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Energy Storage for Manufacturing and Industrial Decarbonization (Energy StorM)

Clifford K. Ho,[1] Prakash Rao,[2] Nwike Iloeje,[3] Amy Marschilok,[4] Boryann Liaw,[5] Sumanjeet Kaur,[2] Julie Slaughter,[6] Kristin Hertz,[1] Lynn Wendt,[5] Sarang Supekar,[3] and Marisa Montes[1]

[1]Sandia National Laboratories
[2]Lawrence Berkeley National Laboratory
[3]Argonne National Laboratory
[4]Brookhaven National Laboratory
[5]Idaho National Laboratory
[6]Ames National Laboratory

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

This report summarizes the needs, challenges, and opportunities associated with carbon-free energy and energy storage for manufacturing and industrial decarbonization. Energy needs and challenges for different manufacturing and industrial sectors (e.g., cement/steel production, chemicals, materials synthesis) are identified. Key issues for industry include the need for large, continuous on-site capacity (tens to hundreds of megawatts), compatibility with existing infrastructure, cost, and safety. Energy storage technologies that can potentially address these needs, which include electrochemical, thermal, and chemical energy storage, are presented along with key challenges, gaps, and integration issues. Analysis tools to value energy storage technologies in the context of manufacturing and industrial decarbonizations are also presented. Material is drawn from the Energy Storage for Manufacturing and Industrial Decarbonization (Energy StorM) Workshop, held February 8 – 9, 2022. The objective was to identify research opportunities and needs for the U.S. Department of Energy as part of its Energy Storage Grand Challenge program.

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EXECUTIVE SUMMARY

This report provides a summary of the Energy Storage for Manufacturing and Industrial Decarbonization (Energy StorM) Workshop, held February 8 – 9, 2022. The objective was to identify research opportunities and needs for the U.S. Department of Energy as part of its Energy Storage Grand Challenge program.

DOE Programs. Representatives from DOE OE, EERE (AMO, BETO, GTO, HFTO, and SETO), and NE provided information regarding activities in each of their programs relevant to industrial decarbonization. There is strong support from many cross-cutting programs and activities within DOE, including bioenergy, hydrogen, geothermal, nuclear, solar thermal, and grid technologies.

Industry Needs. Industry representatives from Shell, Washington Mills, General Motors, ArcelorMittal, Synhelion, and Agri-Industrial Plastics Company, provided information and examples that illustrated needs and potential opportunities for energy storage in their companies. Key challenges included cost, policies, safety, physical size and integration with existing infrastructure. Key opportunities and needs included direct or indirect electrification to enable clean industrial processes, improved round-trip efficiencies, large-scale pilot demonstrations at applicable scales, improved safety and storage for chemicals (e.g., hydrogen) and gases, flexible EV charging for transportation, direct reduction of iron ore using hydrogen, and thermal storage for high-temperature process heat. Key opportunities and needs regarding energy and energy storage for industrial decarbonization are summarized in Table ES- 1.

Table ES- 1. Summary of industry needs and opportunities.

INDUSTRY	OPPORTUNITY	NEED
CHEMICALS	• Process streams and external media can provide thermal storage • Indirect electrification (e.g. electrolytic hydrogen from renewables enable chemical energy storage) • Direct electrification of process heat and electrochemical manufacturing creates opportunity to leverage battery storage	• Industry needs large-scale pilot demonstration of large-scale, long-duration storage under realistic conditions to de-risk investment • Storage technology needs high roundtrip efficiency and safe integration • Traditional processes are designed for steady state operation; need to rethink process design for flexible operation and ramp tolerance
MINERALS MANUFACTURING	• Process is primarily electrified so can already leverage battery storage and demand-response • Furnace waste heat capture and utilization can lead to significant energy savings • Thermal storage (e.g. heated particles) can store this process heat for later use. • The carbon-rich off gases can be processed to produce chemicals	• Industry needs large-scale pilot demonstration of largescale, long-duration storage under realistic conditions to de-risk investment • Promising technologies for thermal storage – e.g. heated particles – still need significant RD&D • Energy conversion and storage expertise (e.g. to chemical) is outside of business core competence

INDUSTRY	OPPORTUNITY	NEED
TRANSPORTATION	• Process is primarily electrified so can already leverage battery storage and demand-response • Opportunity exists to leverage second-life battery modules, as well as flexible EV charging, for storage.	• Industry needs demonstration of storage using second life batteries at relevant scale • Technologies that enable flexible EV charging and smart grid operations scheduling are critical
IRON & STEEL	• Hydrogen storage can play a central role since it can be used for both fuel and process reactions. • Process electrification – replacing blast furnaces with DRI-EAFs – creates opportunity to leverage battery storage • Off-gases can provide limited production buffer and operational backup	• Storage for off gases requires improved safety designs & protection • Gas storage requires large infrastructure because of low volumetric density • Industry needs large-scale pilot demonstration of large-scale, long-duration storage under realistic conditions to de-risk investment • The scale of hydrogen storage required remains significantly beyond any existing deployment
CEMENT	• Thermochemical heat requirement can be met by solar thermal energy (or cheap electricity and electric heating) and thermal storage.	• Requires technical and investment support to scale up and commercialize technologies. • Still needs a solution for the 60% of the CO_2 from process emissions

Electrochemical Storage. Speakers discussed ongoing energy storage activities with consideration of cost, safety, and environmental concerns. Several different electrochemical storage technologies were discussed, along with policy and regulatory drivers. Barriers identified for electrochemical storage for industrial decarbonization included policy, cost, and supply chain. Opportunities and needs included longer-duration electrochemical storage (> 4 hours), potentially using zinc/manganese dioxide and vanadium/redox flow batteries.

Thermal Storage. Thermal processes account for the majority of all energy needs in manufacturing and industrial processes. Challenges include efficient conveyance of heat over long distances from the point of generation or storage to the point of use, increased communication with customers and stakeholders to identify metrics and appropriately value storage, costs, workforce development, technology specific barriers, and lack of policies and investments. Needs and opportunities include efficient high-temperature storage, valuation metrics, workforce development, and appropriate consortiums or hubs for thermal storage. Thermal storage technologies that were discussed employed phase-change, reservoir, molten-salt, rock, molten aluminum, and carbon-block storage media.

Chemical Storage. Presentations included discussions of use cases, hydrogen distribution and storage, formic acid as a hydrogen carrier, ammonia as a fertilizer, fuel, and hydrogen carrier, and conversion of waste to renewable fuels. Key challenges include scaling for on-site chemical storage and chemical carriers for broad use, safety, corrosion with containment materials, efficient chemical separation processes, and costs of chemical processing and infrastructure retrofits. Opportunities include the use of energy-dense chemicals (e.g., H_2, ammonia) for long-duration storage, low-carbon fuels that are compatible with existing gasoline infrastructure, ability to move chemicals long distances, modularity, and associated R&D to address the stated challenges.

Analysis and Valuation. This session provided an overview of energy-storage modeling and analysis tools to assess the economic, emissions reduction, and resilience value of different energy storage technologies. Speakers from Strategen Consulting, Argonne National Laboratory, NREL, and TU Wien spoke about various analysis tools and methods that are available to the public, including Argonne's GREET and pumped-hydro tools, Sandia's QuEST model, NREL's REopt model, and technoeconomic analyses. A significant challenge and need is a centralized repository and classification system for the various DOE analysis and valuation tools for energy storage.

Energy StorM Feedback. Registered attendees of the Energy StorM workshop provided feedback in the areas of energy storage needs for industrial decarbonization, suitable technologies, required durations and capacities, and major challenges. Respondents stated that long-duration storage (10 – 24 hours or more) was required for industrial processes at a capacity of 1 – 100 MW. Preferences for electrochemical storage, thermal storage, and hydrogen storage were identified, along with electrical, solar-thermal, and clean hydrogen for industrial heat processes. Key challenges identified by the respondents included cost/financing/market, scale-up/de-risking, degradation/losses, materials issues, reliability, policy/regulatory, and safety/physical characteristics.

1. INTRODUCTION AND OBJECTIVES

1.1. Background

In 2020, approximately 6 billion metric tons of greenhouse gases (CO_2-equivalent) were emitted from various energy and economic sectors in the United States (Figure 1). Nearly a quarter of all greenhouse gas emissions were from the industrial sector, where a significant amount of energy is required for process heat, chemical processing, materials synthesis, and electrification. Nearly three quarters of the energy required for industry is for heating, and about a quarter is for electricity [1]. Nearly half of the heating required is considered "high temperature" (above 400 °C) for various material transformation processes [1].

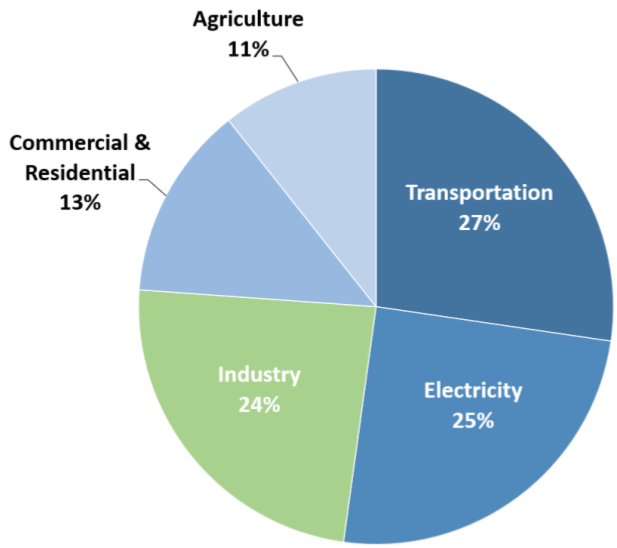

Figure 1. Total U.S. greenhouse gas emissions in 2020 (~6 billion metric tons of CO_2-equivalent). Source: U.S. Environmental Protection Agency [2].

The U.S. Department of Energy (DOE) has begun focusing its attention recently to decarbonizing these industrial processes, as evidenced in recent calls for funding by the DOE Advanced Manufacturing Office (AMO), Solar Energy Technologies Office (SETO), and others. A great deal of attention has been placed on cement and steel production, which combined contribute to ~15% of global anthropogenic greenhouse gas emissions [3, 4]. Ho et al. [5] identified a lifecycle framework to decarbonize the industrial sector, which includes development of (1) carbon-free feedstocks and chemical processes, (2) fossil-free heating and electrification, (3) novel carbon capture and sequestration methods, and (4) recycling, repurposing, and recovery for each application and industrial product.

With regard to heating and electrification, DOE is interested in identifying methods to electrify energy intensive processes, such as cement and steel production. Electric heating is used in arc furnaces to produce steel from scrap metal, and electrical heating and provide relatively lower temperature heat for drying or sterilization processes less than a few hundred degrees Celsius. For some processes that require high-temperature heating (e.g., >1000 °C for calcination processes used in cement production, battery cathode material processing, fuels production, and other decomposition/purification processes), electrification may be challenging due to costs and materials, and concentrating solar thermal technologies are being considered [6-8].

If intermittent renewable energy (solar and wind energy) is used as the primary source of energy for industrial processes, a significant amount large-capacity (GWh), long-duration (>10 hrs) electrical or thermal storage will be required to provide continuous heat and electricity. If clean hydrogen or biofuels are used to replace combustion of natural gas or coal as the heating source, new large-capacity, long-duration storage technologies will also be needed to accommodate these chemical media. Figure 2 illustrates how we can "make[1]," move, store, and use various forms of energy (electrical, thermal, and chemical) for industrial processes. This report focuses on energy storage as an enabler for the use of clean energy, but various advantages and disadvantages of storage technologies depend on the type of energy being conveyed or used.

