Industrial Energy Storage Review

Katherine E. Hurst, Martin Springer, Hope Wikoff, Karlynn Cory, David Garfield, Mark Ruth, and Samantha Bench Reese

National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
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Executive Summary

As the United States moves to net-zero carbon emission by 2050 (Kerry 2021), a transition to renewable energy generation is required. However, the variable nature of renewable energy generation at high penetrations can cause imbalances in generation and transmission of electricity. These imbalances can be circumvented by the deployment of energy storage. Energy storage can add significant value to the industrial sector by increasing energy efficiency and decreasing greenhouse gas emissions (Mitali, Dhinakaran, and Mohamad 2022; Kabeyi and Olanrewaju 2022). Global industrial energy storage is projected to grow 2.6 times in the coming decades, from just over 60 GWh to 167 GWh in 2030 ("Energy Storage Grand Challenge: Energy Storage Market Report" 2020). Flexible, integrated, and responsive industrial energy storage is essential to transitioning from fossil fuels to renewable energy. The challenge is to balance energy storage capabilities with the power and energy needs for particular industrial applications. Energy storage technologies can be classified by the form of the stored energy. The most common forms include thermal, chemical, electrochemical, and mechanical storage technologies (Rahman et al. 2020). The most appropriate storage technology will depend on the unique energy needs of the industrial application.

Thermal energy can be stored and transferred by different mechanisms, including sensible heat via thermal gradients, latent heat via phase change materials (PCM), and thermochemical heat associated with chemical reactions. The pathway for sensible heat storage is the simplest, but is often constrained by defined temperature ranges, low energy densities, or large footprints. Latent heat is associated with materials that absorb and release heat at a constant temperature while undergoing a phase change. In general, PCM provide higher thermal energy storage density than sensible thermal storage materials (El-Dessouky and Al-Juwayhel 1997). Finally, thermochemical heat storage is associated with a chemical reaction that produces or absorbs heat. Chemical energy storage has the potential to store energy with high density for long-term durations.

Currently, large efforts to develop enabling technologies for chemical energy storage in the form of hydrogen fuel are being pursued by industry (F. Zhang et al. 2016). Hydrogen can be produced by renewable (water electrolysis) and nonrenewable energy (steam reforming) pathways, which can then be used in direct combustion, mixed with natural gas, or converted to electricity using a fuel cell. Hydrogen storage and transportation are important technical challenges. Pressurized gas tanks are the most common, yet expensive, method of storing hydrogen. Other efforts in chemical energy storage include chemical reactions for the conversion of CO_2 to higher grade carbon-based fuels, as well as hydrogen storage in metal-organic frameworks (Suh et al. 2012). Current research efforts include the improvement of thermocatalytic CO_2 conversion to fuels, focusing on achieving higher energy efficiency while lowering costs.

Electrochemical energy storage technologies include batteries, CO_2 electrolysis, and water electrolysis (Mathis et al. 2019; Yan et al. 2020). Batteries used in industrial energy have a fast response energy delivery. At large scales, current battery technology is appropriate for short-term stabilization of variable energy supply, whereas long-term storage is not favorable. There is a wide range of battery types, sizes, designs, operating temperatures, and chemistries applicable for industrial energy storage, where the most common battery types include Li-ion, lead acid,

and flow batteries. Electrolysis of water and CO_2 using renewably sourced electricity to produce H_2 and CH_4 (and other carbon-based fuels including methanol) is another promising energy storage technology (Yan et al. 2020). However, there are technical challenges associated with scaling the high-cost catalysts, and the overall size of electrolysis reactors.

Mechanical energy storage systems are often large-scale and have low environmental impacts compared to alternative storage methods─with pumped hydro storage systems being the most developed commercial storage technology, making up 94% of the world's energy storage capacity ("DOE Global Energy Storage Database" n.d.). Two examples of industrial-scale mechanical energy storage systems are flywheels (Amiryar and Pullen 2017; Olabi et al. 2021) and compressed air (Jidai Wang et al. 2017) that can serve as back-up power for industrial use. These systems tend to serve large-scale energy users. Flywheel technology is well-established to store excess energy by converting it into motion of a high-speed rotating disc connected to an electric motor. The stored momentum can then be used to generate on-demand electric energy. For compressed air energy storage systems, excess electricity is used to pump air into tanks and pressurize this air. When energy is needed, the high-pressure air flows through a pathway that turns a turbine and drives a generator.

