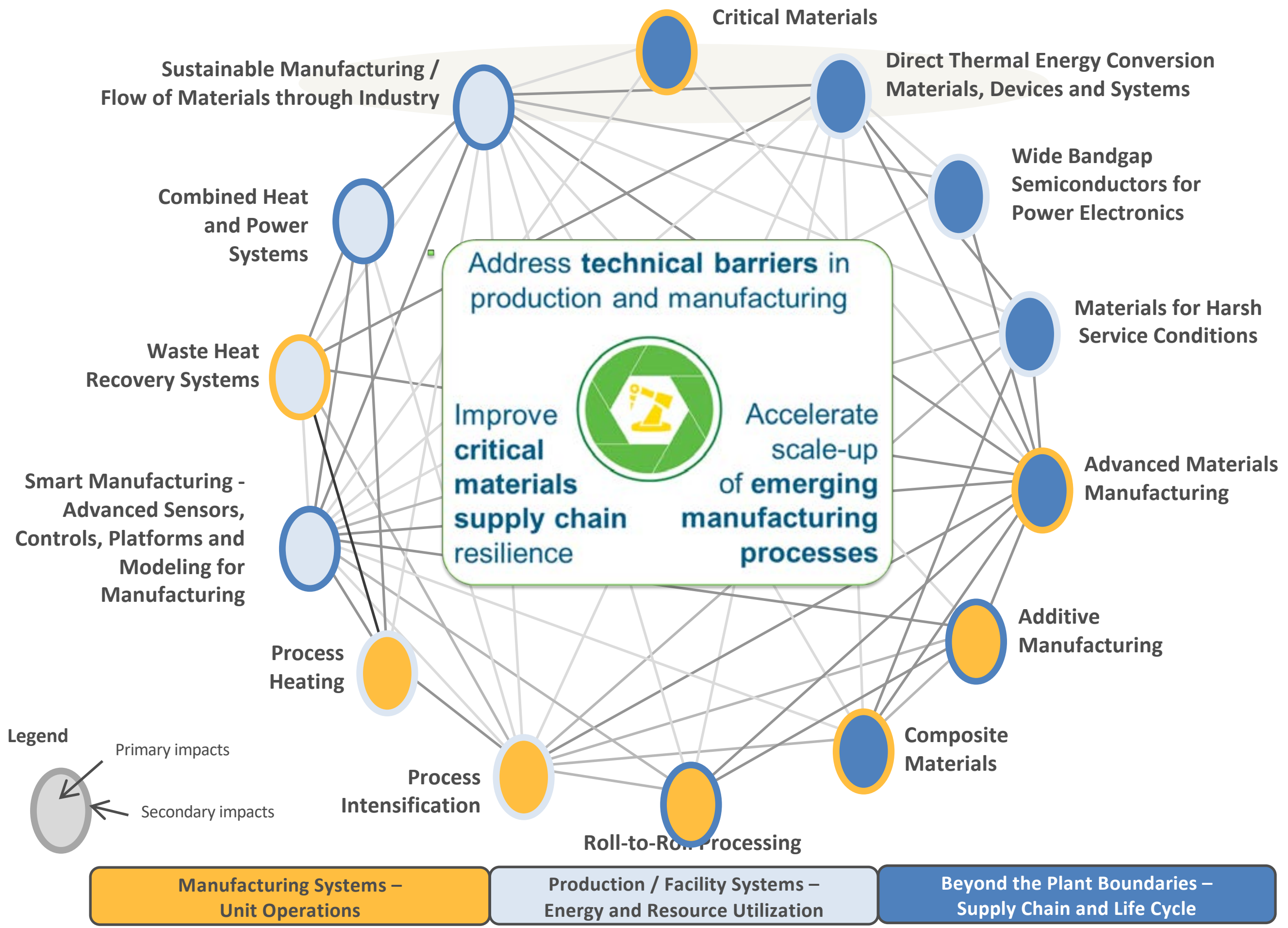
Identified manufacturing challenges for energy storage systems.

		Advance processing and recycling to diversify critical materials sourcing	Lower manufacturing cost			Improve performance (e.g., safety, lifecycle cost)				Accelerate manufacturing scale up/scale out	Standardize systems design and testing protocols to streamline integration of innovations
			Membranes	Advanced anode, cathode, electrolyte, and chemistries	Containment structures and materials	Electrolyzers	Advanced storage materials	Bipolar plates	Heat exchangers		
Storage Type	Lithium-based Batteries	X		X					X	X	
	Other Battery Chemistries	X	X	X			X			X	X
	Flow Batteries	X	X	X	X			X		X	X
	Mechanical Energy Storage						X			X	X
	Chemical Energy Storage	X	X	X		X	X	X		X	
	Thermal Energy Storage				X		X		X		X

ESGC Roadmap – https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge

Leverage AMO core technology areas to address energy conversion & storage challenges



AMO Multi-Year Program Plan:
https://www.energy.gov/eere/amo/downloads/advanced-manufacturing-office-amo-multi-year-program-plan-fiscal-years-2017

AMO Technology Assessments:
https://www.energy.gov/eere/amo/energy-analysis-data-and-reports

Accelerate scale-up of emerging manufacturing processes – R2R Manufacturing Collaborations

AMO DE-FOA-0001980 Topic 1.2 battery manufacturing FY20 awards (co-supported by VTO)

HFTO DE-FOA-0002229 Topic 1 Electrolyzer Manufacturing R&D (co-supported by AMO)

AMO R2R Advanced Materials Manufacturing (AMM) Collaboration

nel · GM · PLUG POWER · Argonne NATIONAL LABORATORY

- Novel deposition via electrospinning
- In-situ characterization via x-ray scattering
- Advanced testing capabilities