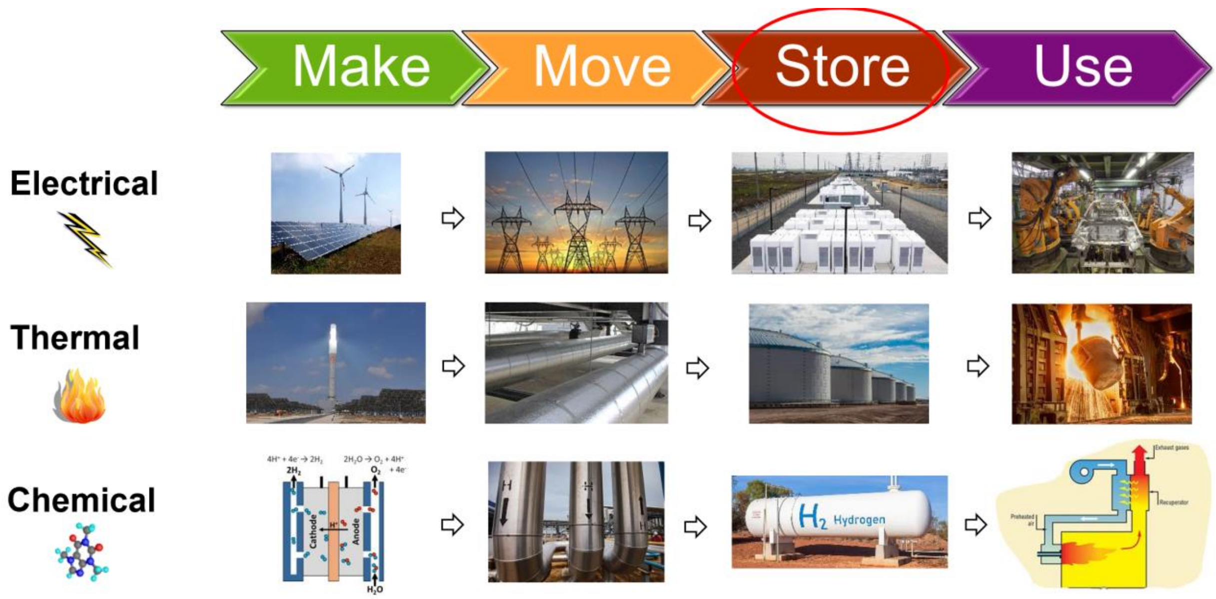

Figure 2. Illustration of how we "make[1]," move, store, and use different forms of energy (electrical, thermal, chemical) for industrial processes.

1.2. Objectives

On February 8 – 9, 2022, nine national laboratories[2] and DOE hosted an Energy Storage for Manufacturing and Industrial Decarbonization (Energy StorM) workshop. The objective of this free, virtual workshop was to bring together members of industry, national laboratories, universities, government, and other stakeholders to discuss the needs, challenges, and opportunities associated with carbon-free energy and energy storage for manufacturing and industrial decarbonization. There were 536 unique attendees on the first day of the workshop, which covered DOE programs and industry needs, and 467 unique attendees on the second day, which featured energy storage technologies and analysis/valuation methods to address the industry needs.

[1] "Conversion" of energy is more technically accurate. In this context, we use the simpler term, "make," to represent the conversion of one form of energy to another.
[2] Sandia National Laboratories, Ames Laboratory, Argonne National Laboratory, Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, Idaho National Laboratory, Lawrence Livermore National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory

This report summarizes the content and findings from the Energy StorM workshop.

1.3. Overview of Report

Section 2 provides an overview of DOE programs that are performing work relevant to industrial decarbonization, ranging from electrification in AMO to alternative heating methods in SETO, Bioenergy Technologies Office (BETO), Hydrogen and Fuel Cell Technologies Office (HFTO), Geothermal Technologies Office (GTO), and Nuclear Energy. Section 3 provides an overview of several industrial needs and challenges regarding decarbonization of their processes and products. Companies including Shell, Washington Mills, General Motors, ArcelorMittal, and CEMEX share their thoughts and perspectives on needs and opportunities. Section 4 reviews various energy storage technologies to meet the industry needs, including electrochemical energy storage (Section 4.1), thermal energy storage (Section 4.2), and chemical energy storage (Section 4.3). Finally, Section 5 provides an overview of tools and methods for analysis and valuation for different energy storage technologies.

2. DOE PROGRAMS AND RELEVANCE TO INDUSTRIAL DECARBONIZATION

The Energy StorM workshop began with introductory talks from members of DOE to discuss the importance and relevance of various DOE offices to the goals of industrial decarbonization. In general, there was strong support for sustained efforts in this area, with relevant programs and efforts highlighted in the Office of Electricity (OE), Energy Efficiency & Renewable Energy (RE), and Nuclear Energy (NE).

Kelly Speakes-Backman, Principal Deputy Assistant Secretary for EERE, leads the planning and execution of EERE's ~$3B portfolio of projects in energy efficiency, renewable energy, and sustainable transportation. Ms. Speakes-Backman spoke about the importance of creating and sustaining U.S. leadership in the transition to a global clean energy economy. As the first CEO of the Energy Storage Association, a national trade organization for the energy storage industry, she expressed the importance of working closely with industry and other stakeholders.

Joe Cresko, Chief Engineer and Strategic Analysis Lead in **DOE's Advanced Manufacturing Office (AMO)** within EERE, leads AMO's development of DOE's Industrial Decarbonization Roadmap. He presented an overview of industrial emissions, which account for over 30% of the nation's primary energy use and over a quarter of CO_2 emissions. He noted that the industrial sector energy demand growth of 30% by 2050 may result in a 15% increase in CO_2 emissions. Mr. Cresko then described AMO's four pillars of industrial decarbonization: (1) energy efficiency, (2) industrial electrification, (3) low carbon fuels, feedstocks, and energy sources, and 4) carbon capture, utilization, and storage. He also provided an overview of energy storage technologies and potential uses in industrial systems.

2.1. DOE Panel – Programs & Priorities for Industrial Decarbonization

Alejandro Moreno, Deputy Assistant Secretary for Renewable Energy, chaired this session, which includes DOE presenters from OE, NE, and EERE's offices of Hydrogen & Fuel Cell Technologies Office (HFTO), Bioenergy Technologies Office (BETO), Solar Energy Technologies Office (SETO), Geothermal Technologies Office (GTO), and AMO (Table 1). Mr. Moreno expressed the importance of working with national laboratories, academia, and industry to address industrial decarbonization.

Table 1. Summary of DOE panel.

Topic	Presenter	DOE Office
Grid Transformation Challenges	Joe Paladino	U.S. DOE Office of Electricity (OE)
Hydrogen Storage	Eric Miller	U.S. DOE Hydrogen and Fuel Cell Technologies Office (HFTO)
Bioenergy and Chemical Storage	Jay Fitzgerald	U.S. DOE Bioenergy Technologies Office (BETO)
Thermal Storage	Avi Shultz	U.S. DOE Solar Energy Technologies Office (SETO)
Geothermal/Reservoir Storage	Alexis McKittrick	U.S. DOE Geothermal Technologies Office (GTO)
Integrated Nuclear Systems	Jason Marcinkoski	U.S. DOE Advanced Manufacturing Office (AMO)

Joe Paladino is a program manager in the DOE OE and focuses on decisions processes associated with advancement and adoption of technologies and policies related to **electric grid transformation**. Joe spoke about how the electric grid will require significant re-engineering and new institutional decision processes to address transformational drivers and administration objectives. Key issues and trends included economics and social concerns, multiple owners at a distribution level, cross-jurisdictional issues, uncertain supply and demand, and electricity flow and control.

Dr. Eric Miller is a Senior Advisor in DOE's HFTO and helps to lead H2@Scale initiatives. Dr. Miller summarized **DOE's Hydrogen Shot** initiative ("1 1 1": $1 for 1 kg of clean hydrogen in 1 decade, which was launched in 2021. Pathways for clean hydrogen production include electrolysis, thermal conversion, and emerging technologies. Use cases include the electrical grid, transportation fuels, chemicals/fertilizer, blending with natural gas, and heating for high-temperature industrial processes. HFTO and other DOE offices are working together to develop production, delivery, delivery, storage, and conversion of clean hydrogen. The Bipartisan Infrastructure Law includes $9.5B for clean hydrogen, including $8B for regional clean hydrogen hubs, $1B for electrolysis research and development, and $500M for clean hydrogen manufacturing and recycling R&D.

Dr. Jay Fitzgerald is the Chief Scientist in DOE's BETO and program manager of BETO's Data, Modeling, and Analysis subprogram. Dr. Fitzgerald spoke about b**ioenergy and chemical energy storage opportunities**, focusing on biomethanation for renewable natural gas and carbon biointermediates. He explained how biomethanation—specialized bugs converting CO_2 and electricity into pipeline-quality renewable natural gas—has advantages such as high volumetric energy density (between hydrogen and liquid fuels), fast start/stop cycles, robustness, low cost, and optimized methane productivity. Biomethanation pilot plants have already been developed, and research continues to go beyond natural gas to upgrade liquid intermediates from CO_2.

Dr. Avi Shultz is the program manager for the concentrating solar-thermal power (CSP) in DOE's Solar Energy Technologies Office. Dr. Shultz summarized how CSP can provide high-temperature heat and electricity with large arrays of mirrors, a receiver, heat-transfer fluid, storage bins, and a power cycle. Over 30 GWh of molten-salt **thermal energy storage** is operating globally, and it has a very low marginal cost of additional energy capacity and duration (versus batteries, which need to be "numbered up"). Dr. Shultz gave an overview of the Gen3 CSP program, which is aimed at achieving higher temperatures (>700 °C) for the turbine inlet temperature to achieve higher efficiencies and lower system costs.

Dr. Alexis McKittrick is program manager with DOE's GTO, leading the Low Temperature & Co-Produced Resources and the Hydrothermal Resources research portfolios. Low-temperature geothermal includes temperatures up to 300 °F, which can be applied to residential or light-commercial geothermal heat pumps (entering water temperature ~40-80°F), direct use and thermal energy storage for buildings, agriculture, and manufacturing (80 – 300°F), and electric power using new organic Rankine cycles (>150°F). **Reservoir thermal energy storage (RTES)** includes aquifer and borehole thermal energy storage applications and is part of DOE's Energy Storage Grand Challenge.

Jason Marcinkoski works in DOE's NE office and focuses on expanding **nuclear energy use in industrial and transportation sectors**, using thermal energy storage to increase flexibility and response to variable grid loads, and developing nuclear-based hydrogen capabilities. Mr. Marcinkoski described a vision of the future integrated energy system to maximize energy utilization, minimize environmental impacts, and maintain affordability, grid reliability, and grid resilience with a combination of nuclear energy and other low-emission energy sources beyond electricity. He described research opportunities including expanding the use of nuclear energy for hydrogen, ammonia, synfuels, and thermal storage; advanced reactor designs, and use of existing fleet of reactors for high-temperature electrolysis.

All presentations and detailed bios of the DOE panelists can be found in the Appendix and at https://www.sandia.gov/ess/storm.

3. INDUSTRY NEEDS

3.1. Background/Context

The integration of different types of energy storage at the industrial scale can enable the transition to net-zero carbon emissions by 2050 through increasing energy efficiency, decreasing CO_2 emissions, and facilitating the shift away from fossil fuel energy sources. Current projections for global industrial energy storage envision a 3X growth to about 170GWh in 2030[9], and is expected to grow more if the aggressive decarbonization targets are to be met. However, the industrial sector has been historically driven by fossil energy and has not deployed large-scale energy storage. Increasing the adoption of storage will require overcoming deployment barriers such as cost, limited process flexibility, variability in process energy needs, as well as inertia. Consequently, integration of storage will require both advances in storage technologies and transformations in the underlying industrial process configurations.

The goal of the industrial needs session was to understand from industry the technical and economic barriers, needs, and opportunities for implementing and integrating energy storage systems into facility operations. The session brought together experts on energy storage from several manufacturing companies. The panelists brought perspectives for medium and high temperature, electrical, and thermochemical energy storage solutions. All the panelists are examining how energy storage might fit into their companies' operations and shared their insights with the workshop attendees. In addition to the industry panel, **Lori Schaefer Weaton**, President of Agri-Industrial Plastics Company, gave a showcase presentation on how her company uses solar photovoltaics and battery storage to store electricity during excess solar production and to shift the peak loads of her manufacturing process to battery storage. This is expected to reduce Agri-Industrial Plastics Company's monthly peak loads (drawing from the grid) by 6%, which reduces cost with a planned return on investment of less than 10 years and a reduction of CO_2 emissions of greater than 10,000 tons of CO_2.