Beyond the types of storage systems, there are specific industrial applications that could benefit from the deployment of energy storage systems. These applications include generating process heat; operating machine drives; and powering heating, ventilating, and air conditioning (HVAC) systems, as well as building systems. Fuel used for process heat represents 51% of energy used in industry ("Manufacturing Energy Consumption Survey" 2018). Multiple thermal energy storage methods could be combined in order to optimize energy efficiencies and reduce fuel usage. The combination of multiple energy storage systems requires the identification of key generalized parameters. For example, denoting common operating temperature ranges, energy capacities, and capital cost targets are necessary to unify energy storage solutions for process heat. However, the highly heterogeneous nature of industrial systems and the need for specific engineering solutions for process and system controls makes the deployment of a combined storage system in industrial settings an ongoing challenge.

Industrial machine drives account for 14% of industrial energy use in the United States ("Manufacturing Energy Consumption Survey" 2018). Currently, batteries offer the best suited energy storage technology to address machine drive applications due to the key features of quick response, durability, energy density, and commercial availability. Continued improvements in battery performance will enhance efficiency in machine drive applications. Lithium-ion (Li-ion) is expected to dominate the battery field for the foreseeable future. It is also possible that some utilities and regional transmission organizations might pay for support to the overall electric system, which could include machine drive storage that supports demand-side control methods, including peak shaving (Elio et al. 2021), and potentially arbitrage in a dynamic-pricing market.

Finally, coupling HVAC with industrial process heat could create unique opportunities for energy gains. The HVAC systems in industrial buildings also represent an opportunity for improved energy efficiency and energy storage. Energy loads such as chillers, packaged air conditioning, and space heating, integrated with process heat recovery, could provide improved efficiencies, see (Fabrizio, Seguro, and Filippi 2014; Brundage et al. 2014) for further details.

The purpose of this report is to provide a review of energy storage technologies relevant to the U.S. industrial sector, highlighting the applications in industry that will benefit from increased integration of energy storage, as well as the respective challenges and opportunities unique to integrating different storage technologies.

Acknowledgments

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List of Acronyms

CAES	compressed air energy storage
GHG	greenhouse gas
HVAC	heating, ventilating, and air conditioning
NREL	National Renewable Energy Laboratory
PCM	phase change materials
TES	thermal energy storage

Table of Contents

List of Figures

List of Tables

1 Current Industrial Energy Storage Landscape

As the United States moves to net-zero carbon emissions by 2050, decarbonizing energy generation and energy use will require increased use of renewable energy and fuels. In the electric sector, balancing of energy supply and energy demand is instantaneous, requiring technology innovations that will allow for new ways to balance supply and demand.

The variability of renewable electricity causes changes in generation availability and transmission of electricity that can be balanced by energy storage, thus matching the supply and demand of electricity. Energy storage can be deployed on the electricity generation supply side and at the transmission scale by utilities or independent system operators in order to support easier system-wide supply-demand balances. Many studies have explained the potential for storage to support effective and efficient U.S. electric supply, particularly variable renewable electric generation (Denholm et al. 2010; Stenclik, Denholm, and Chalamala 2017; Zame et al. 2018).

There is growing recognition that energy storage can be provided at the point of energy use, or on the demand side. In fact, energy storage is being deployed in commercial buildings and residential housing (Wood Mackenzie 2022). Historically, the industrial sector has not attempted to vary its demand to support efficient electric system balancing, nor has it used large-scale energy storage to support the U.S. electric grid. As such, the U.S. grid and its electric generation resources are required to rebalance and follow industrial load requirements.