OAK RIDGE National Laboratory · Kodak · SAINT-GOBAIN

- Colloidal chemistry & surfactant research
- Slurry processing & coating scale-up
- Deposition parameters, drying, and curing

SOLAR WINDOW TECHNOLOGIES, INC. · nel · FISKER · NAVITAS SYSTEMS · NREL NATIONAL RENEWABLE ENERGY LABORATORY

- Physics & methods for coatings / deposition
- Fabrication / In-situ testing
- Novel NDE, QC, and metrology

INDUSTRY

BERKELEY LAB

- Macroscopic mathematical modeling of colloids
- Coating parameter measurement & quantification
- X-ray tomography of dried coatings

Sandia National Laboratories

- Validation of continuum-scale models
- Acceleration of coating designs & scale-up processes
- Prediction of optimum coating / deposition windows

Industry Partnerships for Battery Manufacturing Innovation

Address engineering challenges for advanced battery materials and devices, to de-risk, scale, and accelerate adoption.
Selections announced August, 2020

Lab	Industry Partner	Title
ANL	Albemarle/Ameridia (North Carolina)	**Advanced Brine Processing** to Enable U.S. Lithium Independence
ANL	Hunt Energy Enterprises (Texas)	**Hydrothermal Production** of Single Crystal Ni-rich Cathodes with Extreme Rate Capability
ANL	Koura Global (Massachusetts)	**Continuous Flow Reactor Synthesis** of Advanced Electrolyte Components for Lithium-Ion Batteries
ANL	PolyPlus (California)	**Continuous high yield production** of defect-free, ultrathin sulfide glass electrolytes for next generation solid state lithium metal batteries
ANL	SafeLi LLC (Wisconsin)	**Scale-up Production** of Graphene Monoxide for Next-Generation LIB Anodes
ANL	Saint-Gobain Ceramics & Plastics (Pennsylvania)	**Scaling** halide-type solid electrolytes for solid state batteries
BNL	C4V & Primet (New York)	**Commercially Viable Process** for Surface Conditioning of High-Nickel Low-Cobalt Cathodes
LBNL	Saint-Gobain Research North America (Pennsylvania)	**Scale-Up** of Novel Li-Conducting Halide Solid State Battery Electrolyte
NREL	Clarios, Amplitude, Feasible (New York)	**High-Throughput Laser Processing** and Acoustic Diagnostics for Enhanced Battery Performance and Mfg.
ORNL	PPG (Pennsylvania)	High-Energy and High-Power NMP-Free Designer Electrodes with Ultra-Thick Architectures **Processed by Multilayer Slot-Die Coating and Electrophoretic Deposition**
ORNL	Soteria (South Carolina)	**Multilayer Electrode** with Metalized Polymer Current Collector for High-Energy Lithium-Ion Batteries with Extreme-Fast-Charging Capability
PNNL	Albemarle (North Carolina)	**Scaling-Up** of High-Performance Single Crystalline Ni-rich Cathode Materials with Advanced Li Salts
PNNL	Ampcera Inc. (California)	**Scaling-Up and Roll-to-Roll Processing** of Highly Conductive Sulfide Solid-State Electrolytes

Lab-Embedded Entrepreneurship Programs

Empower innovators to mature their ideas from concept to first product, positioning them to align with the most suitable commercial path to bring their technology to scale.

CHAIN REACTION INNOVATIONS

Argonne NATIONAL LABORATORY

cyclotronroad

BERKELEY LAB

① **Recruit** the best energy technology innovators

Accelerate access to follow-on funding

Position people and technology for market

OAK RIDGE National Laboratory

INNOVATION CROSSROADS

② **Leverage** expert mentorship and world-class facilities at the national labs on a win-win basis

https://www.energy.gov/eere/amo/lab-embedded-entrepreneurship-programs

Energy Conversion and Storage – Lab-Embedded Entrepreneurs

ATLAS ENERGY SYSTEMS, LLC
- A novel radioisotope battery made from nuclear waste
- 2017 CRI Cohort
- Potential markets include space power, military, remote energy storage

volexion
- Graphene-enhanced electrodes
- 2018 CRI Cohort
- Potential markets include Li-ion battery material and cell manufacturers

MESODYNE — OUR MISSION IS TO POWER YOUR MISSION
- Portable thermophotovoltaic power generator
- 2018 CRI Cohort
- Potential markets include U.S. military, emergency response, and drones

JOLT ENERGY STORAGE TECHNOLOGIES
- Organic materials for energy storage
- 2018 CRI Cohort
- Potential markets include electrolyte and Li-ion cell manufacturers

CAPORUS TECHNOLOGIES
- Dielectric materials for high density capacitive energy storage
- 2019 CRI Cohort

EONIX
- Electrolytes to enable more powerful ultracapacitors
- 2018 Innovation Crossroads Cohort
- Potential markets include mobile electronics and electric vehicles

ACTIVE ENERGY SYSTEMS
- Turning low-temperature waste heat into energy storage
- 2017 Innovation Crossroads Cohort
- Potential markets include petrochemical and pulp & paper mfrs

Energy Conversion and Storage – Lab-Embedded Entrepreneurs

SEPION TECHNOLOGIES

- Advanced membranes for beyond Li-ion battery performance
- 2016 Cyclotron Road Cohort
- Potential markets include mobile electronics and electric vehicles

Feasible

- Ultrasound & Machine Learning for Battery Inspection & Metrology
- 2016 Cyclotron Road Cohort
- Potential markets include battery manufacturers and end users