The industrial panelists were as follows:

- **Elizabeth Endler**, Senior Principal Scientist, Shell: Shell is a large, multinational, petrochemical manufacturer with the potential to utilize electrical and thermal storage (across all temperature ranges). Shell participates in several components of the chemical value chain, including extraction of feedstocks, and development of base chemicals and intermediates. Examples of where Shell employs electrochemical energy storage solutions for electricity storage include a 10 MW system at its Sarnia Manufacturing Center in Corunna, Ontario, Canada and 0.6 MW system at its Brockville Lubricants Oil Blending plant in Brockville, Ontario, Canada.
- **Anne Williams**, President, Washington Mills: Washington Mills is a major manufacturer of silicon carbide and synthetically fused minerals in different oxide formulations. Its primary energy use is electricity, with level-load demand of 30-40 MW that can peak at 5,000 MW to 12,000 MW. Washington Mills electricity supply is currently 100% from the grid. The company participates in demand response programs, a form of virtual energy storage in which a facility ramps down its electrical demand as needed to better manage peak load on the grid.
- **Monica Walker**, Green Electron Accelerator, General Motors: General Motors is one of the largest automotive manufactures in the world and has the potential to utilize electrical storage. They have set a goal to source 100% of their electricity from renewable sources in

the US by 2025, and globally by 2035. Energy storage will play a key role in their strategy for meeting this goal. Another key component will be vehicle-to-grid technology, where renewable electricity is stored in vehicle batteries which can be used to support the grid when needed to meet demand, rather than utilities turning on fossil fuel resources. Furthermore, tracking real-time grid carbon emissions to support minimization of its electricity-based emissions is another central component of their energy strategy.

- **Hélder Da Silva**, Group Expert for Energy, ArcelorMittal: ArcelorMittal is one of the largest steel producers in the world, producing 71.5 million tonnes of crude steel in 2020. They have the potential to utilize thermal, chemical, and electrical energy storage. They have set an aggressive carbon reduction goal of 25% by 2030. The steel industry is experienced in energy storage, with current storage capabilities for coal, LPG, waste gas (in the form of blast furnace gas, for example). Storage is used as a buffer, for pressure regulation, and operational safety back-up.
- **Gianluca Ambrosetti**, CEO, Synhelion. Synhelion is a technology company working with CEMEX, one the world's largest cement producers, to develop a solar thermal solution for its operations. Cement production is an energy-intensive process with temperature needs from 300C to 1700C. The majority of the industry's energy needs are thermal, currently served by fossil fuels. Similar to steel production, a large portion of its carbon footprint (62%) is from non-combustion sources

3.2. Challenges/Barriers

The panelists spoke to several of the challenges and barriers associated with implementing energy storage within their operations now or in the future. These challenges include **cost, location, safety, and physical size**, which is governed by energy and power needs.

Cost was highlighted by many of the panelists as a key barrier. Currently, the costs of energy storage do not justify their benefits, particularly when comparing to the cost of natural gas which is often the incumbent energy source that storage would replace. For example, Washington Mills has the potential to use of- gas CO_2, but the chemical synthesis technology still needs to be proven on a pilot scale. The company would like to see energy storage solutions demonstrated at other facilities first before implementing at their own. This would de-risk the implementation while also providing a clearer picture of the costs and savings.

One way to defray costs is to avail of **regional policies and energy storage opportunities**. General Motors stated that time-of-use (TOU) electricity rates influence how they operate plants/process lines and incorporate demand response efforts within our manufacturing footprint. TOU rates facilitate battery storage by allowing a facility to charge off the electric grid when electricity rates are low and discharge to plant operations when rates are high. Location also dictates the feasibility of some energy storage solutions. Some energy markets support demand response opportunities more than others, such as PJM. ArcelorMittal highlighted that biofuels are an option only for plants that are near to biofuel sources. This suggests that the costs and any challenges associated with transporting biofuels significantly counterbalance their benefits.

Safety was cited as a significant concern for many of the companies represented by the panelists. Shell highlighted the need to ensure that storage and its associated electronics can safely co-exist in a process environment. ArcelorMittal highlighted the need for pipeline H_2 in large part to avoid having to store H_2 onsite, which presents safety challenges. Washington Mills highlighted that options for safely turning waste gases into decarbonized fuels onsite are difficult to implement because it would require knowledge and skillsets outside of their core expertise and represent a significant departure from their typical process operations.

The panelists also agreed that **physical size** was another barrier, with the size of current energy storage systems too large for their facilities. The size of an energy storage system is dictated by the energy and power requirements of the energy demand served by the storage system. These parameters vary by industry. Shell stated the need for MW-scale storage with enough storage to meet energy demands for more than ten hours. Washington Mills expressed the need for hundreds of MW of storage at their facilities if they were to meet the demands of their operations 24-7. For thermal energy storage, the industries represented stated a need for medium to high temperature storage. Synhelion stated that the cement industry needs 600 – 1500 °C to meet the demands of its processes. Washington Mills informed attendees that their fused-minerals process operates at 2000 °C. Washington Mills highlighted that processes exist for converting their waste streams into a zero-carbon energy source, but the size of the synthesis plant is too large for their facility. ArcelorMittal also cited size as a constraint, highlighting H_2 storage in particular. However, they are finding that battery solutions for the electrical portions of their operations are becoming smaller and more attractive.

3.3. Opportunities & Needs

In the context of industrial decarbonization goals, ideal energy storage solutions for industry must be affordable, easy to integrate, and have a low footprint. Specifically, they must minimize parasitic cost burden, improve production efficiency without sacrificing safety or compliance, and avoid unnecessary space and infrastructure expansion to accommodate them at the facility. The following detail some of the needs and opportunities identified by the panelists for their respective businesses and industries.

3.3.1. Chemicals

Characteristics & storage needs: Medium-to-high temperature processes; can leverage chemical, thermal, thermochemical and electrochemical storage options

Opportunity: For the chemicals industry, process heat requirements drive energy consumption and consequently, CO_2 emissions. This creates the opportunity for electrification – direct and indirect – to act as a critical lever for decarbonizing process heat and enabling storage integration. Options for direct and indirect energy storage include electrochemical (e.g., battery), chemical (e.g., electrolytic hydrogen from renewables), as well as a range of technologies that support different applications (e.g. thermal).

Needs: Transitioning chemicals production, especially at scale requires high power (MW to GW) and long duration storage technologies characterized by high energy density, high roundtrip efficiency and safe integration. There is also need for technology demonstration at realistic scales and conditions to de-risk the technology options and overcome adoption inertia.

3.3.2. Minerals manufacturing

Characteristics & storage needs: High temperature processes; can leverage electrochemical, thermal, thermochemical, chemical storage options

Opportunity: Manufacture of synthetic, fused and engineered oxide minerals takes place in electric arc furnaces, an energy intensive and high temperature process. This creates the opportunity to directly exploit grid decarbonization and integrate electrochemical energy storage. Furnace waste heat capture and utilization can save energy (up to 40%) and thermal storage can store this process heat for later use. Silicon Carbide is produced in high-temperature furnaces and generates carbon-rich off gases that can be processed to produce syngas or fermented to yield other platform chemicals such as ethanol, isopropyl alcohol, and acetone.

Needs: While electrochemical storage is a very promising technology option for this sector, the required scale and duration (400 – 800 MW) to store and balance load is not yet practical. Pilot demonstration of storage at this scale, including economic feasibility assessments, is required to de-risk adoption. Heated particles could potentially be used for process heat storage, but this technology still needs to be demonstrated at scale. The technologies proposed for off-gas handling involve significant capital costs, carry significant risks, and are tangential to the core-business and core-competence of staff.

3.3.3. Transportation

Characteristics & storage needs: Electrically driven processes; can leverage electrochemical storage options

Opportunity: Manufacturing in the transport sector is largely electrified. Therefore, the decarbonization strategy will involve increasing energy efficiency (of manufacturing equipment), sourcing renewable energy (including virtual power purchase agreements), addressing intermittency via storage, and policy advocacy to enable the commitment necessary for a fully renewable economy. Opportunity exists to leverage second-life battery modules, as well as flexible EV charging for storage.

Needs: Demonstration of storage using second life batteries at relevant scale, as well as technologies that enable flexible EV charging/discharging to prepare the grid for extreme events is critical. Partnering with utility companies to track CO_2 emissions from the grid and scheduling operations in accordance will enable smart use of storage.

3.3.4. Iron & Steel

Characteristics & storage needs: High temperature processes; can leverage thermal, thermochemical, chemical and electrochemical storage options

Opportunity: Energy storage is critical to decarbonizing the Iron & Steel industry. Hydrogen storage can play a central role since it can be used for both fuel and process reactions. Other gas storage – oxygen, nitrogen, propane, and waste gasses – can also be used as a production buffer, operational backup, pressure regulation and energy generation. Process electrification – replacing blast furnaces with direct reduced iron (DRI)-EAFs – also creates opportunity for electrochemical battery storage to support production.

Needs: Waste gas contains carbon monoxide and other toxic gases, which requires safety designs to prevent leakage from gas storage. Moreover, gas storage – natural gas, hydrogen – requires a large storage infrastructure, so storage design optimization is essential to reduce footprint, as well as associated maintenance and costs. Like other industrial sectors, battery storage at the required scale needs demonstration at relevant scale to better understand techno-economic feasibility. Moreover, electrification will reduce waste gases and increase the demand for hydrogen (1 ton DRI requires 800 kg Hydrogen)

3.3.5. Cement Manufacturing

Characteristics & storage needs: High temperature processes; can leverage thermal and thermochemical storage options

Opportunity: Cement manufacturing is primarily driven by thermal processes, creating the opportunity to utilize renewable solar thermal energy to achieve required clinker temperature of up to 1500 °C. The calcination reactions are highly endothermic and require large heat input. Sensible heat stored in the clinker being processes is recovered. Solar thermal use provides the opportunity to leverage thermal storage to extend the operating window into nighttime and across cloud banks. Alternative pathways such as electrothermal cement manufacturing (with electric heating) create the opportunity to leverage cheap renewable power, if available.

Needs: The most immediate challenge relates to technical and investment support needed to bring newer technologies to market readiness levels. Solar-thermal powered cement manufacturing has been demonstrated at pilot scale. Integration of CO_2 separation and sequestration or reuse is essential to ensure a zero-carbon emission process since over 60% of the CO_2 emissions are intrinsic, hard-to-abate process emissions.

3.4. Summary

Table 2 provides a summary of needs and opportunities identified by the industry panelists representing chemicals, minerals manufacturing, transportation, iron and steel, and cement.

Table 2. Summary of industry needs and opportunities.