This report reviews a number of industrial storage demand-side technologies and methods of integration at various capacities and time scales that can ensure predictable energy supply to industry while also better supporting the U.S. electric system. Through integration of complementary technologies, energy storage at the industrial scale can be realized, with the potential for large reductions in global greenhouse gas (GHG) emissions. However, many of these technologies have not reached commercial maturity and are still at the early research, development, and deployment phases. Figure 1 shows various energy storage technologies with respect to their current investment and technology risk compared to the level of maturity and commercialization ("Technology Roadmap - Energy Storage" 2014; Decourt 2013).

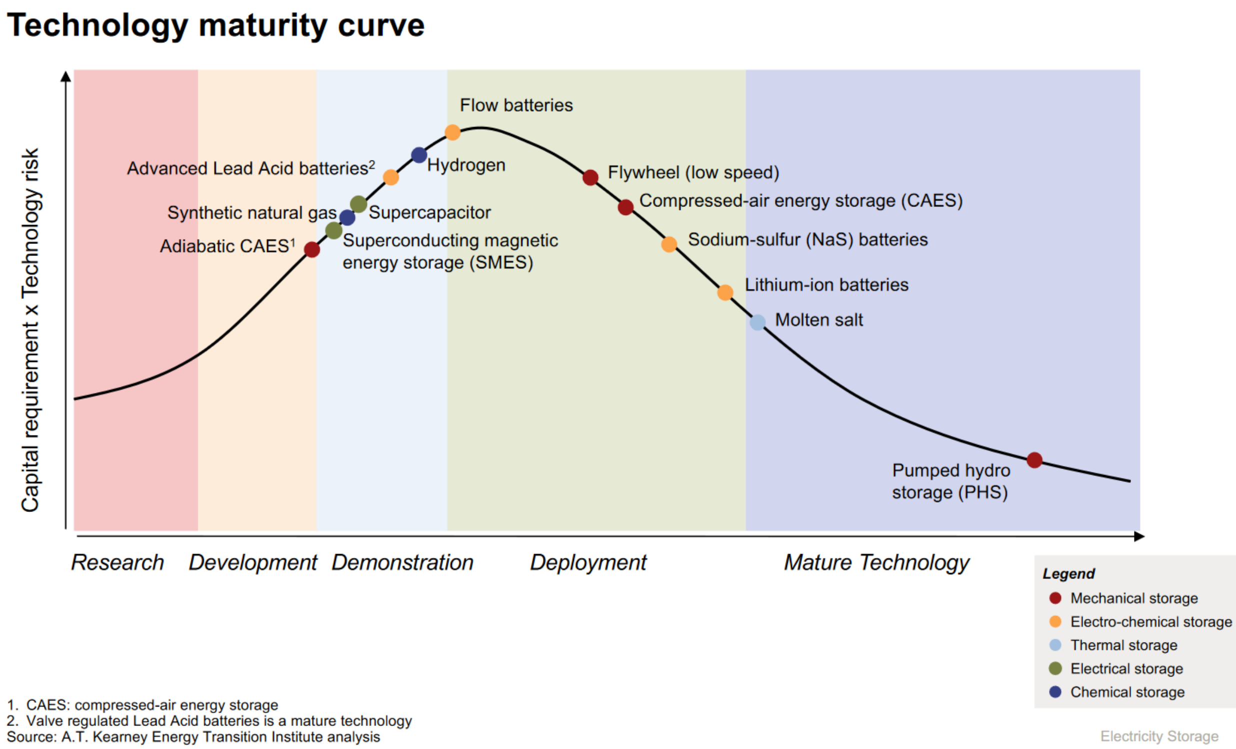


Figure 1. Capital requirement and technology risk for various energy storage technologies as a function of technology maturity

Illustration from the A.T. Kearney Energy Transition Institute (Decourt et al. n.d.).
[1]CAES is compressed air energy storage. [2]Valve-regulated lead acid batteries is a mature technology.

Currently, industry is the largest energy consumer and GHG emitting end-use sector in the world. As Figure 2 illustrates, in 2020 the industrial sector accounted for 36% of the global energy use; of this, 41% derived from natural gas, 33% from coal, and 12% from electricity ("Total Energy Monthly Data - U.S. Energy Information Administration (EIA)" n.d.). The industrial sector's primary energy requirement is thermal energy; therefore, thermal storage could be an integral technology that can reduce carbon emissions, help the industrial sector better integrate into the U.S. electric grid, and ultimately reduce overall energy costs.

