Summary of Energy Storage Grand Challenge Workshop: Manufacturing and Workforce Needs in the Energy Storage Industry

Workshop Report
DOE/PA-0023
January 2021

ENERGY STORAGE
GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY

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1 Overview

Energy storage is the key to enabling the electric vehicle revolution and to creating the grid of the future with integrated resiliency and flexibility. Over the past five years, it has become clear that these changes can fundamentally transform the world and lead to the birth of new industries. Energy storage technology developments have resulted in a worldwide race to capture the energy storage market. This has led to significant interest in developing advanced storage technologies with focus on new materials, designs, and manufacturing processes.

As we examine the needs of the future, it is clear that multiple technology pathways will emerge that can help the transition to the energy system of the future. These include different kinds of battery technologies such as Li-ion, aqueous container batteries, flow batteries, chemical storage technologies, and thermal storage technologies. In each category, different materials are being developed, and a robust innovation pipeline exists that can transform present performance levels relative to the state of the art. Developing agile low-cost manufacturing processes that can move these innovations toward large-scale production will be crucial to ensuring rapid transformation of the new innovations into market impact. Innovations are needed across the supply chain and product lifecycle to help ensure that storage technologies draw from readily available raw material sources and can be sustained over the long term. Activating the supply chain and manufacturing processes of emerging energy storage innovations will be crucial to creating the industries of the future and the associated benefits related to job creation.

In January 2020, the U.S. Department of Energy (DOE) announced the Energy Storage Grand Challenge (ESGC), a comprehensive program to accelerate the development, commercialization, and utilization of next-generation energy storage technologies and to establish American leadership in energy storage on a worldwide basis. One of the ESGC's key areas of focus is on supply chain and manufacturing considerations. Different energy storage technologies face different sets of challenges to improving their manufacturability and strengthening their supply chains.

2 ESGC Virtual Manufacturing Workshop (March 2020)

To understand the manufacturing challenges that affect these technologies, ESGC conducted a virtual workshop on March 16, 2020, to collect information on the bottlenecks faced by stakeholders across the industry. The workshop attracted more than 150 participants from industry, academia, and national labs. Keynote presentations from DOE-ESGC leadership set the stage for the workshop. Breakout sessions on various storage technologies and systems allowed deeper dives into the challenges in scaling and manufacturing of materials, components, and devices; the associated supply chain issues; and workforce needs.

The following sections summarize some of these technical challenges and are grouped by the class of energy storage technology and associated workforce needs. Some challenges are common to multiple technologies and therefore are summarized in a crosscutting section. The workshop allowed detailed discussions on the key material, component, and device manufacturing challenges; the related supply chain issues; and the workforce needs in energy storage. It is clear that U.S. researchers and manufacturers have numerous innovative ideas that can have large impacts in creating the energy storage industry of the future. This large body of researchers, manufacturers, and end users are focused on developing innovative new solutions and have a clear understanding of what is needed to succeed in this competitive industry. DOE is well-positioned to pull this ecosystem together and help shape the energy storage industry for the 21st century to achieve the goals of the ESGC.

3 Electrochemical Energy Storage

Electrochemical energy storage devices (i.e., batteries) have the advantage of being dispatchable under a wide range of discharge times (from ms to hours), enabling their deployment in a wide range of applications; they are especially adapted for applications that require rapid response times, such as transportation and grid frequency modulation. Over the last decade, rapid cost reductions coupled with the performance improvements of Li-ion batteries have led to growing adoption in transportation applications. However, widespread adoption requires further reduction in cost, accompanied by fast charging capability without sacrificing energy density, abuse tolerance, and further related performance metrics. These changes require next-generation Li-ion batteries with improved anodes, cathodes, and electrolytes, and as well systems beyond the Li-ion paradigm, including solid-state batteries and various multivalent systems. In the fall of 2019, the DOE Vehicle Technologies Office (VTO), along with the Advanced Manufacturing Office (AMO), brought together Li-ion battery manufacturers, materials companies, car companies, and academic researchers to explore the manufacturing needs for enabling these new chemistries, the materials supply chain aspects, and the bottlenecks to creating a U.S. manufacturing base. Such challenges include the need to scale from lab to prototype, issues related to the capital costs of new factories, and the lack of a robust supply chain in the United States were discussed. DOE is now embarking on a series of steps to fill the manufacturing and supply chain gaps for Li-ion batteries.