INDUSTRY	OPPORTUNITY	NEED
CHEMICALS	• Process streams and external media can provide thermal storage • Indirect electrification (e.g. electrolytic hydrogen from renewables enable chemical energy storage) • Direct electrification of process heat and electrochemical manufacturing creates opportunity to leverage battery storage	• Industry needs large-scale pilot demonstration of large-scale, long-duration storage under realistic conditions to de-risk investment • Storage technology needs high roundtrip efficiency and safe integration • Traditional processes are designed for steady state operation; need to rethink process design for flexible operation and ramp tolerance
MINERALS MANUFACTURING	• Process is primarily electrified so can already leverage battery storage and demand-response • Furnace waste heat capture and utilization can lead to significant energy savings	• Industry needs large-scale pilot demonstration of largescale, long-duration storage under realistic conditions to de-risk investment • Promising technologies for thermal storage – e.g. heated particles – still need significant RD&D

INDUSTRY	OPPORTUNITY	NEED
	• Thermal storage (e.g. heated particles) can store this process heat for later use. • The carbon-rich off gases can be processed to produce chemicals	• Energy conversion and storage expertise (e.g. to chemical) is outside of business core competence
TRANSPORTATION	• Process is primarily electrified so can already leverage battery storage and demand-response • Opportunity exists to leverage second-life battery modules, as well as flexible EV charging, for storage.	• Industry needs demonstration of storage using second life batteries at relevant scale • Technologies that enable flexible EV charging and smart grid operations scheduling are critical
IRON & STEEL	• Hydrogen storage can play a central role since it can be used for both fuel and process reactions. • Process electrification – replacing blast furnaces with DRI-EAFs – creates opportunity to leverage battery storage • Off-gases can provide limited production buffer and operational backup	• Storage for off gases requires improved safety designs & protection • Gas storage requires large infrastructure because of low volumetric density • Industry needs large-scale pilot demonstration of large-scale, long-duration storage under realistic conditions to de-risk investment • The scale of hydrogen storage required remains significantly beyond any existing deployment
CEMENT	• Thermochemical heat requirement can be met by solar thermal energy (or cheap electricity and electric heating) and thermal storage.	• Requires technical and investment support to scale up and commercialize technologies. • Still needs a solution for the 60% of the CO_2 from process emissions

4. ENERGY STORAGE TECHNOLOGIES

4.1. Electrochemical Storage

4.1.1. Background

The second day of the Energy Storage for Manufacturing started with a session on electrochemical energy storage (EES) technologies for industrial decarbonization. The purpose of the session was to take a deep dive into the specific EES gaps, needs, and potential opportunities for grid type storage that can be used to reduce the carbon footprint of industry applications. While previous sessions covered needs for energy storage for various industries, this session also discussed some of the specific technologies of interest and their benefits. The session brought together leading experts on policy and economics behind the growing need for EES in the electric grid, on power-system modeling and reliability analysis, and on relevant technologies including aqueous zinc / manganese dioxide, vanadium redox flow batteries. The panelists were as follows:

- Lakshmi Srinivasan, Sr. Technical Leader, Energy Storage, Electric Power Research Institute (EPRI)
- Sanjoy Banerjee, Urban Electric Power Inc.
- Carlo Bravero, CEO, StorEn
- Hongtao Ma, North American Electric Reliability Corporation
- Jamie Link, Vice President, Solar & Storage Product Management, EDF Renewables North America.

4.1.2. Summary of Presentations

The presentations during the session provided insights into the safety, economic, policy, reliability, and environmental factors which need to be considered when assessing the viability of EES systems for grid storage and industrial decarbonization. A summary of each presentation is given in Table 3:

Table 3. Summary of presentations in the Electrochemical Energy Storage session.

Presentation	Speaker	Description
Overview of EPRI's Electric Energy Storage Program	Lakshmi Srinivasan	The talk focused on the Electric Power Research Institute (EPRI)'s ongoing activities, which includes collecting field data from installations to characterize performance and predict reliability of energy storage systems with consideration of cost, safety, and environmental concerns. Technologies being benchmarked include Li-ion as well as emerging technologies for long duration storage. EPRI maintains a publicly available forum to advance the integration of energy storage systems through open, technical collaboration.
Energy Storage to Decarbonize the Industrial Sector Through Direct Electrification	Sanjoy Banerjee	Zinc/ manganese dioxide batteries which have application for decarbonization of the industrial sector were discussed. The technology is durable over thousands of cycles. Examples of successful deployment were described.

Presentation	Speaker	Description
Cost-Effective Vanadium Flow Battery for Energy Storage	Carlo Brovero	Vanadium redox flow technology as an alternative long duration storage technology was presented. StoreEn Technologies is developing comprehensive proprietary intellectual property for improving the technology to reduce cost.
Energy Storage for Power System Reliability	Hongtao Ma	Power system modeling, reliability analysis and standard development for the grid transformation was discussed with a focus on increasing penetration of renewable energy resources, including wind and solar, and energy storage.
Li Ion Storage and Hybrid Renewable Energy/Storage Solutions for Decarbonization of the Industrial Sector	Jamie Link	The presentation focused on policy and regulatory drivers boosting the value of energy storage on the grid. While Li-ion currently dominates the market, cost volatility affects deployment. Huge increases in demand have created opportunities for other technologies to be competitive.

4.1.3. Challenges/Barriers

The panelists highlighted several challenges in the areas of public policy, cost, and supply chain issues that impact the viability of EES deployment for industrial decarbonization.

1) **Policy** – The uncertainty in public policy and its effects on planning and forecasting was highlighted as a major concern for industrial decarbonization. In the policy space, market rules and regulations are constantly evolving. Technology viability is impacted by decarbonization goals and mandates, and renewable and storage deployment targets, which ultimately impact the justification of energy storage valuations. Policy and regulatory drivers can boost the value of storage technologies making them competitive. It is also noted that decarbonization policy requires a large penetration of synchronous retirement of generators, which is not currently being implemented.

2) **Cost** – Li-ion batteries are current economically competitive for storage durations of less than four hours. However, there is a significant need for long duration storage due to seasonal, weekly, and daily shifts in renewable energy sources and their availability, which require longer storage duration. For this application, new EES technologies are needed. However, long duration storage is still not commercially viable, thus most of the profitable business opportunity still resides in short duration storage. A clear business model for long duration storage does not exist. Companies are waiting for the market to materialize, and it is important to get pilot projects and demonstrations online to show viability of new technologies. Volatility of cost is also an issue for Li-ion technology. Lithium carbonate prices increased 4-5x in 2021 and continue to rise in 2022. Cost increases affect battery cathode and electrolyte. Lithium supply is important with new Li mines taking years to come online, lagging demand. The cost of other commodities such and Al and Cu needed to fabricate Li-ion batteries have also increased. Li cost increases may disproportionatly affect the stationary market, accelerating adoption of alternate storage technologies.

3) **Supply Chain** – Securing a domestic supply chain for EES technologies is a critical issue if the US is going to transition to a renewable energy-based grid. The lack of domestic sources for Li-ion battery raw materials creates high political and national security risks, though recycling can alleviate the risks and provide a path forward. Switching to alternative technologies with more abundant

resources can effectively mitigate these risks. For example, for zinc/manganese dioxide batteries, both Zn and Mn can rely on domestic sources with less supply chain issues. Likewise, there is a domestic supply chain for vanadium/redox flow batteries. Currently, 18% of vanadium is sourced from mining and can be mined in the United States, while the other 82% can be produced from steel refining and industrial waste.

4.1.4. Opportunities/Needs

The panelists identified medium/long duration storage (> 4 hr storage) EES technologies as a significant opportunity space where advances could lead to significant decarbonization of the industrial sector. Direct greenhouse gas emissions from industrial processes, as well as indirect emissions from electricity used by industry, are 28% of global emissions. Approximately 60% of these emissions would be impacted by zero-carbon electricity.

Two technologies—zinc/manganese dioxide and vanadium/redox flow batteries—in particular were highlighted as having potential to address medium/long duration storage. Zinc/manganese dioxide systems are fabricated from low-cost materials that have the potential of reaching a cost below $70/MWh. Current technology produced by Urban Electric power is configurable for 2 hr – 24 hr charge/discharge cycles with modular, flexible design and have been deployed as backup power for supercomputer centers. The battery components can also be domestically sourced.

Vanadium/redox flow batteries have been demonstrated to have high durability over 20,000 cycles and 100% capacity retained over lifetime. They are also 100% recyclable and can scale up easily by increasing the size of storage tanks. Currently the technology is at the beginning of its development cycle with ongoing formulations leading to reduced cost. As with zinc/manganese dioxide batteries, the active vanadium has a domestic supply chain.

A summary of the opportunity and potential solutions is shown in Table 4.

Table 4. Opportunities identified for EES.

Opportunity	Description
Medium/long duration EES Storage Technologies	There is a significant need for longer duration (> 4hr) EES technologies to account for seasonal, weekly, and daily shifts in renewable energy production. Current Li-ion is economically viable for short term storage. Scaling up to long duration storage faces two major challenges: risks of safety and resource scarcity. Zinc/manganese dioxide and vanadium/redox flow batteries may have the potential to fill this opportunity space, with the benefits to address the two major challenges.

4.2. Thermal Storage

4.2.1. Background

Thermal processes account for approximately 63% of all energy used in manufacturing and span a range from well below freezing to above 1700 °C [10]. Currently, most thermal-based processes use electricity or fossil fuels to create the temperatures/thermal environments needed. With increasing penetration of intermittent renewable energy sources, large amounts of energy storage are required. This session of the workshop explored how Thermal Energy Storage (TES) can help decarbonize manufacturing and industry. It also looked at the challenges, barriers, opportunities and needs for integrating TES to decarbonize manufacturing. The session covered a broad range of temperatures and technologies as shown in Table 5, biographies and presentations are included in the Appendix.

Table 5. Summary of TES presentations.

Company/ Presenter	Temperature range	Technology	Applications/Status/Other notes
Phase Change Solutions (Reyad Sewafta, Co-Founder & Chief Technology Officer)	-50 - 170 C	Bio-based phase change materials	Applications: built environments, data centers, cold chain/food services, refrigeration, and thermal energy storage. Status: Modular tanks from 10 to 120 tons of storage are available. PCS technology demonstrated in the chemical industry saving 43% energy cost and reduced energy consumption by 7%.
Idaho National Laboratory (Travis McLing, Research Scientist)	Up to 160 C	Reservoir (brine)	Applications: Convert excess energy into hot geothermal fluid, store excess energy in subsurface, recover hot water/brine as needed. Target is large-scale community storage – power plant, district heating/cooling Status: Need pilot projects
Malta Inc. (Bao Truong, Technical Lead, Strategic Initiatives)	High temp heat for electricity generation, Discharge heat: ~120 C	Molten salt (heat)/Anti-freeze (cold)	Applications: Targeted toward electricity generation/storage with 6+ hour duration, recovered heat can be used for industrial/district heating
Siemens Gamesa (Maxwell Steffen Cameron-Jones, Process Project Engineer)	300-600 C	Volcanic rocks	Applications: Storing renewable energy as heat in volcanic rocks, supplying heat, steam, or electricity Status: Demonstrator 130 MWh in 2019,

Company/ Presenter	Temperature range	Technology	Applications/Status/Other notes
			Commercial pilot in 2021
Azelio (Torbjörn Lindquist, Chief Technology Officer)	High temp heat for electricity generation (~600 C), discharge heat (55-65 C) for direct use	Molten recycled aluminum	Applications: Storing renewable energy as heat in recycled aluminum, supplying electricity and usable heat on demand Status: TES.POD, installations deployed
Heliogen (Paul Gauche, Head of Engineering)	Up to 1000 C	Concentrating solar, solid media storage	Applications: Renewable energy for heat, power, or fuel (green hydrogen)
Antora (David Bierman, Co-Founder)	Up to 1500 C	Carbon blocks	Applications: Storing renewable energy as heat in carbon blocks, supplying heat, steam, or electricity

4.2.2. Challenges/Barriers

1) Efficient conveyance of heat over long distance is a common problem for all TES technologies

TES provides the opportunity to store excess energy from intermittent sources (e.g. electricity or heat) as thermal energy which can then be used to generate electricity or provide direct heat for industrial processes. Providing heat without converting it to electricity will ultimately result in thermal energy at the lowest possible cost. However, transferring heat over long distances is challenging – especially for high-temperature heat. When energy sources are located far from point of use, the energy must be converted to either electricity or another medium (e.g., steam, hydrogen) which can more readily be moved to where it is needed.

2) Communication with customers and stakeholders to understand the true needs – what is the value proposition for various stakeholders?

Thermal energy is used in a wide range of industrial processes, so it is critical to understand what the customer needs (electrical power, heat, etc.), what their motivation and goals are, and what their ultimate value proposition is. As one example, Phase Change Solutions was able to recover heat from a latex-paint reactor (exothermic reaction) to lower the reactor temperature and expedite the latex cycling time. The stored thermal energy was then used to seed the next batch and reduce energy needs. While this is one very specific use case for TES, this growing industry needs agreed upon metrics that industrial customers can use to compare storage technologies (thermal, batteries, chemical, etc.) on an even playing field.

3) Customization increases cost – more plug and play solutions are required.
While each industrial process and customer has unique needs, customization comes at a cost. Azelio and Antora have modular solutions that can be scaled by adding modules. Malta Inc. uses off-the-shelf components and provides large-scale solutions to keep costs competitive while Siemens-Gamesa and Heliogen use low-cost solid storage media for large-scale thermal energy storage.