CUBERG

- Advanced Electrolyte for stable high-voltage Li-metal batteries
- 2016 Cyclotron Road Cohort
- Potential markets include U.S. military, energy producers, and drones

noon ENERGY

- A new class of ultra-low-cost flow battery
- 2018 Cyclotron Road Cohort
- Potential markets include wind and solar energy producers

Antora Energy

- Low-cost thermal batteries for grid-scale energy storage
- 2018 Cyclotron Road Cohort
- Potential markets include the U.S. military and energy providers

Improve critical materials supply chains

DOE GOALS

Enhance critical materials resiliency for energy technologies through R&D approaches to:

- Diversify the supply chain for critical materials, including domestic production and processing
- Develop element, material, and/or system substitutes to reduce dependence
- Drive recycling, reuse, and more efficient use of critical materials

aligned with Executive Order 13817

KEY CRITICAL MATERIALS SUPPLY CHAINS FOR AMO

Rare earth elements for permanent magnets for electric machines

Cobalt and lithium for electric vehicle batteries and grid storage

Gallium for LEDs and power electronics

Address **technical barriers** in production and manufacturing

Improve **critical materials supply chain** resilience

Accelerate scale-up of **emerging manufacturing processes**

Critical Materials Institute (CMI)

- DOE Energy Innovation Hub
- Led by Ames Laboratory
- Aligned with DOE priorities
- $25M per year, directed by Congress

Energy Storage Grand Challenge Crosscut

- Battery manufacturing projects $45M: FY19 FOA
- Strategic analysis: Battery recycling case studies
- Lithium-ion Battery Recycling Prize
- Battery Manufacturing Lab Call

$30M in funding for field validation and demonstration and next-generation technologies

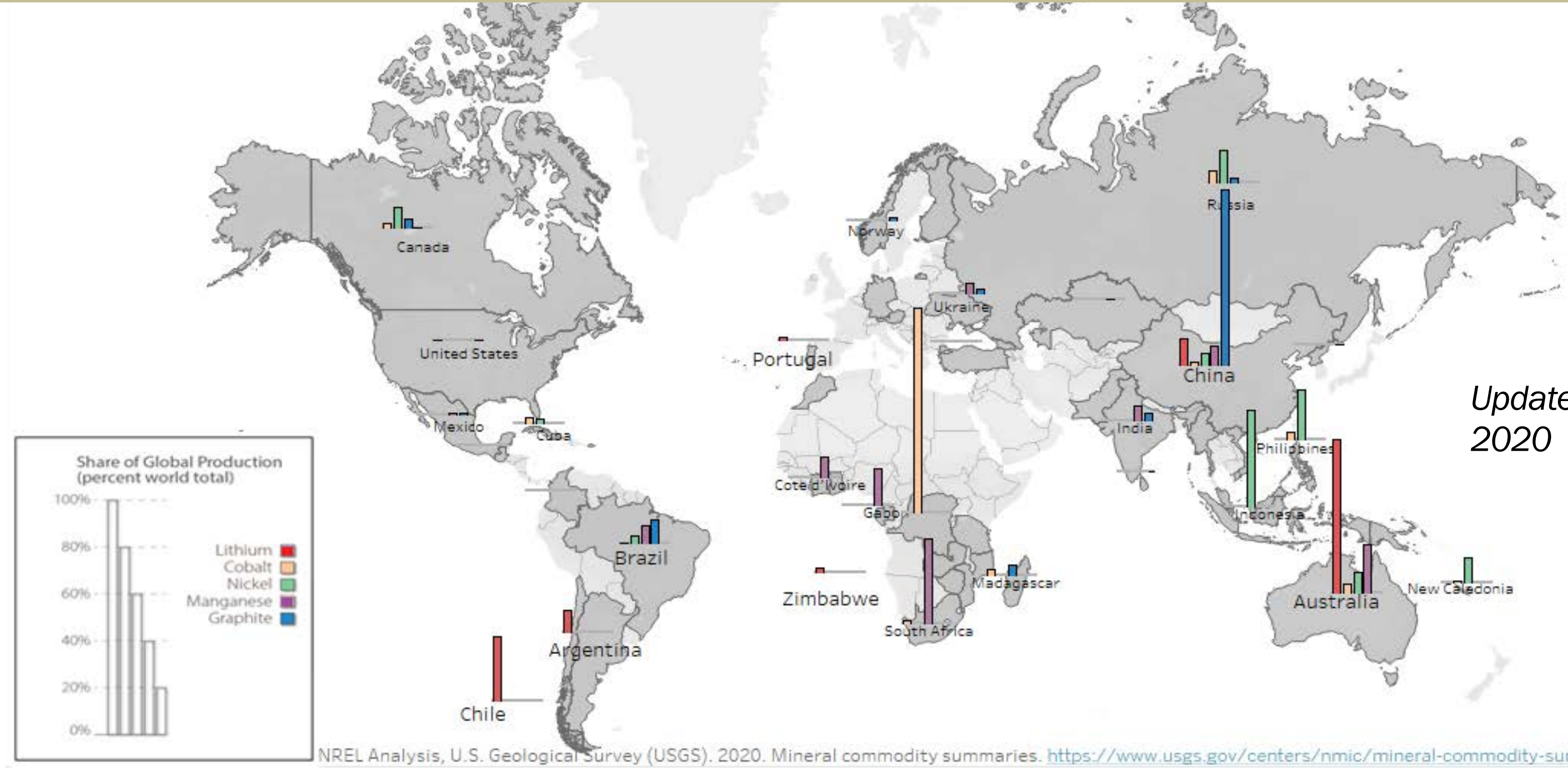
SELECTIONS COMING SOON

SBIR/STTR and Technology Commercialization Fund

projects to advance technologies beyond the lab, NREL

Materials sources for lithium-ion batteries

In 2019, 41 countries accounted for all global production of Li, Co, Ni, Mn and Graphite, with > 50% of production of three elements (Co, Graphite, Li) originating in one country.