In addition to transportation, Li-ion batteries are also entering the stationary storage market. However, electrochemical storage is often more expensive on an energy capacity basis than alternatives such as pumped hydro and thermal storage; the details of their comparative economics depend primarily on the deployment scale, system design, local geography, and required storage duration. For a given timescale, the optimal electrochemical storage approach depends broadly on the combination of chemistry and the cell configuration. Presently, the incumbent Li-ion is most cost effective for shorter durations — those less than 4–6 hours. Long duration is becoming increasingly important for high penetration renewables and increased grid resiliency, and so the projected market for flow cells, in which the power (kW) of the battery is decoupled from the storage capacity (kWh) – thereby enabling improved economics at > 6 hour duration - is growing quickly. In flow cells, the storage compounds are dissolved in an electrolyte that is pumped past "bare" electrodes to generate power; duration is increased by increasing the size of the tanks storing the electrolyte. Vanadium (V) redox couples were the first commercial flow cell chemistry. However, because vanadium is not a commodity resource, this approach has lost competitiveness as Li-ion prices continue to drop. New flow cell chemistries with new lower-cost actives are now emerging in response to the fundamental long-duration design advantage but addressing the need for lower-cost actives. Table 1 compares the various electrochemical energy storage approaches and their targeted applications.

Table 1: Types of Cells, Their Chemistries, and Typical Application Focus

Type of Cell	General Chemistry	Specific Chemistry	Application Focus
Coated electrodes	Li-ion	NMC[a]/graphite	T and G-S
		NCA/graphite	T
		LFP/graphite	T and G-S
	Aqueous	Lead Acid	T and G-S
		Zn-MnO_2	G-S
		Other-1	-
		Other-2	-
Flow Cells	Organic	Anthraquinone based	G-S; G-L
		Viologins	-
		Other-2	-
	Inorganic	V based	G-S; G-L
		Zn-Br	G-S; G-L
		Fe-Fe, ferrocene	G-S; G-L
		Other-1	-

[a] T = transportation; G-S = Grid short duration <4–6 hours; G-L = Grid long duration >6–8 hours; NCA = lithium nickel cobalt aluminum oxide; NMC = lithium nickel manganese cobalt.

3.1 Types of Batteries

3.1.1 Li-ion

As noted above, manufacturing supply chain issues are being examined closely by DOE; the materials used in these technologies are often subject to unstable pricing, and raw materials originate from places that are not easily accessible to U.S. industries. Various new efforts, such as reducing dependence on expensive cobalt and developing methods to scale manufacturing of solid-state batteries, are underway. These new technologies will often require new manufacturing processes. The collection of efforts is expected to continue to decrease the cost of batteries, thereby allowing greater penetration in addressing the different use cases for storage.

3.1.2 Other Chemistries

The cost and safety requirements for stationary storage have led to the reexamination of aqueous batteries and sodium-ion (Na-ion) and sodium solid-state (Na-SS) batteries as alternatives. Various Na-ion materials are under development (e.g., oxide cathodes, Prussian blues) both in aqueous and non-aqueous electrolytes. Na-ion batteries may be slightly more competitive than Li-ion batteries but only if they do not contain cobalt or other expensive elements. In contrast, Na-SS, which uses sodium metal as the anode, could outperform Li-metal solid-state technologies because the sodium metal electrode can accept higher current density than lithium metal electrodes before the onset of dendrites. However, breakthroughs are needed with the Na-SS option in sodium-ion-conducting membranes (e.g., NASICON) that are thinner (~25 microns) and maintain mechanical robustness when cycling at temperatures up to 60°C. These membranes also need to be larger, on the order of 400 cm^2 area, without pinholes or cracks.

In addition, there has been a revolution in improving the cyclability of some of the older aqueous batteries. Examples include rechargeable Zn-MnO_2 cells, Zn-air batteries, and advanced lead-acid (PbA) batteries. Although these chemistries borrow from manufacturing methods used previously, returning to them will require significant supply chain efforts to procure new materials or modified versions of the available commodities at acceptable costs.

One particular area of interest in PbA batteries is the development of bipolar plates, which have the potential to more than double the energy density of PbA from ~25 Wh/kg up to ~60–80 Wh/kg. Progress on the PbA bipolar cell design can be extended further if better methods of sealing dissimilar materials (e.g., silicon wafer in bipolar plate, and sealing polypropylene to Pb or copper [Cu] posts) can be found. However, the PbA manufacturing industry is well established, which means there is a need to engineer whole new lines of machinery that can form and assemble bipolar hardware on a global scale.

One significant concern facing the PbA industry recently is the contamination of its recycling stream with Li-ion batteries; this occurrence is causing serious safety incidents at the PbA recyclers/smelters. Methods are urgently needed for easily separating battery technologies at recycling stations, perhaps using a radio frequency identification (RFID) tag system.

3.1.3 Flow-Cells

Flow cells can address the need for longer duration for grid storage. However, they have not yet achieved a deployment level sufficient to provide broad economies of scale, as the refining of their technologies are still somewhat nascent. Thus, flow cells are not a brand-new technology facing the first “valley of death”; rather, they are proven products with proven designs that need to scale to commodity economics. These final scaling steps may require government support. In addition, as illustrated in Table 2, the stack can require expensive materials and presently non-standardized components, necessitating examination of aspects of the supply chain.