4) Need for workforce development. Labor cost and lack of skill availability is an issue.
While many of the TES technologies can take advantage of the existing workforce, some companies have unique workforce requirements. Azelio uses sodium as a heat transfer medium which requires specific skills and training that is not widely available. Phase Change Solutions has not been able to find material scientists and manufacturing labor with needed expertise in bio-based phase change materials.

5) Technology-specific challenges.
Each of the different TES technologies has its own unique challenges. For geothermal storage, changing earth subsurface can foul, change permeability, and cause chemical changes which impacts the performance. High temperature storage is currently limited by available materials and would benefit from new materials for storage and efficient transport of heat. All technologies need more pilot-scale demonstration projects that show the long-term and large-scale benefits of TES for industrial decarbonization.

6) Lack of policies and investments.
While societal pressure for decarbonization in all areas is growing, there is a lack of motivation to change in well-established industries. There is a perception that thermal energy storage is difficult to implement in mature industries and processes and that it is expensive – without external pressure (e.g. carbon tax, regulations), many industries are reluctant to invest in TES. Regulatory changes and public investment may be needed to facilitate widespread adoption.

4.2.3. Opportunities/Needs

Thermal energy storage systems can reduce the carbon footprint of and help balance supply and demand for individual facilities or power grids by storing energy and time-shifting by utilizing thermal battery technologies. As discussed in the "Industrial Needs" session, thermal storage solutions must be cost-effective, easy to implement, and space efficient. There are many opportunities for TES to contribute to decarbonizing the manufacturing sector as well as needs identified by the panelists for specific technologies and TES in general.

Opportunities:

- Direct use of stored thermal energy
  - Cold temperature TES can fulfill a wide range of needs such as vaccine shipment, food storage, and industrial cold processes
  - Low temperature TES (<150 C) provides a huge opportunity for direct heating for industrial processes, district heat, and water heating.
  - Direct use of high temperature heat to decarbonize industrial processes is a large untapped sector.

- Providing for both heat and electrical power needs of the customer.
  - High temperature TES can provide for both heat and power and be of added value to the customers.

- A value solution that can economically provide electricity while utilizing low temperature heat makes it more attractive.

- Putting a value on decarbonization
  - Recognizing the value of carbon (e.g. carbon tax) could help deployment of emerging TES technologies and provide motivation to change across various stakeholders.

Needs:

- High Temperature TES
  - Material development and optimization for high temperature energy storage.
  - Effective methods of heat conveyance over long distance.
  - Development of high R-value insulation

- Valuation and metrics for direct comparison of TES and other storage technologies
  - A clear value proposition for TES is required – why would customer need it? What are the benefits?
  - Simple tools to evaluate the impact of different storage technologies to decarbonize specific industrial processes
  - Agreed upon metrics - It is really important to have something that customers can use to compare energy storage technologies.

- Pilot demonstrations and proof-of-concept systems
  - Simple integration TES solutions are required so that the technologies are more plug-and-play.
  - Modular systems with minimum customization are needed for all temperature ranges of TES solutions so that it can be more cost-competitive.
  - Especially for grid-scale storage, there is a need for more pilot demonstrations and simple models so that customers understand the value and benefits of the TES solutions.

- Workforce Development
  - Support training for technology development, manufacturing, installation and maintenance.
  - Reach out to community colleges and training programs.
  - Additionally, outreach to plant engineers in school can help educate future workforce

- Hub or Consortium
  - Currently there is limited cross-talk between various stakeholders which is hindering adoption of TES solutions. There is a need for a close collaboration between TES providers, manufacturing and industrial sectors, utilities and researchers from national labs and academics. Something similar to following various hubs and consortia[3]—Joint Center for Energy Storage Research, HydroGEN (1.0 and 2.0),

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[3] Websites: https://www.jcesr.org/, https://h2awsm.org/, https://h2new.energy.gov/, https://hymarc.org, https://millionmilefuelcelltruck.org, https://www.fcpad.org, https://www.duramat.org

H2New, Hydrogen Materials Advanced Research Consortium (HyMARC), Million Mile Fuel Cell Truck (M2FCT), Fuel Cell Consortium for Performance and Durability (FC-PAD), and DuraMAT Consortium—that were formed to accelerate the development and deployment of battery, fuel cell, and hydrogen production technologies. Having a consortium focused on energy-storage solutions for industrial decarbonization would allow for accelerated development and deployment of TES solutions and would allow for TES providers to better present their case to regulators and policy makers. Additionally, this will ensure that solutions are best tailored to the needs of all stakeholders.

4.3. Chemical Storage

4.3.1. Background

Chemical storage offers carbon-free energy alternatives for manufacturing and industrial processes. Hydrogen, ammonia, synfuels, biofuels, and other chemicals may be viable alternatives for providing heat, feedstocks, and other energy resources for manufacturing or industrial process. Liquid and gas intermediates may serve as energy carriers to overcome geospatial distribution challenges. On-site storage of these fuels may be required to supply the intense energy requirements for industrial processes like cement and steel production. Chemical storage supports both grid-level storage and distribution (spanning large distances and quantities) needs as well as local supply and demand for both electricity and heat. A better understanding of the needs, gaps, and opportunities associated with chemical storage and its potential integration with the manufacturing and industrial sectors is needed. The Chemical Storage session included the speakers and topics listed in Table 6, and the biographies and full presentations may be found in the Appendix.

Table 6. The list of speakers in the Chemical Storage session. Biographies and full presentations may be found in the Appendix.

Company/ Presenter	Technology	Summary
Electric Power Research Institute (EPRI)/ Brittany Westlake	Grid-Level	A broad look at how the variety of decarbonization energy pathways impact end use cases with an eye on chemical pathways
SoCalGas/ Hilary Petrizzo	Grid-Level (Hydrogen)	Grid-level hydrogen distribution and geologic storage
BayoTech Inc./ Dr. Sumanth Addagarla	Hydrogen Local Production and End Use	Local, small scale hydrogen production close to end use to minimize transportation
OCOchem/ Todd Brix	Formic Acid Hydrogen Carrier	Formic acid one-step production and release to facilitate liquid hydrogen carriers

Company/ Presenter	Technology	Summary
Ammonia Energy Association/ Trevor Brown	Ammonia	Ammonia as a fertilizer, fuel, and hydrogen carrier
Enerkem/ David Lynch	Waste/biomass to synthetic gas	Enerkem produces renewable methanol and ethanol from non-recyclable, non-compostable municipal solid waste

Grid-Level: Energy Pathways to End Use, Brittany Westlake, Electric Power Research Institute (EPRI), Low-Carbon Resources Initiative

Overview

This presentation gave a broad look at how the variety of decarbonization energy pathways impact the end use cases with an eye on chemical pathways. The power sector has worked towards decarbonization through energy efficiency, cleaner electricity, and is moving towards efficient electrification that builds on the battery industry, and other low-carbon resources. The push to 100% decarbonization doesn't have the technologies at the scales in which they are needed.

At the grid level, hydrogen and other chemical carriers (ammonia, synfuels, biofuels) meet a similar need as coal and natural gas (also chemical carriers). The comparison to batteries is less relevant at this scale. With this in mind, part of the solution is indirect electrification where electricity either at the point of production (i. e. nuclear, wind, solar) or from the grid is used to convert electrical or thermal energy into a chemical carrier and then the carrier is moved or stored.

The success of 100% decarbonization is marrying production with end use applications. The specific application needs reviews that identify those areas where chemical carriers balance performance, cost, and value over the lifetime of the use. Chemical carriers are not the solution to everything.

Not only do the technologies for production, delivery, storage, and end use need to be considered, overarching areas are the safety and environmental aspects as well as the economics of the integrated energy system.

Advantages and Capabilities

- Chemical carriers provide flexibility in that production may support the grid or be locally generated.
- Indirect electrification

Challenges and Gaps

- The key challenge is in scaling chemical carriers for broad use, particularly with distribution and storage.
- Identify the application needs that optimally balance performance and cost throughout the lifetime from production to end use

- Metrics – may need to shift how metrics are measured. For example, increased production costs but lower delivery or storage cost, so the value is increased

Grid Level Hydrogen Storage, Hilary Petrizzo, SoCalGas

Overview

California has a diverse mix of energy sources including oil and gas fields, geothermal fields, wind, and solar. The challenge is what to do during the times when renewables are curtailed. This energy can be leveraged to make hydrogen, use it as a battery (storage), and integrate into grid for distribution.

A goal is to have a week of gas supply for situations when production is curtailed. Currently, this is in natural gas underground storage fields. Underground storage is dependent on regional geologic formations, so not a currently viable solution for all regions.

Salt storage has been proven for hydrogen. Oil and gas reservoirs are more common; however, they will always have residual oil or gas that require a method of separation to purify the hydrogen. To broaden the use of underground storage to oil and gas reservoirs, aquifers, or hard rock; good reservoir modeling is needed. If a system is not viable for hydrogen, it may be for carbon sequestration.

At the grid level SoCalGas sees the decarbonization pathway including:

- Electrification
- Carbon capture
- Hydrogen natural gas blending
- Hydrogen

Pipes are a good storage vessel as well. They also allow for hydrogen production to be in the dessert and use to be miles away. If hydrogen/natural gas blends are transported in the pipelines then at receipt points for hydrogen application there will need to be a separation capability. Current membrane technology is successful.

Advantages and Capabilities

- Underground salt cavern storage is a proven technology.
- As other underground storage is studied, if it isn't viable for hydrogen it may be for other gases such as ammonia or carbon.

Challenges and Gaps

- Regional H2 underground storage availability is dependent on formations. Good field modeling is needed to expand possible hydrogen underground storage beyond salt caverns.
- Good hydrogen separation from methane will be needed if storing hydrogen in depleted oil and gas residues and if hydrogen is piped with natural gas.

Hydrogen Local Production and Use, Sumanth Addagarla, BayoTech

Overview

Hydrogen spans the entire chain of make, move, store, and use in industrial applications. The value proposition is small local hydrogen hubs that produce 1000 kg/day (on ¼ acre of space) of Hydrogen and can be distributed locally. Goal is to reduce GHG with 15-25 mile distribution. DOT approved Type III cylinders (7500 psi solutions), lifetime of 15 years are a convenient solution.

Advantages and Capabilities

- Energy density: a 20 ft container has 6+ MWh of hydrogen and 3MWh Li-ion battery
- No degradation of capacity over time in Hydrogen storage cylinders.

Challenges and Gaps

- Rate of adaptation of hydrogen by industry. Smaller businesses transforming to hydrogen with needs that are balanced to production capability.
- Currently rely on SMR for production and carbon-based trucks for delivery. Conversion to clean technology

Formic Acid: OCOchem, Todd Brix

Overview

The current problem with long-duration energy storage is that renewable energy cannot be presently stored or moved at large-scale and low cost for long durations. Hydrogen can help, but the form of hydrogen is important. Green liquid hydrogen carriers (hydrogen chemically bonded with low-cost substrate like CO_2 or N_2) can be stored and moved as a drop-in compatible with ambient liquids. It can serve as a green liquid-hydrogen carrier and moved at a 90% lower cost than gas-hydrogen carriers. OCOchem's approach is to make, store, and move green hydrogen in a stable, non-flammable liquid carrier form by electro-catalytically bonding hydrogen to CO_2 as formic acid.

Advantages and Capabilities

- Volumetrically energy-dense liquid; 68% more volumetrically dense than gasoline
- The formic acid is safe at room temperature, making it easy to move around
- One-step process
- Non-flammable
- Lower cost way to make and distribute hydrogen

Challenges and Gaps

- Efficiency and cost of formation process

Ammonia, Trevor Brown, Executive Director, Ammonia Energy Association

Overview

Ammonia (NH_3) is used widely as a fertilizer, and it can be used effectively as a hydrogen carrier. It is also being considered for maritime fuel, and electric power.