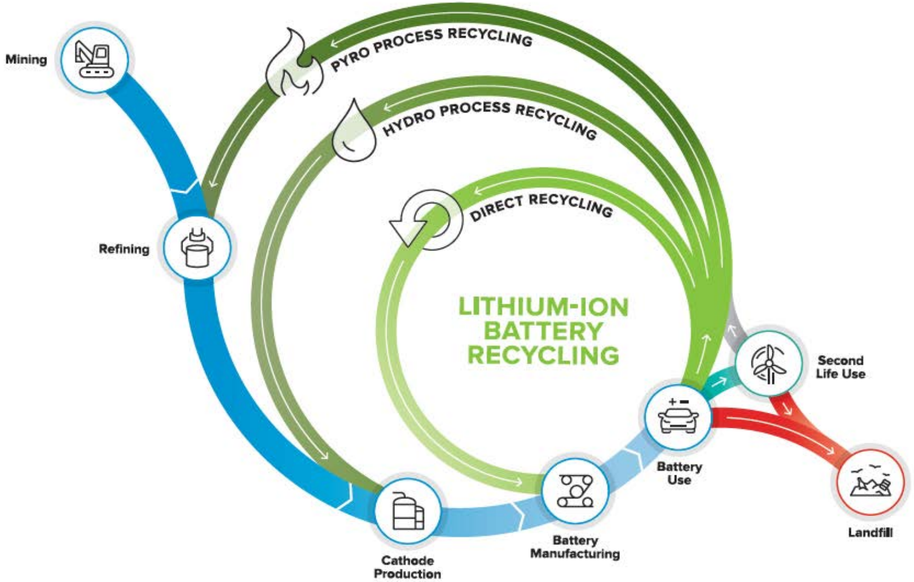


Updated March 2020

NREL Analysis, U.S. Geological Survey (USGS). 2020. Mineral commodity summaries. https://www.usgs.gov/centers/nmic/mineral-commodity-summaries

Opportunities for a more circular economy for LIBs

	Natural Resources		Spent Batteries
One ton of battery-grade cobalt can come from:	 **300 TONS** OF ORE		 **5-15 TONS** OF SPENT LITHIUM-ION BATTERIES
One ton of battery-grade lithium can come from:	 **250 TONS** OF ORE	 **750 TONS** BRINE	 **28 TONS** OF LITHIUM-ION BATTERIES



- Less dependence on foreign sources
- Material supply chain stability
- Domestic job creation
- Lower battery costs

Q. Dai, J. C. Kelly, and A. Elgowainy. Cobalt Life Cycle Analysis Update for the GREET Model. September 2018. https://greet.es.anl.gov/publication-update_cobalt.

But what about energy conversion & storage systems for the industrial sector?

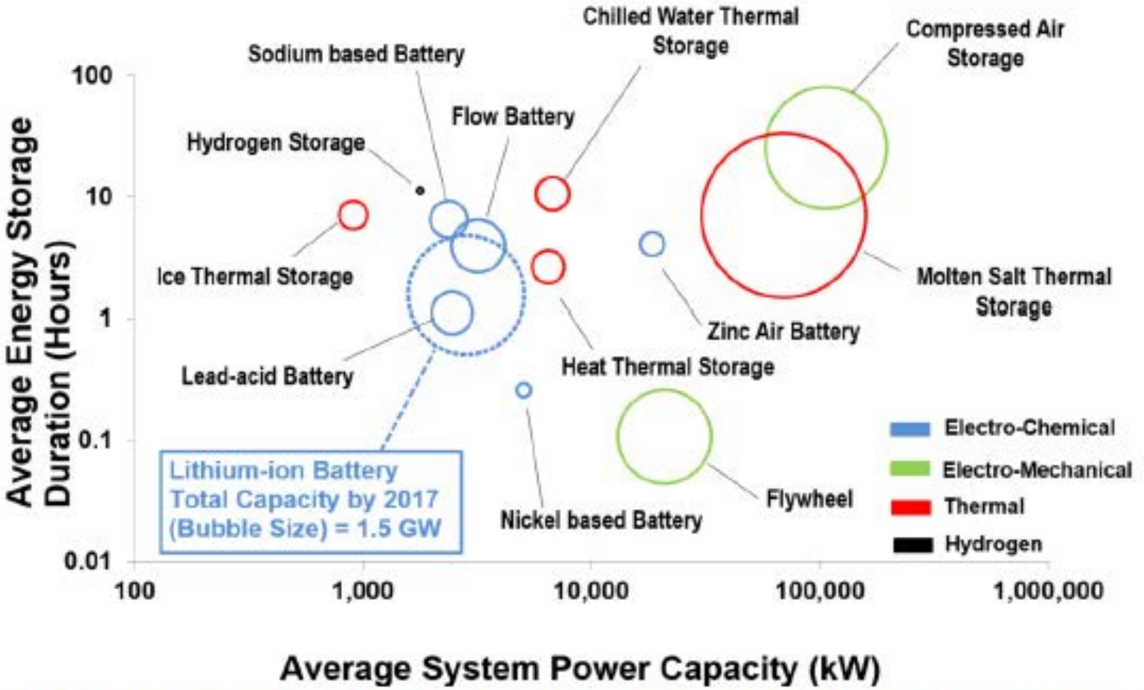
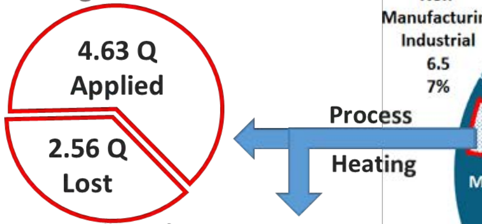