Table 2: Flow Cell Manufacturing and Supply Chains: Common Issues

Component Category	**Component**	**Comment**	**Issue Severity**
System Design	Standardized system designs and test protocols	There is a broad lack of standardization for everything from research to scale-up; for example, (1) research needs standard cells and protocols for first-pass evaluations of new materials; and (2) a BatPaC software type of analytical rigor and standard scaling using standard input are needed so that there is a common "language."	Severe
	Standard system hardware	A complete system package representing standard configurations needs to be available for purchase so that new materials researchers do not waste years establishing cell competencies.	Severe
Stack	Stack sealing	Sealing is very challenging, and achieving desired results is very expensive at present. There are problems with the nonstandard flow fields built into these manifolds: while they often involve trade secrets, they are needed for viable system economics.	Medium
	Current collectors	Carbon felts/cloths are available but are not fundamentally low in cost. Today, they are produced by a batch process; however, if the market grows, the process should become continuous — which will require investment that is not available. The interplays between wetting, mass transport, and electrolyte formulation are complex.	Medium
	Membranes	Polymeric: Fluorinated membranes typically used today because they are readily available (chlor-alkali and fuel cell markets) but are too expensive for widespread commercial adoption and are over-engineered for typical aqueous flow cells. Hydrocarbon-based membranes increasingly *are* being adopted, but without an understanding of trade-offs (a center of excellence would be an ideal place to study this option). Promising new polymers do not have routes to conversion into robust films. Because there is no U.S. supply chain, as a result the cycle time for obtaining membranes from Japan (for example) significantly impedes project timelines and can even shut down otherwise good projects. A national resource for membranes could impact not	Severe

		only flow-cell innovation cycles, but also those of fuel cell and electrolysis cells. Inorganic: Use of inorganic membranes presents difficulties: synthesis of powders does not take place in sufficient quantities or quality to obtain an understanding of film manufacturing; again, a center of excellence would be ideal for teaching and nurturing researchers in how to make films that balance mechanical strength with performance at sizes larger than about 2” × 2”. A final consideration for inorganic membranes would be the manufacturing economics when evaluated rigorously.	
	Tanks	Plastic tanks of sufficient strength can be too expensive; there is a need for robust and low-cost metal containment. Standardization will also greatly reduce cost and simplify the supply chain.	Low
	Bipolar plates	This is a promising/nascent area; there needs to be manufacturing support for broad use.	Severe
Actives	Inorganic	Materials tend to be commercially available and of known purity; supply chain is not a significant issue. However, vanadium industry representatives believe that there is still a place for it, and its manufacture could benefit from processes to extract it from lower-quality ores (of which there are quite a few).	Low
	Organic	Organic actives are now emerging, and multiple issues are becoming apparent: (1) an inability to understand cost and scale and the best synthetic route to low cost; (2) an inability to obtain material of sufficient purity and quantity for evaluations once merit is established; (3) a lack of established methods to evaluate differences between cycle and calendar life with a largely nonexistent supply chain. Guidance is needed for better linkages between the discovery efforts and material cost evaluation to ensure that new research and development (R&D) can be impactful in terms of satisfying market needs.	Severe

3.2 Workforce Needs

Three specific items were shared by the participants related to electrochemical storage, many of which were also common for the hydrogen-based chemical storage industry:

- The country has largely moved away from education in electrochemical engineering and electrochemistry, so the knowledge of electrochemical systems is becoming lost. A robust curriculum is needed so that this expertise can be reinstated into industry. DOE could work with 4-year universities to create new curricula to train students in multidisciplinary fields.
- Electrochemical storage requires knowledge of fields such as chemistry, mechanics, etc. DOE could work with community colleges to create 4- to 8-week training courses for production-level workers so they can be trained in storage manufacturing.
- DOE could work with national labs to host “battery boot camps” for 1–2 months where a company could send an employee to be trained/embedded to learn the basics of battery electrochemistry, electrode coating, cell assembly, material compatibility, and system design.

4 Hydrogen-Based Chemical Energy Storage

Hydrogen has significant potential for providing solutions for grid-scale energy storage. To store electrical energy, electrolyzers split water into hydrogen and oxygen with the energy being stored in the chemical bonds of hydrogen. The main factor in determining the cost of hydrogen produced by electrolysis is the cost of electricity; and in situations where renewable electricity is available at low cost, hydrogen produced by electrolysis can be competitive with that produced by steam methane reforming. Hydrogen can be stored as a gas or liquid at the generation site or transported to a different site. Alternatively, hydrogen can undergo additional chemical or electrochemical processing to generate hydrogen-rich, energy-dense hydrogen carriers, such as ammonia, methanol, or methylcyclohexane, which can be readily transported to a different location using the current infrastructure. Once relocated, the hydrogen carrier can undergo a chemical or electrochemical reaction to release hydrogen. To “regenerate” electrical energy, the hydrogen is used as a fuel for fuel cells or combusted in boilers and gas turbines. While a number of different hydrogen carriers have been proposed, such as ammonia or methylcyclohexane, each has its own set of challenges with regard to regenerating the hydrogen. For chemical storage to be competitive with other storage technologies, the cost of both the electrolyzer and the hydrogen storage method must be significantly reduced. Achieving reductions in storage and transportation costs are absolutely critical as they are considered major bottlenecks for the infrastructure required to use hydrogen as a storage medium.