Advantages and Capabilities

- Ammonia is energy dense and can be an effective energy carrier
- Storage and transport methods already exist
- Long-duration storage is possible

Challenges and Gaps

- Need to shut down or convert over ½ for the worlds current ammonia plants if one is going to decarbonize
- Trying to make "reusable" ammonia
- Reduce cost of hydrogen storage, transport, and handling

Local waste/energy: Enerkem, David Lynch

Overview

Enerkem converts non-recyclable and non-compostable municipal solid waste to renewable methanol and ethanol to address hard to decarbonize sectors such as transportation fuels and chemicals production. According to their website, Enerkem uses a thermochemical process that recycles carbon in waste or Biomass to produce a synthetic gas. The syngas is then converted to low-carbon biofuels and chemicals using catalysts. The process can be leveraged to use renewable energy directly or store renewable energy chemically by storing hydrogen in product molecules. The process can also use biomass and / or CO2 sequestration to make exceptionally low carbon intensity fuels or hydrogen.

Advantages and Capabilities

- Recycled biofuels provide a source of long-duration energy storage that can be used for industrial heat processes and transportation

Challenges and Gaps

- Policy, investment, deployment

4.3.2. Challenges/Barriers

- The size and scale of required on-site chemical storage may be significant
- Safety of chemical storage (e.g., hydrogen)
- Corrosion and reaction with containment materials
- Cost of retrofitting or installing infrastructure to accommodate the conveyance, storage, and conversion of chemicals
- GHG is a concern with usage of any of the chemicals, are we really reducing emissions – carbon utilization and CO_2

4.3.3. Opportunities/Needs

- Conveyance: Chemicals enable the "move" of the make, move, store, and use construct; chemicals are easier to transport longer distances than high-temperature heat.
- Scale
    - Ammonia industry is huge scale; what is the correct scale for hydrogen and other chemical production and storage?
    - Can implement modular scales being developed by Bayotech or have extremely large scales like ammonia (ship across seas)
- Interest in low-carbon fuels and chemicals due to its compatibility with gasoline infrastructure and use
- Chemicals allow for longer duration storage, but developing a value proposition for seasonal storage is challenging (policy needs)
- Hydrogen separation and purity may be required based on transportation and end use.

5. ANALYSIS AND VALUATION

5.1. Overview

Workshop sessions prior to this session discussed several electric and thermal energy storage technologies in the context of their technological characteristics. These discussions underscore the promise of energy storage in reducing not only the energy and carbon *intensities* of industrial processes, but also for achieving *absolute reductions* in total carbon emissions from industry by mid-century. While the driver of this workshop was the urgent need to decarbonize the industrial sector, we heard time and again from industry stakeholders about the importance of the economic and operational factors in determining the value proposition and the ultimate integration of energy storage technologies in core industrial processes.

In the analysis & valuation session, our goals were (1) to provide to industry stakeholders and other participants from DOE National Labs a brief overview of the variety of DOE-supported energy storage modeling and analysis tools that assess the economic, emissions reduction, and resilience value of various energy storage technologies, and (2) to identify and understand industry's needs for analysis support, with the objective of leveraging existing analysis tools with those needs and identifying data or analysis gaps that DOE could fill in the near future. The session was comprised of six 10-minute presentations by expert panelists from industry and DOE National Labs, followed by a discussion that solicited participants' feedback on the greatest priorities for assessing the value of energy storage and the opportunities for developing technology-level and systems-level valuation and policy databases and tools that DOE could support.

5.2. Summary of Presentations

This section details the panel of experts that was invited to discuss analysis and valuation tools for energy storage and key findings from their talks.

1. **Erin Childs**, Senior Manager, Strategen Consulting
   Valuation of Energy Storage for Manufacturing and Industrial Decarbonization
   - This talk started with outlining the scale, significance, and challenges associated with mitigating industrial greenhouse gas (GHG) emissions, calling particular attention to the need for novel and transformative industrial processes that rely on greater use of electricity. The speaker highlighted that different stakeholders need different sets of questions answered to make smart and informed technology R&D investment and deployment decisions. Different questions need different analytical tools, and therefore it is important for DOE to make it easier for industry stakeholders to be able to articulate their analysis questions and learn which DOE analysis and valuation tools are most appropriate for answering those questions. For instance, an industry looking to bio-based feedstocks and fuels as forms of chemical energy storage would want to know exactly what the life cycle emissions benefits of those technologies would be when considering both global and regional perspectives. For such analyses, the Argonne National Lab's GREET tool [11] could be useful. Another example of chemical energy storage assessment cited was that of hydrogen, and how the DOE's H2A suite of analysis tools [12] could help with techno-economic analysis of hydrogen production and transportation to understand its cost-competitiveness relative to fossil fuels under a range of scenarios. The panelist also briefly described how green hydrogen technology and infrastructure could help decarbonize refineries and high-temperature industrial processes (e.g., steel making), and marine transportation. The panelist also discussed

how co-benefits of energy storage technologies such as impacts on air quality, reliability, etc. should be incorporated into valuation tools.

2. **Patrick Balducci**, Manager – Power Systems & Market Research Group, Argonne National Laboratory
Energy Storage Valuation Tools and Methods for Industry, PSH, and Monetizing Resiliency
This talk went into quite a bit of detail into select energy storage analysis and valuation tools from DOE including Pacific Northwest National Lab's BSET and other models [13], Sandia National Lab's QuEST model [14], the Electric Power Research Institute's StorageVET model [15], National Renewable Energy Lab's REopt model [16], Argonne National Lab's PSH valuation tool [17]. The speaker discussed the various features and use cases of each of these models, including services such as bulk energy storage, arbitrage, capacity expansion, frequency regulation, power reliability, congestion relief, and demand load management. Also discussed were different methodological approaches behind these models such as optimization, heuristic and hierarchical algorithms for electricity dispatch and unit commitment, and decision-making under imperfect foresight. The speaker briefly discussed how energy storage could enhance grid resilience and how DOE tools could help with valuation of resilience benefits using damage functions, risk of injuries/fatalities or loss/interruption of production, and other risk attributes relevant to services provided by energy storage technologies using probabilistic analyses. A key point highlighted by the speaker was that no tool possesses the capability to fully capture the value of energy storage in multiple industry applications give that this value accrued at multiple levels of the electric grid as well as the end use location. As such, it is likely that industry stakeholders would have to use multiple tools in sequence or concurrently to address questions surrounding the valuation, economic, and environmental impacts of energy storage.

3. **Emma Elgqvist**, Renewable Energy Market & Policy Analyst, National Renewable Energy Laboratory
Energy Storage Analysis with REopt
   - Continuing the theme of evaluating cost savings and resilience benefits of energy storage, this talk discussed the REopt tool and its application to distributed energy technologies. The speaker called out the importance of using the correct tools, modeling parameters and scenarios in valuation of distributed energy resources since these could significantly influence the cost-benefit analysis. Starting with an overview of the modeling framework behind the REopt tool, the speaker described the structure, input data, decision variables, and outputs of the tool, which included modeling of electric as well as thermal loads. The tool considers the trade-offs that may exist between ownership costs of an energy storage technology in the context of a distributed energy resource and the savings it generates across multiple value streams in deciding optimal size and dispatch of these resources in conjunction with energy storage. The speaker then presented key findings from case studies where REopt was used to make decisions around economics, resilience, environmental emissions, and health outcomes. Of note were results that photovoltaic (PV) installations augmented with PV storage were able to provide four additional days of supply under multiple outage scenarios when compared with diesel generators at overall costs that were equal to or slightly less than diesel generators. In another example, the tool was able to estimate hourly and total emissions savings that

would result from resilience-, cost-, and health-focused objectives in the operation of PV utility and residential energy storage technologies. A simplified version of the REopt tool called REopt-Lite, which can be used for free via a web interface, was introduced at the end of this talk as a way of conducting basic first-order analyses to evaluate economic, environmental, and resiliency benefits of energy storage in industrial facilities using hourly load profiles.

4. **Franziska Schöniger**, PhD Candidate – Energy Economics Group, TU Wien, Austria
   Dispatchable Solar Power – Comparing Cost and Performance of CSP and PV with Thermal or Battery Storage
   - This talk focused on economic analysis of molten salt as a thermal energy storage (TES) technology and compared the specific costs (per kWh of electricity stored) of concentrated solar power (CSP) assisted with TES against PV with battery storage and PV with TES while trying to address the underlying research question of which system is economical for dispatchable electric solar power. Accounting for various factors such as seasonal availability of solar power for CSP and PV and seasonal variations in grid demand, site-specific costs and expected improvements in costs over time, the study [18], on which the talk was based, provided some interesting insights. The researchers found that PV + battery storage was most economical for short duration storage of 2 – 3 hours and it could be suitable for up to 10 hours of storage if battery costs drop at an optimistic rate, although the uncertainties associated with these estimates were higher than the CSP + TES option. CSP with molten salt TES was found to be more economical for medium to long duration storage (4+ hours) and had much less uncertainty in its estimates. It was also pointed out that CSP + TES systems could provide electricity and heat, and thus would have multiple value streams that could further improve its economic favorability and applicability over PV + battery systems, since it could also be used to store waste heat from industrial facilities. The speaker highlighted the importance of energy storage size in determining economic competitiveness of the two systems and pointed out that while their analysis was generalized, niche applications for each technology could exist in industry, particularly when considering co-benefits of stored electricity and heat.

5. **Jeremy Twitchell**, Energy Research Analyst, Pacific Northwest National Laboratory
   Industrial Energy Storage Policy
   - This talk focused on the policy and regulatory aspects of energy storage, particularly in the industry context. The speaker noted that decisions by industrial customers on energy storage investments are shaped in large part by policy, even when the technical and valuation case for energy storage is strong. Policies are found to not be uniform across the country, and industrial customers face different options and constraints based on where they are located. The speaker then described in detail 5 policies and regulations that facilitate the deployment and operation of customer-sited energy storage technologies, noting that these policies affect how industrial customer purchase and use their energy storage technologies and how they are compensated. The five policies included industrial rate design, investment tax credit, distributed energy storage programs, Federal Energy Regulatory Commission (FERC) Order 2222, and the Public Utilities Regulatory Policy Act (PURPA). While describing the strengths and weaknesses of each policy using real-world examples, the speaker pointed out to the vast power that

regulatory signals and incentives have in influencing deployment and use of energy storage technologies. The speaker also called to attention the nuanced nature of policy design by showing examples of policies that were designed to encourage update of energy storage technologies and reduce costs and emissions, but ended up creating perverse incentives, increased costs and/or emissions and/or inequities in certain cases. While some programs and policies have been successful in the residential sector, the speaker outlined the need for industry-specific policies that factor in the business structure, load shapes and load uncertainties, and need for a greater coordination between regional transmission and distribution system operators.

5.3. Challenges, Opportunities, and Next Steps

Several interesting discussions around topics presented emerged in the Q&A and panel discussion session that followed. There was a consensus that a centralized repository of the various DOE analysis and valuation tools for energy storage technologies and systems should be made available to the public, and that this repository should ideally have some basic intelligent features that could help industry stakeholders and analysts identify the best tool(s) for their specific needs. In response to these comments and concurrent to activities in the Manufacturing & Supply Chain Analysis and Policy & Valuation tracks within the cross-lab Energy Storage Grand Challenge – Manufacturing and Supply Chain Working Group, there is an effort to compile a list of energy storage modeling tools and capabilities from across DOE National Labs. A classification schema featuring various attributes of the energy storage technologies and the modeling tools themselves will be used to categorize a list of nearly 80+ tools and capabilities. A *draft* version of this schema is shown below in Section 5.3.1.