Figure 1. Average characteristics of energy storage systems built worldwide between 1958 and 2017, by technology, from the DOE Energy Storage Database (2018), sample size = 1,041 (pumped hydro not shown because of its very large global capacity)

Fu, Ran, Timothy W. Remo, and Robert M. Margolis. *2018 US Utility-Scale Photovoltaics-Plus-Energy Storage System Costs Benchmark*. No. NREL/TP-6A20-71714. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2018. https://www.nrel.gov/docs/fy19osti/71714.pdf

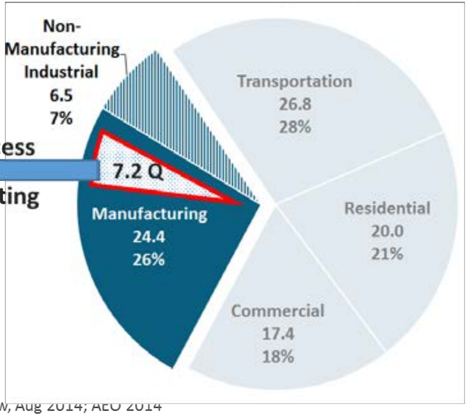
Thermal opportunity

Process Heating in the manufacturing sector: 7.2 Quads

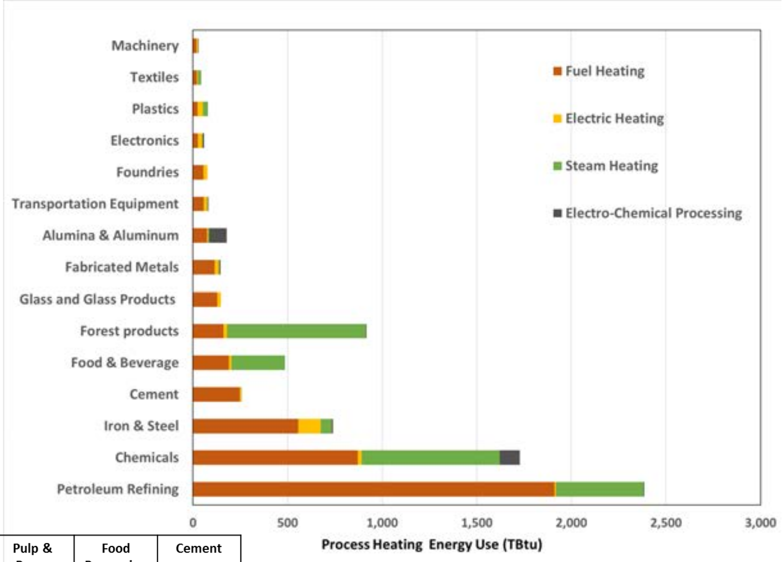


Approximately 2.5 Quad opportunity in process heating alone

U.S. Economy: 95 Quads



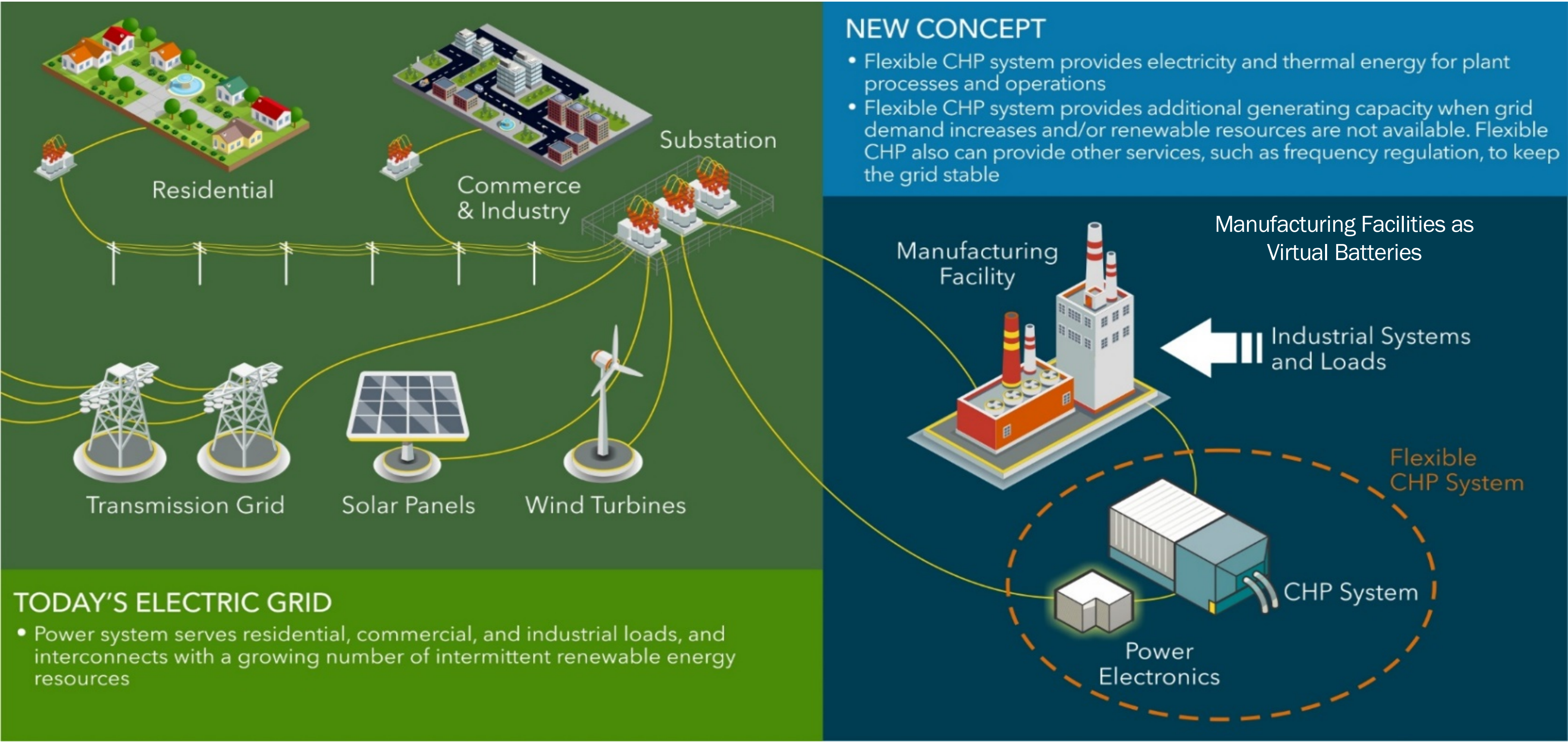
Source: EIA Monthly Energy Review, Aug 2014; AEO 2014