For industrial energy storage to be successful and to allow industry to continue required operations, technology innovations need to be developed and operational indicators need to be standardized. Identifying key generalized parameters for storage is needed to address large segments of industrial process heat. For example, denoting common operating temperature ranges, energy capacities, and capital cost targets are necessary to unify energy storage solutions for process heat. Additionally, identifying the potential target technologies to address these common energy specifications are needed.

This report examines the different types of energy storage most relevant for industrial plants; the applications of energy storage for the industrial sector; the market, business, regulatory, and policy opportunities for industrial energy storage; and an outlook of energy storage for the industrial sector.

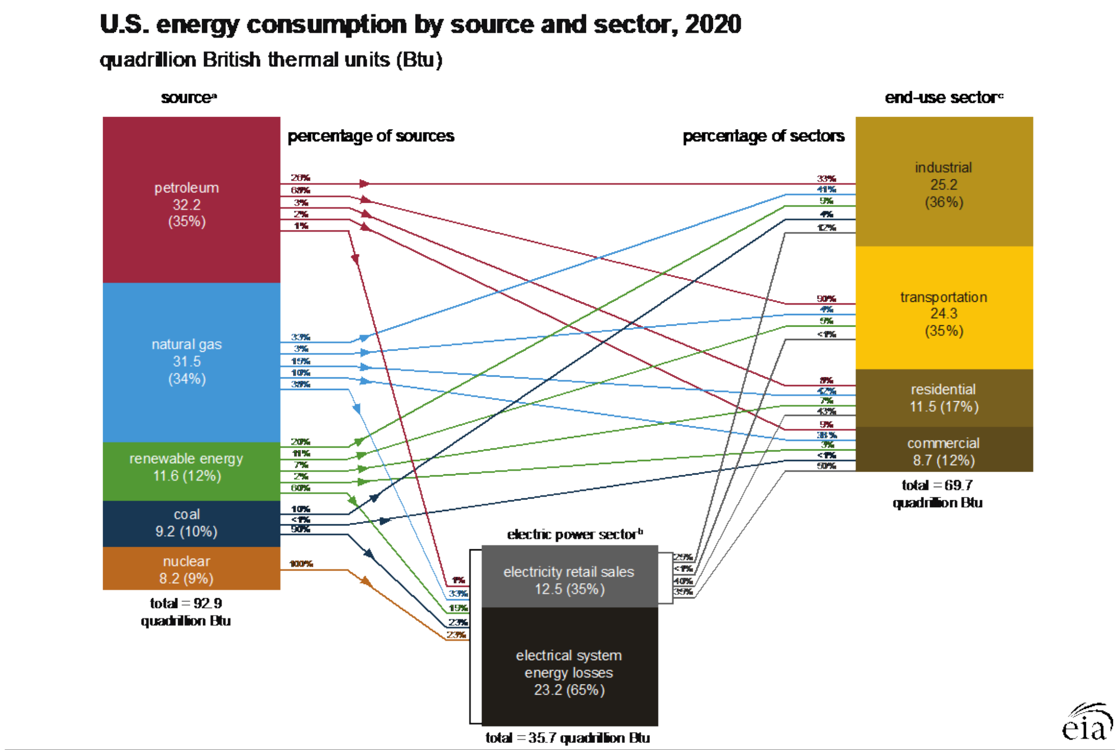


Figure 2. Current energy generation and consumption

Illustration from the U.S. Energy Information Administration ("Total Energy Monthly Data - U.S. Energy Information Administration (EIA)" n.d.).

2 Types of Energy Storage

With the goal of reducing GHG and overall energy usage in industrial applications, the world is moving away from energy stored in fossil fuels and toward applying a hybrid approach using a variety of energy storage types. In this section, we describe different types of energy storage, including thermal, chemical, electrochemical, and mechanical. Each type has multiple configurations, which can be more suitable for the different industrial storage applications. For more information on the different types of energy storage for industrial use, there are several thorough reviews, such as (Behabtu et al. 2020; Koohi-Fayegh and Rosen 2020; Nguyen et al. 2017).