5.3.1. Draft Parent Classification Scheme for Energy Storage Analysis & Valuation Tools

- Type of capability
  - Tool
  - Expertise/Analysis
  - Technology
- ES technology
  - Electrochemical
  - Mechanical
  - Thermal
  - Pressure-driven
  - Chemical
  - Others
- Type of analysis
  - Planning
  - Supply chain analysis
  - Life cycle analysis
  - Technoeconomic analysis
  - Material flow analysis
  - Technology deployment and adoption
  - Siting/logistics
  - Valuation of benefits
    - Economic

        - Environmental
        - Social
        - Resilience
        - Trade-offs
- Segment
    - Whole life cycle/system
    - Extraction and raw materials
    - Manufacturing
    - Use: Energy supply
        - Generation
        - Transmission
        - Distribution
        - Cross-cutting
    - Use: Energy demand
        - Buildings and communities
        - Industry
        - Transportation
        - Cross-cutting
    - End of life
- Type of service[4]
    - Grid services
        - Peaking capacity (medium)
        - Energy arbitrage (medium + long)
        - Frequency response (short)
        - Frequency regulation (short)
        - Spin/Non-spin reserve (medium)
        - Critical infrastructure upgrade deferral (medium)
        - Resilience (short, medium and long)
    - Behind-the-meter services
        - Energy charge reduction (medium and long)
        - Demand charge reduction (medium and long)
        - Demand response (medium and long)
        - Resilience (short, medium, and long)
- Temporal resolution
    - <=15-min
    - Hourly
    - Annual
    - Decadal
- Spatial resolution
    - City or county-level
    - State-level
    - Regional (as described by a federal agency, e.g., FERC)
    - National
    - Global
- Availability[5]

[4] Short: 1-4 hours, Medium: 4-10 hours, Long: >10 hours
[5] Availability in each category could be cloud-based or standalone

    - Open source – independent
    - Open source – with lab collaboration
    - Proprietary (licensed) – full
    - Proprietary (licensed) – partial (e.g., dataset, solver, …)
- Dependencies on other models and/or datasets
- Papers, case studies and other use case examples
- Lead lab, Contact person(s)

A public-facing webpage hosted and managed by DOE Lab Partnering Services [19] is envisioned for this capabilities list, and the webpage is expected to provide guidance tools to help users select appropriate tools for their needs based on a short questionnaire. Additionally, the Policy & Valuation sub-working group and other staff at PNNL recently compiled a report [20] detailing a significant portion of energy storage valuation tools and their use cases.

Other important ideas and questions that came up during the panel discussion included (1) the need for a reliable and readily accessible database that quantifies the co-benefits of energy storage technologies; (2) the need for transparent rate databases for non-utility value streams for energy storage end users; (3) would energy storage valuation differ for industrial facilities in vertically integrated vs. wholesale markets and if so, how might those differences be captured in existing models; (4) how should industrial facilities plan integration of energy storage into their unit operations in the face of uncertainties related to tariffs, policies, distributed energy resource availability, social cost of carbon; (5) what tools exist to evaluate supply chain impacts and risks associated with energy storage materials and environmental impacts from production of energy storage technologies; and (6) there appears to be an imbalance between the number and variety of tools available for the analysis and valuation of electric energy storage and thermal energy storage technologies – this is an important gap to be filled, particularly in the context of the large proportion of industrial emissions that result from high to medium temperature unit processes with little to no thermal storage currently.

6. ENERGY STORM FEEDBACK

Feedback was solicited from the registered attendees of Energy StorM prior to the workshop. We received 169 responses with most of the respondents from industry, followed by national labs, academia, government, utilities, non-profits, and consultants. Figure 3 through Figure 6 show the results of a number of questions regarding energy storage needs, technologies, and challenges for industrial decarbonization.

With regard to industries that respondents wanted to see decarbonized, chemical and petrochemicals was the greatest, followed by cement and steel, automotive manufacturing, food processing, drying processes, and consumer good. Other areas included agriculture, glass and aluminum, biofuels, aviation, and buildings (Figure 3, right). Respondents felt that suitable technologies for energy storage for industrial processes included thermal, electrochemical, hydrogen, pumped hydro, and biofuels followed by other technologies (Figure 4, left). Carbon-free heating methods to address nearly three-quarters of industries energy requirements were identified as renewable electrical heating, solar thermal heating, and clean hydrogen. Waste heat and clean biofuels were also identified.

The required duration of energy storage systems for industrial decarbonization was identified primarily as 10 – 24 hours, followed by 4 – 10 hours and then days (Figure 5, left). The identified capacity of this required energy storage was split evenly between 1 – 10 MW and 10 – 100 MW.

Finally, the biggest challenges facing integration of energy storage for industrial decarbonization were identified as cost/financing/market barriers, followed by scale-up and de-risking, degradation losses (thermal, electrical, leaks), materials issues (supply chain, end of life, environmental impacts), reliability, policy/regulatory, and safety/physical characteristics (hazards, size).

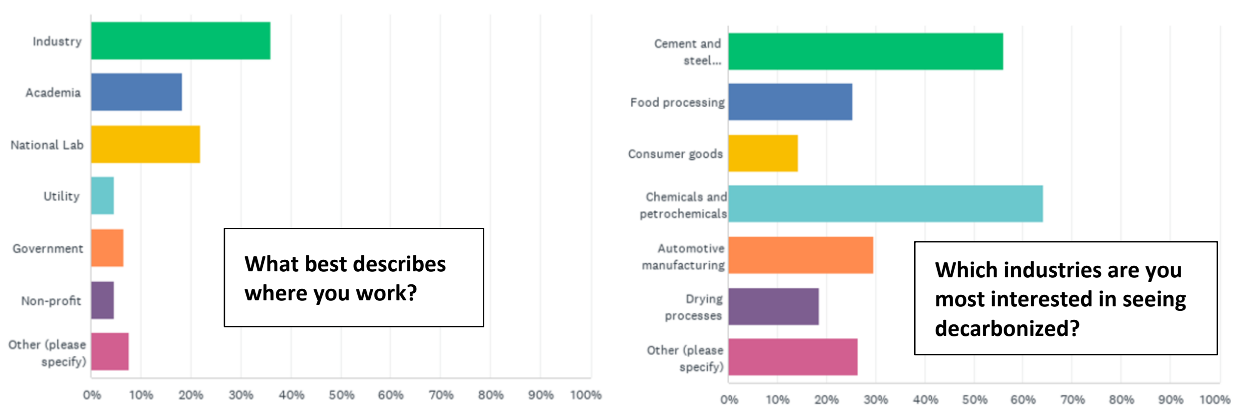


Figure 3. Institutions providing feedback (left) and decarbonization interest (right).

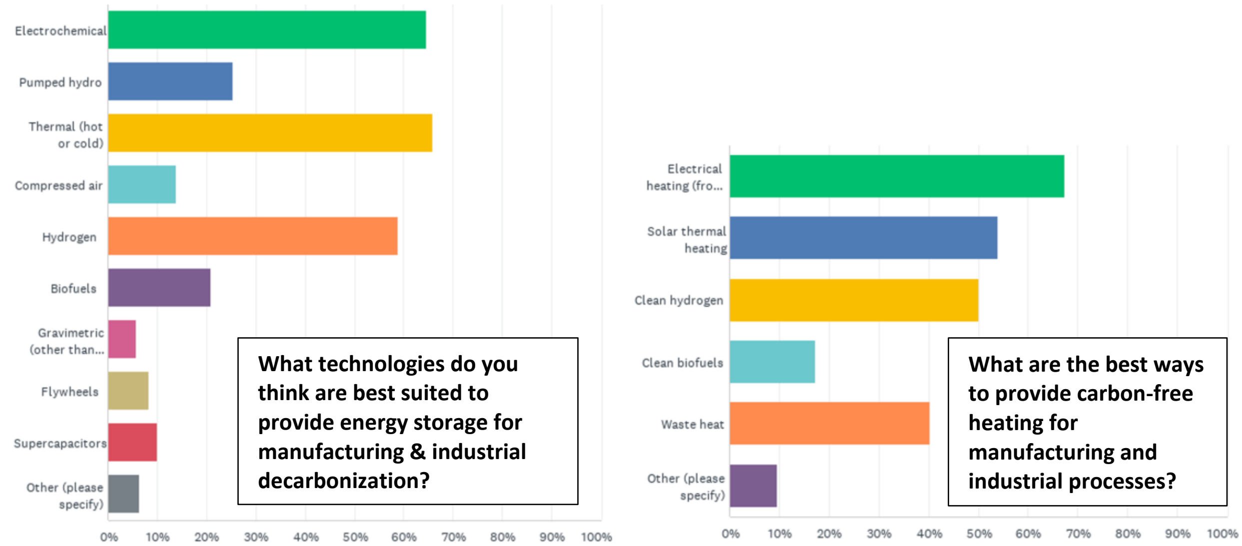


Figure 4. Technologies suited to provide energy storage (left) and carbon-free heating (right).

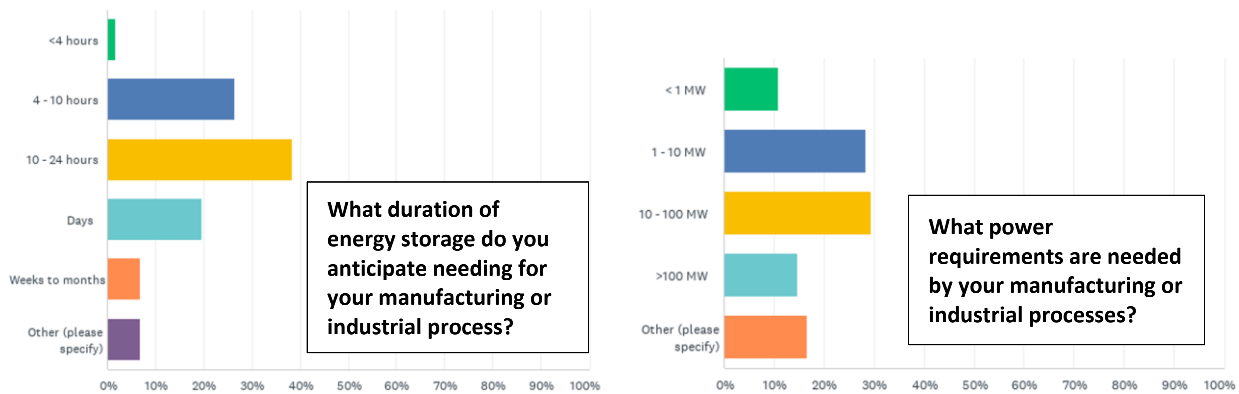
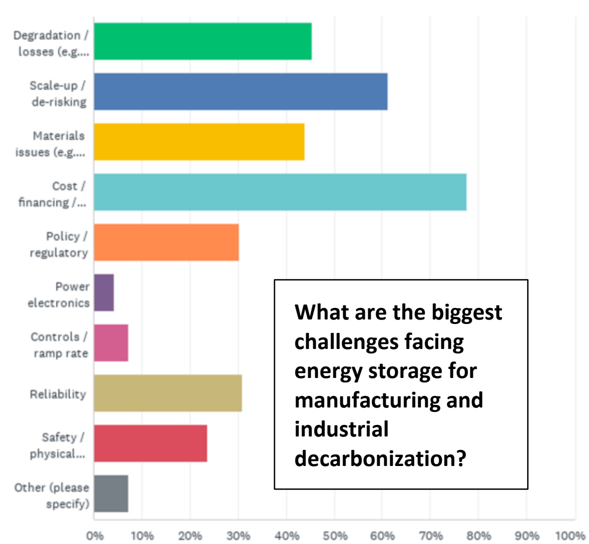


Figure 5. Energy storage duration (left) and capacity (right) requirements.



ANSWER CHOICES	RESPONSES	
Degradation / losses (e.g., thermal losses, electrical losses, liquid or gas leaks)	45.32%	63
Scale-up / de-risking	61.15%	85
Materials issues (e.g., supply chain, end-of-life, environmental impacts)	43.88%	61
Cost / financing / market	77.70%	108
Policy / regulatory	30.22%	42
Power electronics	4.32%	6
Controls / ramp rate	7.19%	10
Reliability	30.94%	43
Safety / physical characteristics (e.g., hazards, size)	23.74%	33
Other (please specify)	7.19%	10

Figure 6. Challenges facing energy storage for industrial processes.

7. SUMMARY

This report provides a summary of the Energy Storage for Manufacturing and Industrial Decarbonization (Energy StorM) Workshop, held February 8 – 9, 2022. The objective was to identify research opportunities and needs for the U.S. Department of Energy as part of its Energy Storage Grand Challenge program.