Thermal Process Step	Iron & Steel	Petroleum Refining	Chemical Industry	Glass	Aluminum	Pulp & Paper	Food Processing	Cement
Calcining								
Curing and forming								
Drying								
Fluid heating								
Heat treating (metal & nonmetal)								
Metal and non-metal reheating								
Metal and non-metal melting								
Other heating - processing								
Reactive thermal processing								
Smelting, agglomeration, etc.								
Steam generation								

Temperature Range	Color
Low Temperature (<800°F)	
Medium Temperature (800 to 1400°F)	
High Temperature (>1400°F)	

Flexible manufacturing facilities



NEW CONCEPT

- Flexible CHP system provides electricity and thermal energy for plant processes and operations
- Flexible CHP system provides additional generating capacity when grid demand increases and/or renewable resources are not available. Flexible CHP also can provide other services, such as frequency regulation, to keep the grid stable

TODAY'S ELECTRIC GRID

- Power system serves residential, commercial, and industrial loads, and interconnects with a growing number of intermittent renewable energy resources

What does the intersection of energy storage and manufacturing look like going forward?

Highly efficient, productive, flexible and resilient manufacturing operations, systems and facilities.

Robust, dynamic, adaptable supply chains. Reverse supply chains.

Data analytics, machine learning, artificial intelligence for robust cyber-physical systems.

Building new capabilities and rebuilding lost capabilities.

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GLEN MERFELD

Vice President and
Chief Technology Officer
Albemarle
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Albemarle Lithium

Leading positions in lithium hydroxide, lithium carbonate, organometallics & metal

Vertically integrated access to largest & most concentrated brine & spodumene resources[1]

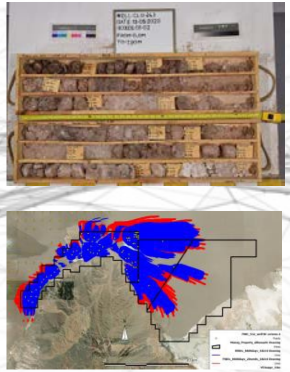
Driving low-cost operations, sustainable production, and disciplined capital expansion

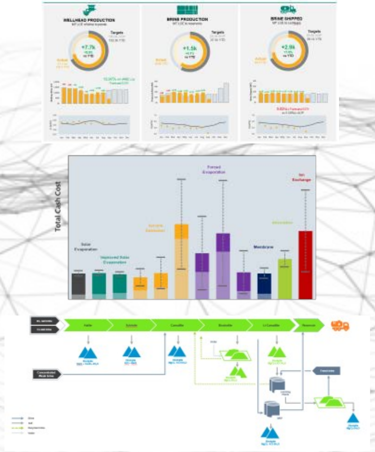
Lithium demand to reach 1 million MT LCE by 2025, 20%+ CAGR driven by EV penetration in new vehicle sales[2]

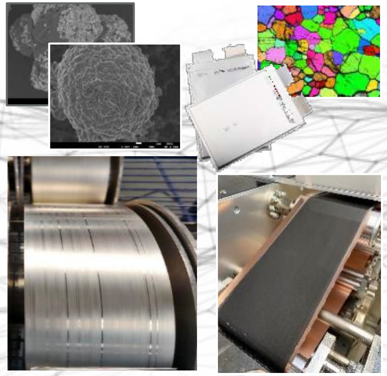
[1]Resource & Reserve Data According to Roskill: Lithium Outlook to 2028. [2]**Lithium Intensity of Energy Storage Demand**: 0.95, 0.76, and 0.78 kg LCE/kWh in 2018, 2019, and 2025, respectively; calculated from demand model output of total lithium demand (total real consumption and YOY inventory change), which accounts for lithium consumption of different technologies and applications. **New Car Sales**: 95, 89, and 102 million in 2018, 2019, and 2025, respectively

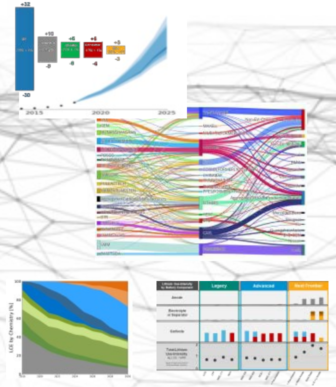
Lithium Technology – Spanning from Minerals to Market