2.1 Thermal Energy Storage

The three main types of thermal energy storage include sensible heat, latent heat, and thermochemical heat. Sensible heat storage relies on the temperature change of a material as heat is absorbed or released. Latent heat is associated with a substance absorbing/releasing heat while changing phase, usually at a constant temperature, as seen in the change from ice to water at constant indoor room temperature. Thermochemical heat storage is associated with the heat of a chemical reaction that produces or absorbs heat.

2.1.1 Sensible Heat

Sensible heat-based thermal storage systems can be inexpensive and have a simple design. It is also possible to aggregate heat across many different heat sources of different temperatures. A simple system could be imagined by cool air flowing over a hot rock that increases the temperature of the air, which in turn heats a room. Equation 1 describes sensible heat, Q, as determined from the volume, density, and specific heat capacity (V, ρ, and C_p, respectively) for the hot material and the difference in temperature. To accomplish successful thermal energy storage, the desired properties include a smaller volume, higher density, and a high specific heat capacity. Examples of common materials for sensible heat thermal storage include water, rocks, sand, and molten salt. Compared to the other two thermal energy storge types, sensible heat has the lowest energy density and, therefore, requires a large footprint.

$$Q = V\rho C_p \Delta T \qquad (1)$$

2.1.2 Latent Heat

Latent heat is associated with materials that absorb and release heat at an almost constant temperature, while changing phase reversibly from either solid to liquid, liquid to gas, solid to gas, or vice versa. Additionally, solid-solid PCMs exist that retain their bulk properties while undergoing a phase transition from a (solid) crystalline or semi-crystalline phase to another (solid) amorphous, semi-crystalline, or crystalline phase (Fallahi et al. 2017). Latent heat thermal storage allows for higher energy densities than sensible heat storage and reductions in the footprint size. The near-constant temperature at which the material phase change occurs allows for tighter process control. However, specific materials are required that undergo the desired phase transition in a usable temperature range that fits the input/output requirements of the system. The latent heat energy can be described by Eq. 2, where n is the number of moles of the material, and H_m is the heat of the phase change (i.e., molar heat of vaporization).

$$Q = n\Delta H_m \qquad (2)$$

Many different PCMs have been investigated, including organic (paraffins and polymeric materials), inorganic (salts and salt hydrates), and eutectic materials. They share common desired properties of PCMs that are listed in Table 1. There are a number of thorough reviews for PCM materials and their usage in energy storage applications, such as (Pielichowska and Pielichowski 2014; Sarbu and Dorca 2019).

Table 1. Desirable Material Properties for PCMs

Thermal Properties	Physical Properties	Kinetic Properties	Chemical Properties	Economics
(1) Melting temperature in desired operating range	(1) Small vapour pressure at operating temperatures	(1) Little or no super-cooling during freezing	(1) Chemical stability	(1) Abundant
(2) High latent heat of fusion per unit volume	(2) Small volume variation on phase change	(2) High nucleation rate to avoid super-cooling	(2) Complete reversible freezing/melting cycle	(2) Large-scale availabilities
(3) High specific heat	(3) High density	(3) Adequate rate of crystallisation	(3) Compatibility with container materials	(3) Effective cost
(4) High thermal conductivity of both phases			(4) No toxic, no flammable and no explosive material	

Source: *International Journal of Energy Research* (Dicaire and Tezel 2013)

2.1.3 Thermochemical Heat

Thermochemical heat storage derives from reversible endothermic/exothermic reactions that store energy in the chemical potential of the materials. Charging of energy (i.e., energy storage), occurs during an endothermic reaction, and the discharge of energy (i.e., energy release) comes from the exothermic reaction.