4.1 Materials and Supply Chain

Some electrolyzer components require materials for which there is no domestic source in the United States, creating supply chain risk points that are commonly characterized as critical materials challenges. For example, platinum- and iridium-based catalysts used in fuel cells and electrolyzers, respectively, are precious metals with low abundance and are obtained mainly from regions outside of the United States, which will create critical supply chain issues as manufacturing volumes are ramped up. If these technologies are to be more widely adopted, it is important for the United States to find ways to source these critical materials domestically through improved recovery from obsolete parts and the creation and discovery of new domestic raw material sources. There are opportunities to decrease reliance on these materials through technological advances that lower the amount of material required or that lead to development of replacement materials.

Today's low-temperature, polymer-based electrolyzer and fuel cell systems consist of one or more fuel cell stacks and the balance-of-plant to support the operation of the stack(s). Stacks are made by assembling hundreds of individual cells together. Each cell contains an anode and cathode layer, a membrane electrode assembly (MEA), which consists of a polymeric membrane that is sandwiched between an anode and a cathode layer, integrated with gas diffusion layers, and supported by two bipolar plates. These systems share many common aspects to flow batteries (detailed in the previous section).

Alkaline and polymer electrolyte membrane (PEM) electrolyzers are commercially available today, whereas electrolyzers based on solid oxide and polymer anion exchange membranes are in development. Commercial alkaline electrolyzers were developed in the late 1800s; large systems requiring ~50 MW of power input became available in the 1920s. Alkaline electrolyzers immerse the electrodes in concentrated potassium hydroxide electrolyte, with a porous diaphragm separator sandwiched between the electrodes and bipolar plates. These systems can use inexpensive nickel-based catalysts and nickel and stainless-steel bipolar plates, but they are limited in current density and operating pressure. PEM electrolyzers use a polymer membrane, typically Nafion, as the electrolyte. The acidic environment of PEM electrolyzers requires more corrosion-resistant catalysts, such as platinum and iridium oxides, and bipolar plates made of titanium which significantly increase the cost. PEM electrolyzers offer a number of benefits over alkaline electrolyzers including higher efficiencies, higher current densities, and the ability to operate and generate hydrogen at higher pressures.

4.2 Manufacturing Challenges

There has been significant growth in the low–temperature, polymer-based electrolyzer and fuel cell industries over the past decade; however, manufacturing costs are still high because the projected cost reductions resulting from economy-of-scale production — at levels of tens to hundreds of thousands of stacks annually — have not yet been realized. Many of the current manufacturing processes are designed for low volume production and are too slow, expensive, and labor intensive. Emerging manufacturing technologies, such as roll-to-roll manufacturing, additive manufacturing (3D printing), and automation of the cell and stack assembly processes, are currently at the R&D stage and need to be scaled up to enable higher production volumes that will lower manufacturing costs.

Current manufacturing methods and the materials used for producing bipolar plates are costly. Manufacturers employ multistep, high-pressure stamping processes because of the low formability of the metals used; however, these processes compromise the flow-field channel design, resulting in suboptimal performance. Advanced manufacturing methods utilizing additive manufacturing or photochemical etching could enable rapid coating and forming of bipolar plates made of steels and other metals. The coating processes used to prevent corrosion require batch processing after the stamping. Processes for welding bipolar plates together and for applying gaskets to seal the MEA to the bipolar plate are time consuming. Although carbon composite bipolar plates provide better corrosion resistance, processing speed is an issue including the time required to seal the plates to minimize permeability to hydrogen (H_2) or oxygen/air. Automation could accelerate stack assembly process of stacking the individual cells, adding end plates, applying pressure, sealing, etc., which would significantly reduce cost.

Advanced methods for manufacturing the anode and cathode catalyst layers have the potential to improve performance and reduce cost. For example, 3D printing could be used to create unique catalyst layer structures that would improve transport of reactants within and reaction products out of the catalyst and gas diffusion layers; such an approach could lead to better fuel cell and electrolyzer performance thus reducing the amount of the expensive platinum and iridium catalysts required. Additive manufacturing could be beneficial for preparing anode supports for electrolyzers. MEAs made with gradients in the catalyst content could lead to high catalyst utilization which would lower the amount of catalysts and lead to further cost reductions.

The cost of the membranes contributes significantly to the cost of PEM fuel cells and electrolyzers, particularly at low manufacturing volumes. PEM electrolyzers require thicker, stronger membranes to withstand higher pressures, which increases cost. New manufacturing techniques that would enable use of thinner membranes would reduce cost. Increasing production volumes is expected to have a significant impact on reducing costs.

Integrating fuel cells and electrolyzers with the grid is another major challenge. Large-scale power electronics include converters for step-up voltage to integrate fuel cells to the grid and large-scale transformers to integrate electrolyzers to the grid. These devices present a number of major challenges. There are no U.S. manufacturers of power transformers greater than 10 MW. Currently, these transformers are manufactured in South Korea, with production requiring 18 to 24 months of lead time.