ALBEMARLE®









Hydrogeology
Protect Environment & Sustain Resource

Extraction
Maximize Lithium Recovery & Purity

Advanced Materials
Create Customer Solutions & Performance Differentiation

Data Science
Link Technical Potential to Economic Impact

Technology Differentiation Across The Value Chain

Lithium Resources

ALBEMARLE®

Brine

Hardrock

Oil Field Brines

- ✓ **Geographically Diverse**
- ✓ **High Quality**
- ✓ **Large Scale**
- ✓ **Low Cost**

FRONTIERS IN MATERIALS MANUFACTURING

THE FUTURE OF ENERGY STORAGE

TIM ELLIS

President
RSR Technologies

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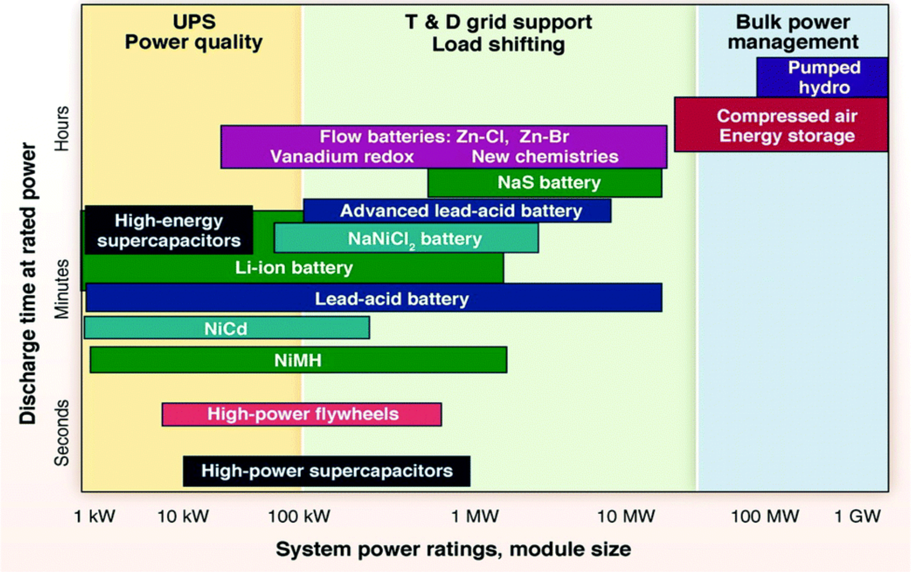
Need for R&D to Meet Changing Requirements for More Powerful, Sustainable and Economical Batteries



Source: Energy & Environmental Science, Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. Turgut M. Gür, October 1, 2018)

Cost Goals for Current Technologies
Manufactured at scale

Li-ion Batteries (cells only)	$100/kWh
V/V Flow Batteries (stack+PE)	$300/kWh
Zinc Manganese Oxide ($Zn\text{-}MnO_2$) 2 Electron System	$ 50/kWh
Low Temperature Na / Na-ion based Batteries	$ 60/kWh
Aqueous Soluble Organic (ASO) Redox Flow Batteries (stack+PE)	$125/kWh
Advanced Lead Acid	$ 35/kWh

Source: DOE OE – Making a business case for long duration energy storage, Energy Storage Digital Series, May 11, 2020

Meeting Growing U.S. Demand & Performance Needs

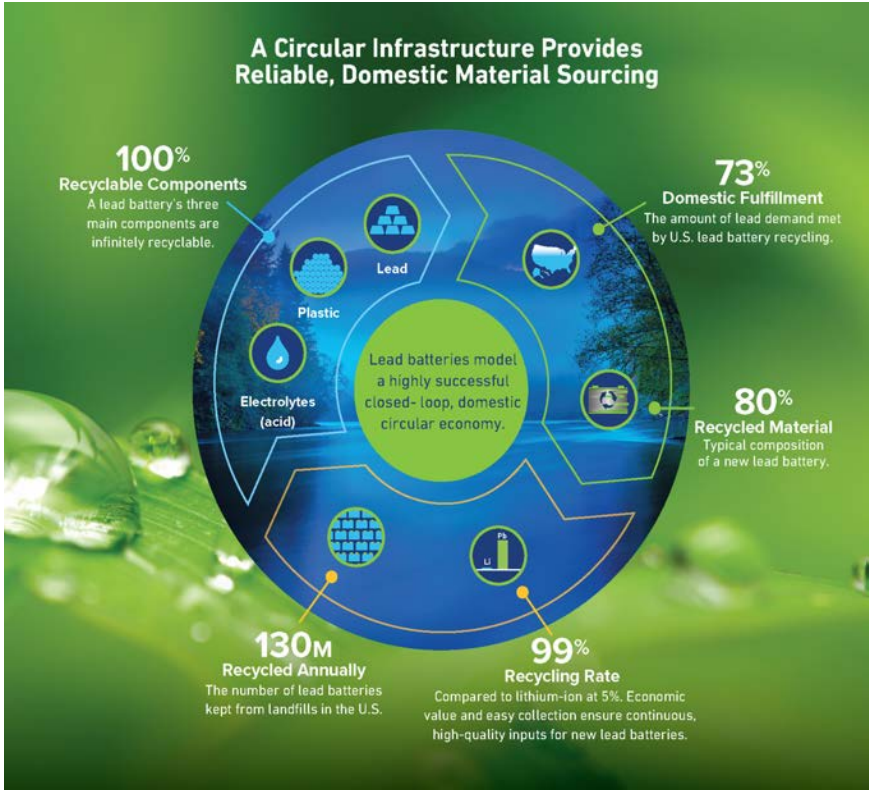
ECOBAT TECHNOLOGIES

Domestic Manufacturing & Recycling

- $26.3 billion industry
- North American lead battery manufacturing supplies 90% of North American demand
- Using recycled lead uses 90% less energy, 90% less greenhouse gases vs. virgin ore