DOE Programs. Representatives from DOE OE, EERE (AMO, BETO, GTO, HFTO, and SETO), and NE provided information regarding activities in each of their programs relevant to industrial decarbonization. There is strong support from many cross-cutting programs and activities within DOE, including bioenergy, hydrogen, geothermal, nuclear, solar thermal, and grid technologies.

Industry Needs. Industry representatives from Shell, Washington Mills, General Motors, ArcelorMittal, Synhelion, and Agri-Industrial Plastics Company, provided information and examples that illustrated needs and potential opportunities for energy storage in their companies. Key challenges included cost, policies, safety, physical size and integration with existing infrastructure. Key opportunities and needs included direct or indirect electrification to enable clean industrial processes, improved round-trip efficiencies, large-scale pilot demonstrations at applicable scales, improved safety and storage for chemicals (e.g., hydrogen) and gases, flexible EV charging for transportation, direct reduction of iron ore using hydrogen, and thermal storage for high-temperature process heat.

Electrochemical Storage. Speakers discussed ongoing energy storage activities with consideration of cost, safety, and environmental concerns. Several different electrochemical storage technologies were discussed, along with policy and regulatory drivers. Barriers identified for electrochemical storage for industrial decarbonization included policy, cost, and supply chain. Opportunities and needs included longer-duration electrochemical storage (> 4 hours), potentially using zinc/manganese dioxide and vanadium/redox flow batteries.

Thermal Storage. Thermal processes account for the majority of all energy needs in manufacturing and industrial processes. Challenges include efficient conveyance of heat over long distances from the point of generation or storage to the point of use, increased communication with customers and stakeholders to identify metrics and appropriately value storage, costs, workforce development, technology specific barriers, and lack of policies and investments. Needs and opportunities include efficient high-temperature storage, valuation metrics, workforce development, and appropriate consortiums or hubs for thermal storage. Thermal storage technologies that were discussed employed phase-change, reservoir, molten-salt, rock, molten aluminum, and carbon-block storage media.

Chemical Storage. Presentations included discussions of use cases, hydrogen distribution and storage, formic acid as a hydrogen carrier, ammonia as a fertilizer, fuel, and hydrogen carrier, and conversion of waste to renewable fuels. Key challenges include scaling for on-site chemical storage and chemical carriers for broad use, safety, corrosion with containment materials, efficient chemical separation processes, and costs of chemical processing and infrastructure retrofits. Opportunities include the use of energy-dense chemicals (e.g., H_2, ammonia) for long-duration storage, low-carbon fuels that are compatible with existing gasoline infrastructure, ability to move chemicals long distances, modularity, and associated R&D to address the stated challenges.

Analysis and Valuation. This session provided an overview of energy-storage modeling and analysis tools to assess the economic, emissions reduction, and resilience value of different energy storage technologies. Speakers from Strategen Consulting, Argonne National Laboratory, NREL, and TU Wien spoke about various analysis tools and methods that are available to the public, including Argonne's GREET and pumped-hydro tools, Sandia's QuEST model, NREL's REopt model, and technoeconomic analyses. A significant challenge and need is a centralized repository and classification system for the various DOE analysis and valuation tools for energy storage.

Energy StorM Feedback. Registered attendees of the Energy StorM workshop provided feedback in the areas of energy storage needs for industrial decarbonization, suitable technologies, required durations and capacities, and major challenges. Respondents stated that long-duration storage (10 – 24 hours or more) was required for industrial processes at a capacity of 1 – 100 MW. Preferences for electrochemical storage, thermal storage, and hydrogen storage were identified, along with electrical, solar-thermal, and clean hydrogen for industrial heat processes. Key challenges identified by the respondents included cost/financing/market, scale-up/de-risking, degradation/losses, materials issues, reliability, policy/regulatory, and safety/physical characteristics.

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APPENDIX – AGENDA, BIOS, AND PRESENTATIONS FROM ENERGY STORM WORKSHOP

Tuesday, February 8, 2022: Defining Energy Needs and Priorities for Manufacturing and Industrial Decarbonization

Time (EST)	Presentation	Presenter	Organization
Workshop Introduction (Chair: Cliff Ho)			
Download Speaker Biographies			
View Workshop Introduction Recording			
11:00 AM	Introduction and Overview	Cliff Ho	Sandia National Laboratories
11:10 AM	DOE Opening Remarks	Kelly Speakes-Backman	U.S. DOE Office of Energy Efficiency and Renewable Energy (EERE)
11:25 AM	Energy Storage for Manufacturing	Joe Cresko	U.S. DOE Advanced Manufacturing Office (AMO)
11:45 AM	Industrial Decarbonization: Renewable Process Heating from Concentrating Solar Thermal	Avi Shultz	U.S. DOE Solar Energy Technologies Office (SETO)
11:55 AM	Overview of Related Industry Workshops: TMCES 2021 and IPER 2022	Jeff Moore	Southwest Research Institute
12:05 PM	**Break**		
DOE Panel - Programs & Priorities for Industrial Decarbonization (Chair: Alejandro Moreno)			

Time (EST)	Presentation	Presenter	Organization
Download Speaker Biographies			
View DOE Panel Recording			
12:15 PM	**Introduction**	**Alejandro Moreno**	**U.S. DOE Office of Energy Efficiency and Renewable Energy (EERE)**
12:20 PM	DOE OE - Grid Transformation Challenges	Joe Paladino	U.S. DOE Office of Electricity (OE)
	DOE HFTO - Hydrogen Storage	Eric Miller	U.S. DOE Hydrogen and Fuel Cell Technologies Office (HFTO)
	DOE BETO - Bioenergy and Chemical Storage	Jay Fitzgerald	U.S. DOE Bioenergy Technologies Office (BETO)
	DOE SETO - Thermal Storage	Avi Shultz	U.S. DOE Solar Energy Technologies Office (SETO)
	DOE GTO - Geothermal/Reservoir Storage	Alexis McKittrick	U.S. DOE Geothermal Technologies Office (GTO)
	DOE - Integrated Nuclear Systems	Jason Marcinkoski	U.S. DOE Office of Nuclear Energy (NE)
1:10 PM	**Q&A**		
1:30 PM	**Lunch Break**		
2:00 PM	Showcase: Real-world Example of Energy Storage for Manufacturing	Lori Schaefer-Weaton Download Speaker Biography	President, Agri-Industrial Plastics Company

Time (EST)	Presentation	Presenter	Organization
Industry Needs (Chairs: Prakash Rao and Nwike Iloeje)			
Download Speaker Biographies			
View Industry Needs Panel Recording			
2:20 PM	**Introduction**	**Prakash Rao**	**Lawrence Berkley National Laboratory**
		Nwike Iloeje	**Argonne National Laboratory**
	Chemicals & Petrochemicals	Elizabeth Endler	Sr. Principal Scientist, Shell
	Minerals Manufacturing	Anne Williams	President, Washington Mills
	Transportation Manufacturing	Rob Threlkeld	Global Manager, General Motors
	Steel Production	Helder Silva	Group Expert for Energy, ArcelorMittal
	Cement Production	Gianluca Ambrosetti	CEO, Synhelion (with contributions from CEMEX)
3:25 PM	**Q&A**		
3:50 PM	Wrap-up	Cliff Ho	Sandia National Laboratories
4:10 PM	**Adjourn**		

Wednesday, February 9, 2022: Energy Storage Technologies and Integration for Manufacturing and Industrial Decarbonization

Time (EST)	Presentation	Presenter	Organization
10:45 AM	Welcome and Review	Cliff Ho	Sandia National Laboratories
Electrochemical Storage (Chairs: Amy Marschilok and Boryann Liaw)			
Download Speaker Biographies			
View Electrochemical Storage Panel Recording			
11:00 AM	**Introduction**	**Amy Marschilok**	**Brookhaven National Laboratory**
		Boryann Liaw	**Idaho National Laboratory**
11:05 AM	Overview of EPRI's Electric Energy Storage Program	Lakshmi Srinivasan	Electric Power Research Institute (EPRI)
	Energy Storage to Decarbonize the Industrial Sector Through Direct Electrification	Sanjoy Banerjee	CUNY Energy Institute, Urban Electric Power
	Cost-Effective Vanadium Flow Battery for Energy Storage	Carlo Brovero	CEO, StorEn
	Energy Storage for Power System Reliability	Hongtao Ma	North American Electric Reliability Corporation
	Li Ion Storage and Hybrid Renewable Energy/Storage Solutions for Decarbonization of the Industrial Sector	Jamie Link	Vice President, Solar & Storage Product Management,

Time (EST)	Presentation	Presenter	Organization
			EDF Renewables North America
11:55 AM	**Q&A**		
12:15 PM	**Break**		
Thermal Storage (Chairs: Sumanjeet Kaur and Julie Slaughter)			
Download Speaker Biographies			
View Thermal Storage Panel Recording			
12:25 PM	**Introduction**	**Sumanjeet Kaur**	**Lawrence Berkley National Laboratory**
		Julie Slaughter	**Ames Laboratory**
12:30 PM	Cold Storage	Reyad Sawafta	Phase Change Solutions
12:35 PM	Malta Pumped Thermal Energy Storage System - Green Heat & Power Application	Bao Truong	Malta Inc.
12:40 PM	Phase Change	Torbjorn Lindquist	Azelio
12:45 PM	Thermocline Sensible Storage	Maxwell Steffen Cameron-Jones	Siemens Gamesa
12:50 PM	Carbon-Block Storage	David Bierman	Antora
12:55 PM	Solid-Media Storage	Paul Gauche	Heliogen

Time (EST)	Presentation	Presenter	Organization
1:00 PM	Terrestrial Storage	Travis McLing	Idaho National Laboratory
1:05 PM	**Q&A**		
1:40 PM	**Lunch Break**		
Chemical Storage (Chairs: Kristin Hertz and Lynn Wendt)			
Download Speaker Biographies			
View Chemical Storage Panel Recording			
2:10 PM	**Introduction**	**Kristin Hertz**	**Sandia National Laboratories**
		Lynn Wendt	**Idaho National Laboratory**
2:15 PM	Storing Electrons as Chemical Molecules	Brittany Westlake	Electric Power Research Institute (EPRI)
	The Role of Hydrogen Storage in Decarbonization: A Utility Perspective	Hilary Petrizzo	Commercial Development Manager CCUS, SoCalGas
	Hydrogen Storage Solutions - A Necessary First Step toward Decarbonization	Sumanth Addagarla	Vice President, Bayotech
	Using CO2 to Carry Stored Hydrogen Energy	Todd Brix	CEO, OCO Inc.
	Ammonia: The Other Hydrogen	Trevor Brown	Executive Director, Ammonia

Time (EST)	Presentation	Presenter	Organization
			Energy Association
	Enerkem Integration with Energy Storage Systems	David Lynch	General Manager R&D, Enerkem
3:05 PM	**Q&A**		
3:25 PM	**Break**		
Analysis and Valuation (Chairs: Sarang Supekar and Daniel Ginosar)			
Download Speaker Biographies			
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3:35 PM	**Introduction**	**Sarang Supekar**	**Argonne National Laboratory**
		Daniel Ginosar	**Idaho National Laboratory**
3:40 PM	Trends and Needs in Industrial Energy Storage Valuation and Policy	Erin Childs	Strategen
3:50 PM	Energy Storage Valuation Tools and Methods for Industry, PSH, Monetizing Resiliency	Patrick Balducci	Argonne National Laboratory
4:00 PM	Energy Storage Analysis Using ReOPT	Emma Elgqvist	National Renewable Energy Laboratory

Time (EST)	Presentation	Presenter	Organization
4:10 PM	Value of Thermal Energy Storage with CSP vs. PV	Franziska Schoeniger	TU Wien
4:20 PM	Industrial Energy Storage Policy - Challenges and Opportunities	Jeremy Twitchell	Pacific Northwest National Laboratory
4:30 PM	**Q&A**		
4:45 PM	Closing Remarks	Rebecca O'Neil	Pacific Northwest National Laboratory
4:50 PM	Summary and Wrap-Up	Cliff Ho	Sandia National Laboratories
5:10 PM	**Adjourn**		

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