The heat stored (Q) is shown in Eq. 3, where X is the reaction conversion, n_b is the number of moles for the limiting reactant, and ΔH_r the molar enthalpy of the reaction. Thermochemical reactions can have a higher energy density than latent heat storage. However, sometimes the heat required for an acceptably fast kinetic reaction rate can result in an inefficient process and the loss of energy. Heat storage using thermochemical pathways also requires more complex engineering than other forms of thermal storage.

$$Q = X n_b \Delta H_r \qquad (3)$$

Adsorption (exothermic) and desorption (endothermic) of a gas onto solid material is one example of thermochemical energy storage. An example of such a process is the reversible reaction of CaO and CO_2 to form the solid oxide $CaCO_3$.

There are various factors that may motivate industrial processes to transfer thermal energy into process heating systems. A fuel-driven process is directly dependent on fuel costs that may fluctuate over time. Alternatively, a thermally driven process reduces the variable costs by decreasing the amount of fuel used but requires a higher capital investment upfront.

2.2 Chemical Energy Storage

In chemical storage, energy is transferred and stored by creating and breaking chemical bonds, creating the potential for long-term, high-density energy storage which can be retrieved on demand. Chemical energy storage technologies enable the reversible transformation and storage of (excess) electricity, heat, or other forms of energy in chemical bonds. Growing interest in chemical energy storage is driven by the long-term stability and high energy density compared to thermal or electrochemical storage (Elmegaard et al. 2013).

Technologies for chemical energy conversion and storage range from direct power to chemicals (e.g., electrolysis for hydrogen production) to indirect or hybrid systems involving secondary fuel/chemical reforming. Spatio-temporal variations in manufacturing systems create conditions for the availability of excess heat or electricity, which can be stored in chemical bonds and released back to the process when needed. One of the additional benefits of chemical energy storage is that the produced chemicals can be used in other applications, including fuels for transportation, and feedstock for chemicals manufacturing (Lanzafame et al. 2017). One of the most widely studied forms of chemical storage is hydrogen, which has great potential for providing large-scale, long-duration storage, with the added advantage of being a versatile fuel. Thermal CO_2 hydrogenation is also attracting a lot of interest because of the added advantage of CO_2 utilization (Fan and Tahir 2021).

2.2.1 Hydrogen

Hydrogen is a high-energy-density carrier that has great potential to decarbonize the industrial sector. Hydrogen can be produced from renewable or nonrenewable energy sources and can be stored physically either as gas or liquid, or on the surfaces of solids through adsorption or within solids through absorption ("Hydrogen Storage" n.d.). The hydrogen molecules serve as the storage medium. Hydrogen can be used as fuel to deliver energy directly or can be converted to electricity via a fuel cell.

Hydrogen production is currently 75 million tons worldwide, with 76% produced by steam reforming of methane, and 23% by coal gasification; both routes give rise to carbon emissions (World Nuclear Association 2021). Hydrogen production from methane pyrolysis provides a route to produce H_2 without CO_2 byproduct by heating CH_4 to >900˚C in an anaerobic atmosphere that produces only hydrogen and solid carbon. Techno-economic analysis of this process has shown that if solid carbon can be sold above $3/kg, H_2 from methane pyrolysis could be profitable (assuming $3/MMBtu) (Dagle et al. 2017). Therefore, developing direct synthesis of high-value, high-volume solid carbon products using methane pyrolysis presents an interesting opportunity to create inexpensive H_2 (Taylor et al. 2021).

Hydrogen storage and transportation is an important technical challenge. Currently, pressurized gas tanks are most commonly used to store hydrogen. However, high-pressure tanks require strong materials, such as carbon fiber—which increases cost—as well as gas compressors. Liquefaction can increase the volumetric energy density of hydrogen (theoretical energy density is 2.8kWh/L), but it also incurs costs associated with liquefaction and the active cooling required to maintain hydrogen at 20 K during storage.

New research in hydrogen energy storage could improve the prospect of using hydrogen for industrial energy storage. The development of solid-state hydrogen storage materials, including sorbent materials, metal, and chemical hydrides, is an active area of research. In these reversible systems, the hydrogen carrier can be recharged to hold the hydrogen. For example, toluene/methylcyclohexane, which can be stored and transported at ambient conditions, can be used as a method for carrying hydrogen. A thorough analysis of energy and economic cost for the chemical energy storage including H_2, CH_4, CH_3OH, NH_3 can be found in (Dias et al. 2020).