4.3 Workforce Needs

In addition to manufacturing needs, the participants expressed needs concerning a future workforce, which were similar to those identified and summarized in the electrochemical storage topic (Section 3.2).

5 Thermal Energy Storage

Thermal energy storage (TES) systems allow heat to be stored and recovered using three main approaches: (a) sensible heat, (2) latent heat (phase change), and (3) thermochemical heat. Among these three approaches, sensible and latent heat storage are the most technologically advanced and are used for a variety of applications. TES applications can be categorized based on the temperature of use. For high-temperature applications such as solar-thermal and process heat, storage systems typically operate at temperatures >400°C. For intermediate temperatures (100°C–400°C), applications include waste heat recovery, combined heat and power, and the like. For low-temperature regimes, storage needs are in building heating/cooling. Because of the wide range of applications and operating conditions, TES systems have their own unique challenges. In general, TES systems are relatively inexpensive compared to other storage technologies; however, they have lower energy storage densities.

For sensible heat storage, a two-tank approach is used. The storage medium, usually molten salt, is heated up and stored in the "hot" tank. During discharge, salt is moved to a "cold" tank through a heat exchanger where the heat is recovered. Typically, nitrate salts are used as the storage medium; more recently, for temperatures >700°C, chloride salts and supercritical carbon dioxide (sCO_2) are being investigated. For low temperatures, phase-change materials (PCMs) are used, which absorb heat while undergoing a phase change (e.g., melting), and they release heat upon freezing. In general, a variety of organics, salt hydrates, and even ice are used for low-temperature phase change-based storage. These systems operate in a narrow temperature range around the phase change temperature of the storage medium. Thermochemical storage systems generally have high energy storage densities as compared to the other two approaches and are based on various reversible chemical reaction systems, such as salt hydration and compound decomposition.

The manufacturing and supply chain needs for TES systems can be broadly classified into the following categories.

5.1 Materials Manufacturing Issues

- ***Storage media*** (organics/inorganic salts/particles) have issues concerning production, purity, long-term repeatable performance, and supply.

  - Mined storage materials like rocks (for sensible storage), cryogenic liquid nitrogen (LN_2) expanding to the gas phase, and metal hydrides can also be considered as thermal energy storage materials; low-cost manufacturing of metal hydrides and LN_2 is needed.
  - Manufacturing processes for dual media storage systems should be explored (e.g., sensible and encapsulated PCM systems).

- ***Containment systems*** are needed to hold the storage media: tank manufacturing using corrosion- and oxidation-resistant alloys for high-temperature storage.
  - Encapsulated PCMs suffer from expansion problems as does the containment (encapsulation) material. Using metal hydrides, ammonia, and other materials in the encapsulation leads to the expansion problems.
  - High-temperature containment is very expensive. Manufacturing of better foundation materials is needed because concrete alone is susceptible to cracking at very high temperatures.
  - Carbon steel with refractory lining is a candidate for high-temperature foundation material.
  - Coating carbon steel to replace Ni alloy and stainless steels can bring down costs.
  - Ni alloy tanks for high-temperature materials are very costly. Use of refractory-lined, high-carbon steel tanks can lower costs. Refractory lining materials manufacturing is key.
  - For low-temperature storage (i.e., 5–15°C), several entities are developing graphite encapsulation. Hybrid storage systems should be considered.

- ***Heat transfer fluids*** – For high-temperature storage uses over 700°C, manufacturers are exploring use of supercritical carbon dioxide (s-CO_2) as well as mixtures of s-CO_2 and other fluids. Manufacturing of piping/components needs to be developed to mitigate erosion/corrosion problems.

- ***Insulation materials/systems*** – These materials include firebricks, refractory, fiber-glass, ceramic felts. High-temperature insulation is expensive: it is often applied layer by layer, which makes it labor intensive. Faster processes like spraying would reduce cost. The same high costs for insulation and application must be used on low-temperature systems.

5.2 Component-/Device-Level Manufacturing Issues

1. ***Efficient heat exchange*** involves high thermal conductivity enhancers or high-performance heat exchangers to rapidly move heat in and out from the TES system. Regarding heat exchange enhancers and heat pumps/engines, the following points were raised:
   - Manufacturing of encapsulation variations are needed to reduce cost. The porosity of encapsulated PCMs or sacrificial materials may provide solutions to the expansion problem. However, at present, creating consistent porosity in encapsulated PCMs is a problem. Most work in this area is being carried out by German companies.
   - Contact resistance between fluids and encapsulated PCMs is a problem, as well as between foams and other heat transfer structures. Research to alleviate the problem

should include memory foams, composites, and the general topic of reducing contact resistance.
- Waste heat utilization is often employed in harsh environments. Improvement may be provided by coatings.
- Channel heat exchangers are being investigated as a means of effective heat exchange. Manufacturing technologies are needed.
- Compressors are limited to operating at approximately 480°C, and manufacturing of higher-temperature units is needed.
- Reversible turbo-machines in the area of dual-mode machinery could reduce cost.
- Cost reductions could be realized by integrating the heat exchange from heat pumps and engines.
- Heat exchangers in closed thermal cycles are plagued by leakage. The manufacturing of low-leakage seals and bearings is needed to improve efficiency. Mitigating leakage in units at temperatures above 200°C and in large sizes presents the toughest challenges. High-pressure seals that operate at low temperature are currently available, but not any that can operate reliably at high temperatures.