Research Driving Performance Improvements

- **Advanced Product Architecture:** increasing Pb use efficiency (e.g., Bi-Polar)
- **Increase Material Utilization:** only 40% of the active material is utilized (70% = $35/kWh)
- **Controls Technology:** understanding interrelationship between materials & processes powers further R&D - particularly in energy storage



Pb-batteries @ Advanced Photon Source

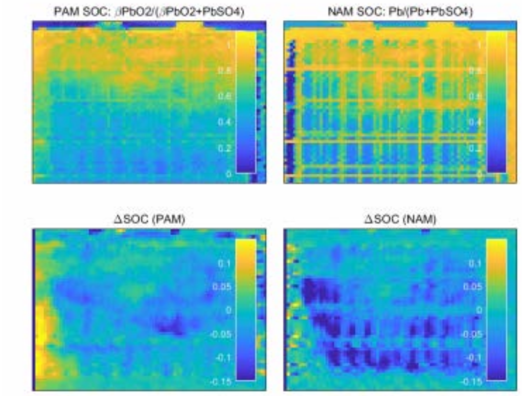
ECOBAT TECHNOLOGIES

East Penn Manufacturing/RSR Tech CRADA

- Cooperative research and development agreement studying varying effects from multiple elements/additives in batteries
- Evaluating next generation Pb alloy performance using advanced analytical techniques

Lead Battery Science Research Program (LBSRP)

- Cooperative research between 16 US battery manufacturers and other Pb companies with Argonne National Lab to study fundamental and chemical physics of Pb battery performance



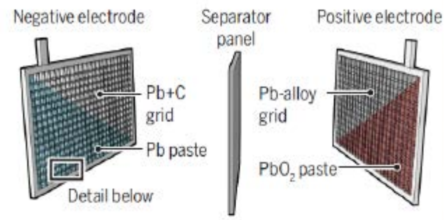
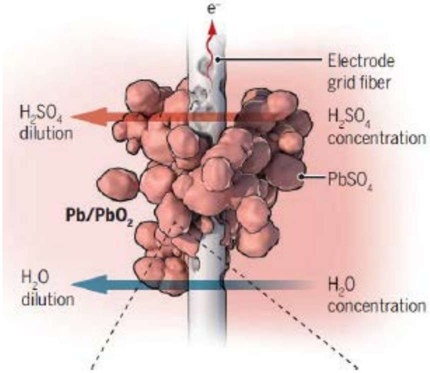


Figure adapted from: Papa Lopes *et al.*, *Science*, 360 (2020)



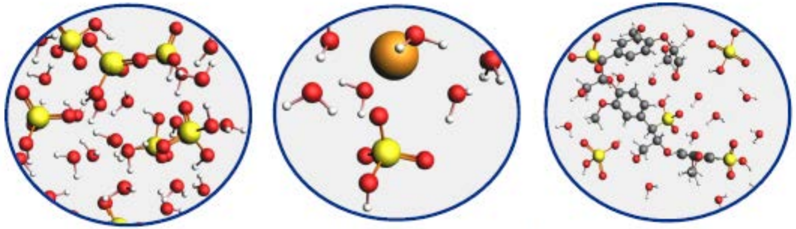
Pb Research Programs

Pacific Northwest National Lab (PNNL) Grid Storage group

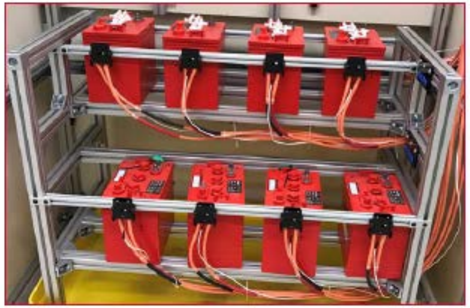
- Measurement of 6V batteries made with/without advance active materials to test performance.
- Advancing control algorithms to map application to basic physics/chemistry

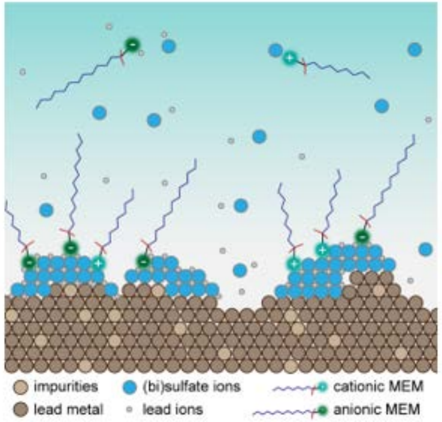
Pending Project with Argonne National Lab/University of Toledo/US Industry Partners

- Design and study of battery additives to improve battery performance
- Electrochemical testing of Pb in combination with impurities/various additives/synthetic molecules



H_2SO_4 (aq) PbSO$_4$ (aq) Lignosulfonate (aq)





Mapping Industry Needs To Laboratory Capabilities

ECOBAT TECHNOLOGIES

Materials and Control		
Argonne	East Penn/RSRTech	Fundamental Material Science
Ames Lab DOE	RSRTech	Advanced Materials Development
PNNL/Argonne	RSRTech	Battery Evaluation
Argonne/PNNL	16 U.S. Lead Bat. Cos.	Fundamental Material Science
Argonne	5 U.S. Battery Mfrs.	Technology Transition -— **NEW**
Product Architecture		
Argonne	RSRTech/East Penn	CRADA
US DOE	U.S. ESGC	***Multiple FOA Responses Planned***
Resource Recovery		
Re-Cell Center(Argonne)	RSRTech	Battery Recycling Technology
Argonne	RSRTech	Resource Recovery Process Validation

Lead Battery Science Research Program

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