2. ***Pumps/valves***
   - Coatings on the inside of valves are expensive. Improvement is needed for high-temperature, high-pressure applications. Ni alloys, castings, and powders are all of interest.
   - Novel geometries are needed for high-temperature and high-pressure applications to reduce manufacturing costs. Additive manufacturing and casting techniques for manufacturing valves using high Ni alloys may hold promise
   - Valves without actuators that expand and contract based on an external force would reduce cost for high-temperature, high-pressure applications.

3. ***Sensors/flowmeters***
   - Manufacturing of sensors for harsh conditions represents a gap in successful applications.
   - Coating for sensors should be pursued for use in harsh environments.

4. ***Joining/integration manufacturing***
   - Repeated consistent robotic welding is needed and can reduce cost especially in the field.
   - Brazing is not an issue.

5. ***Modular storage systems***
   - Cost reduction, factory fabrication, and transportable TES are all issues in this area.

5.3 Supply Chain Issues

- Intermittent orders for molten salts are a supply chain problem. More continuous orders would lead to reduced prices.
- The quality and purity of molten salts ordered for use in storage media are inconsistent.

- One commercial representative stated that quality and purity are not a problem for his company for nitrate salts; however, chloride molten salts suffer from corrosion and hydrogen chloride (HCl) release problems.
- The need exists for lower-cost alloys for chloride salts. Nickel alloy steels are too costly. DOE is sponsoring work using additives to develop alternative alloys.

5.4 Other

- Energy density for storage is not the key parameter in TES. Instead, the driving parameter is the volume for the entire plant’s energy storage.
- Scaling from prototypes to full-scale manufacturing is a problem.
- There are several low-temperature organic PCMs available in the 5–85°C range. Some are proprietary and others are patented. There is a need for PCMs in this temperature range.
- Supply chains are not well developed and operate with low levels of competition, lowering incentives to develop innovations that can reduce material costs and/or manufacturing time.

5.5 Workforce Needs

Participants expressed the need for experienced engineers and technicians for the thermal storage industry. Retraining workers from the fossil/coal industry provides a possible path toward addressing this need. DOE could examine the pathways to help ensure this retraining outcome as the thermal industry flourishes.

6 Industries as Storage

An emerging area of interest is the adaptation of industrial processes to ensure flexible use of energy and to allow participation in various grid services. For example, electricity-intensive processes such as aluminum production from electrolysis (the Hall-Heroult process) can be made flexible using innovative thermal approaches to maintain the molten bath temperature without continuous use of electricity. This type of approach provides opportunities for demand flexibility and allows lower electricity use during peak load periods. Another example is the formation step in post-Li-ion manufacturing, where the battery is charged and then discharged in order to form a passive layer in the anode (the solid electrolyte interphase). Using the energy released from the battery to power the production of the cells or to form the next batch of cells would lower energy demand. Going beyond this simple implementation, an innovation could lead to co-optimizing the formation process to production with the aim of minimizing energy use. With the growing use of electricity in many industries, opportunities may exist to adapt the manufacturing process to ensure flexibility in demand.

While this area is nascent, a few different approaches can be envisioned, such as the following:

1. Processes that can be ramped up and down rapidly to adapt to changing energy prices will enable plants to decrease their energy demand during peak periods.
2. New process designs with built-in storage buffers (such as thermal buffers in high-temperature processes) will allow the system to maintain operation while using lower energy.
3. Utilizing energy wasted during manufacturing processes will enable plants to offset generation and use in space and time.

There are some key needs for the industrial process and manufacturing industries, where their lack is limiting current industry from developing and adopting processes with more energy use flexibility, including in the following areas:

- A clear understanding of opportunities for energy storage and thermal sharing. Even good reference documents listing thermal demands by temperature range are lacking.
- A clear understanding of the safety impacts and control challenges that result from flexible energy use.
- More demonstrations of different process adaptations to more flexible use along with clear analysis of the benefits and long-term impacts on equipment lifetime and product quality.
- Aligned metrics that assess the true value of providing energy storage and efficiency beyond the economic boundary of the facility and the typical 10- to 20-year economic planning stage, especially when many industrial systems have lifetimes of upwards of 25 years.
- R&D into design adaptation solutions that are appropriate for brown field (existing processes optimized for steady state) in addition to green field (new processes) applications.
- Development of incentives/market structures that reduce the price fluctuations and risks of providing services to the grid even if it means reducing potential profits.

In addition, the emerging areas of artificial intelligence (AI)/machine learning (ML) tools could be crucial to ensuring that energy pricing signals are used to adjust manufacturing processes automatically. Forecasting tools (e.g., solar incidence tools) integrated into these AI/ML tools would help in ensuring that industrial production makes use of the most current tools used in buildings. Engineers and designers are needed who have with cross-disciplinary training (in processes, manufacturing, controls, power grid basics, AI/data science) and are capable of connecting the dots and leading interdisciplinary design teams.

6.1 Workforce Needs

Participants expressed important views on training related to this concept:

- Industrial manufacturing lines are largely run in steady-state mode or operation, and all training and incentives are geared toward production targets, rather than minimizing cost of production. Retraining is needed to ensure that everyone on the manufacturing floor,

from workers to managers, are trained in emerging technologies to take advantage of processes as a means of storage and demand response.
- The industrial workforce needs to gain knowledge about the power grids (both electrical and natural gas), and curricula should be updated to include this topic.

7 Cross-Cutting Manufacturing/Workforce Challenges

While the above sections describe manufacturing challenges in specific technologies, there are numerous common challenges that cut across these different technologies. Details on the topics discussed follow.

7.1 Hybrid Systems

The nature of the energy storage market use cases are such that multiple technologies may need to be used in hybrid systems to satisfy requirements. Developing methods that can allow these hybrid systems to become cost effective would be important for the long-term needs of the ESGC.

7.2 Grid Integration Technologies

All of the technologies for storage discussed above will require grid integration technologies (e.g., inverters) to allow their use in the grid. For example, there are no domestic manufacturers of power transformers greater than 10 MW, thus requiring a lead time of 18–24 months for importing one of that size or larger. This gap represents an area where local expertise needs to be built back up, necessitating that a comprehensive approach is taken to help ensure that this area does not remain a bottleneck. Further workshops could be planned to explore this one area alone.

7.3 Raw Materials Availability

Many of the energy storage technologies require materials that are not readily available in the United States. Examples include platinum, iridium, cobalt, silicon, lithium, etc. In addition, some of the components that make up the devices are not manufactured domestically. Both of these aspects stifle innovation, add additional burdens for commercialization, and threaten U.S. leadership in this critical technology. A comprehensive effort is needed to ensure that these bottlenecks are also taken into consideration in the ESGC.

7.4 Translating Low Technology-Readiness-Level (TRL) Innovations to Higher TRL Prototypes

Many of the storage technologies require new innovations that are still in the low TRL stage. Moving to a higher TRL usually takes years and can be expensive. This process has been seen as a challenge in multiple industries. Examining different approaches to enable rapid movement of ideas from the laboratory to prototypes should be considered.

7.5 Workforce Challenges

The energy storage industry has an urgent need for a trained workforce at all levels to ensure that the goals of the ESGC are achieved. The gaps in the workforce cut across the education pipeline, from attracting more high school students to STEM fields; to providing increased training for engineers, technicians, and other workers in manufacturing methods; to training plant/operations managers to take advantage of emerging technologies; to expanding the workforce of highly specialized energy storage researchers. In addition, the multidisciplinary nature of many energy storage technologies necessitates training mid-level (bachelor’s and master’s degree) students in more than one discipline (e.g., chemical and mechanical engineering). Attendees felt that DOE could help facilitate training by working with community colleges and 4-year universities to incentivize developing new curricula and working with industries and the national labs to provide internship opportunities to excite the next-generation workforce. In addition to training the manufacturing workforce, attendees also commented on the urgent need for federal/state codes to protect the safety of both the communities next to large energy storage systems and the first responders (fire personnel, emergency medical technicians, etc.). Municipalities need to have their personnel, such as the AHJ (Authority Having Jurisdiction), and other permit approvers properly trained to understand the magnitude of the risks that each ESS brings to its community and how to respond. This type of effort is better coordinated at the federal/state level, as most individual communities may not be well equipped to properly assess the system technology and the best methods to respond to a system failure.

Appendix

Energy Storage Grand Challenge Manufacturing and Supply Chain
Webinar

Monday, March 16, 2020

All times listed are Central Time

10:30 a.m.	**Begin Webinar**
10:30 a.m. – 10:50 a.m.	**Welcoming Remarks and Energy Storage Grand Challenge Overview** Alex Fitzsimmons (Deputy Assistant Secretary for Energy Efficiency, EERE)
10:50 a.m. – 11:10 a.m.	**Report from the Fall 2019 Battery Manufacturing and Supply Chain Roundtable** Dave Howell (VTO)
11:10 a.m. – 11:50 a.m.	**Breakout Sessions – explanation of procedure and overview of topics:** **(I) Thermal storage** **(II) Flow** batteries **(III) Other batteries (excluding Li-ion batteries)** **(IV) Chemical storage** **(V) Industries/buildings as storage**
11:50 a.m. – 12:30 p.m.	**Moderated Question & Answer Session**
12:30 p.m. – 1:30 p.m.	**Convene to Breakout Rooms Where Leads will Give Next Directions**
1:30 p.m. – 3:00 p.m.	**Concurrent Breakout Sessions:** **(I) Thermal storage (Moderator) – Room A240** **(II) Flow batteries (Moderator) – Room A241** **(III) Other batteries (excluding Li-ion batteries) – Room B218** **(IV) Chemical storage (Moderator) – Room A253** **(V) Industries/buildings as storage (Moderator) – Room A253B**

3:15 p.m. – 4:30 p.m.	**Reconvene for Moderated Discussion on Cross-Cutting Manufacturing Challenges:** **(i) Membranes for energy storage** **(ii) Hybrid systems**
4:30 p.m.	**Webinar Concludes**

Meeting Attendee List

Full Name	Company
Al-Hallaj, Said	NETenergy
Allison, Tim	Southwest Research Institute
Amogne, Dereje	Vacuum Process Engineering, Inc.
Amy, Caleb	Massachusetts Institute of Technology
Angara, Godfrey	Illinois Department of Commerce's Office of Trade & Investment
Arsuaga, Pedro	GE Research
Atienza, Dianne	Nissan
Babinec, Sue	Argonne National Laboratory
Barron, Josh	Southern Company
Baxter, Richard	Mustang Prairie Energy
Beauchamp, Shawn	Heatric
Bilnoski, Daniel	Baker Hughes
Boetcher, Sandra	Embry-Riddle Aero Univ
Booras, George	EPRI
Borskey, Chrissy	General Electric
Boulay, David	IMEC
Bowen, John	Solar Turbines
Brix, Todd	OCO Inc.
Brown, George	Art Form inc
Bruozas, Meridith	Argonne National Laboratory
Brzowski, Rita	Argonne National Laboratory
Burke, Jennifer	Lockheed Martin
Burkhardt, Craig	Barnes & Thornburg LLP (with URBIX)
Burwen, Jason	Energy Storage Association
Calderaro, Andrea	Baker Hughes
CANNON, MATT	Shell
Capp, Bill	Bright Energy Storage Technologies
Carlisle, John	Argonne National Laboratory
Carlos, Francisco	PROMAN
casubolo, giuseppe	SQM International NV
Chamberland, Ray	General Electric
Chen, Junhong	Argonne National Laboratory/University of Chicago
Corbo, Simone	Baker Hughes
Cotton, Chip	General Electric Global Research
Cuevas-Gomez, Nicolas	Urbix Resources LLC

Dees, Dennis	Argonne
Dennis, Richard	US DOE NETL
DeRosa, Don	Eonix
Dhindsa, Kulwinder	Nissan North America
Di Federico, Gianluca	Baker Hughes
Ding, Yulong	University of Birmingham
Duggal, Anil	GE Research
Eglash, Steve	SLAC National Accelerator Laboratory
Endler, Elizabeth	Shell International Exploration & Production Inc.
Espinoza, Neva	EPRI
Estrada, Roman	Nebraska public power district
Flowers, Daniel	LLNL
Fluitt, Aaron	Argonne National Laboratory
Forsberg, Charles	Massachusetts Institute of Technology
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Gallegos, Yuri	Quasar Design Inc.
Gammell, Chris	Analog Life, LLC
Gillespie, Rebecca	UniEnergy Technologies
Graves, Christopher	Noon Energy Inc.
Greenberger, James	NAATBatt International
Grey, Christine	Siemens Gamesa Renewable Energy
Guarr, Tom	Jolt Energy Storage Technologies, LLC
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Harris, David	Commonwealth Science and Industrial Research Organisation
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Helring, Stuart	PPG
Hendrickson, Stephen	U.S. Department of Energy - Office of Technology Transitions
Hoffmann, Jeff	National Energy Technology Laboratory
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Holmberg, Johan	Cadenza Innovation Inc

Howell, David	DOE EERE VTO
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Jansen, Andrew	Argonne National Laboratory
Jenkins, Roger	Lockheed Martin
Jeter, Sheldon	Georgia Institute of Technology
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Maxson, Andrew	EPRI
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Merl, Jena	State of IL
Miller, David	NETL
Mount, Bernard	EA Engineering, Science, and Technology, PBC
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Nandwana, Vikas	Northwestern University
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Otgonbaatar, Ugi	Exelon
Ovan, Milos	Navitas Systems
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Wang, Wei	Pacific Northwest National Laboratory
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Woodside, Luke	Nuovo Pignone International
Woodside, Rigel	NETL
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The ESGC is a crosscutting effort managed by DOE's Research Technology Investment Committee (RTIC). The Energy Storage Subcommittee of the RTIC is co-chaired by the Office of Energy Efficiency and Renewable Energy and Office of Electricity and includes the Office of Science, Office of Fossil Energy, Office of Nuclear Energy, Office of Technology Transitions, ARPA-E, Office of Strategic Planning and Policy, the Loan Programs Office, and the Office of the Chief Financial Officer.

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