Hydrogen can be combusted directly to recover the stored energy, or mixed with natural gas in different proportions to optimize the combustion system. Direct combustion of hydrogen can be used to create energy in a process that results in H_2O as the reaction product and does not directly produce carbon. The adiabatic flame temperature for hydrogen in air is about 2,045˚C, but combustion in that temperature region requires high-temperature-resistant materials and the prevention of NO_x formation, which presents a major technical challenge. By controlling the H_2 and O_2 mixture prior to combustion, the flame temperature can be regulated, which greatly reduces NO_x formation. Ongoing research is being performed on whether existing combustion engines can be modified to handle various fuel-hydrogen mixture compositions, while achieving high thermal efficiencies and low emissions requirements. Recent simulations have helped to bridge the gap between lab-scale experiments and larger industrial processes (Amaduzzi, Ferrarotti, and Parente 2021; Ferrarotti et al. 2018).

2.2.2 Thermal CO_2 Hydrogenation

The conversion of CO_2 to value-added fuels such as methane can be converted via electrochemical or thermocatalytic processes (Vogt et al. 2019). The thermally driven Sabatier reaction, shown in Eq. 4, uses the energy stored in hydrogen. This reaction can be 100% selective and 80% energy efficient (El Sibai, Rihko-Struckmann, and Sundmacher 2015). Use of the energy released from the exothermic reaction could also be integrated into other on-site process heating. Importantly, the infrastructure and technology for methane transportation and storage is already developed, although not widely implemented.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad \Delta H_{298} = -165 \text{ kJ mol}^{-1} \tag{4}$$

CO_2 can also be converted to more complex chemical fuels such as olefins, aromatics, and gasoline via Fischer-Tropsch synthesis or methanol reaction-based hydrogenation over select catalysts (Ye et al. 2019). This potential for conversion to a broad array of chemical fuels demonstrates the promise of a long-term, stable storage solution. However, these technologies will require improvements in cost and efficiency. More specifically, continued cost reduction in catalyst materials and continued progress in H_2 integration with captured CO_2 for synthetic hydrocarbon synthesis are necessary for advancing the technology.

2.3 Electrochemical Energy Storage

Electrochemistry provides a pathway for converting chemical energy to electricity or vice-versa. These storage systems are based upon reversible half reactions that involve the transfer of electrons. Examples relevant to energy storage include CO_2 electrolysis, water electrolysis, and batteries.

2.3.1 Electrolysis and Electrochemical Conversion to Fuel

Electrolysis of water to produce H_2 is a promising route to store energy, where the H_2 is a usable fuel to be subsequently used in either direct combustion or an H_2 fuel cell. Technical challenges to industrial scaling are the high-cost catalysts and overall size of electrolysis reactors. Economical hydrogen production by electrolysis at scale is currently an active area of research.

Electrochemical conversion of CO_2 is an important method for decoupling the industrial production of chemicals from carbon-emitting fossil-fuels (Küngas 2020). Electrolysis of CO_2 can be employed to create organic feedstock chemicals for many industrial chemical synthetic processes, such as CO, formic acid, methanol, and ethanol. Using air-captured CO_2 and water with solar-powered electrolysis was reported to produce methanol at a theoretical efficiency of ~50% (Smith et al. 2019). However, many technical challenges arise when this process is used to produce methanol at scale. New innovative electrolysis methodologies with increased efficiency and less land use are needed to scale bench-sized chemistry results to large-scale production.

2.3.2 Batteries

Chemical energy is stored in batteries and converted to electricity through the use of two half reactions that are linked together through an electrolyte and an external circuit. Batteries used in industrial energy applications target fast response time applications (Andrijanovits, Hoimoja, and Vinnikov 2012). At large scales, batteries have thus far proven appropriate for short-term variable energy but lack demonstration for long-term storage due to the energy losses that can occur over time (Kebede et al. 2022). There is a wide range of battery types, sizes, designs, operating temperatures, and chemistries. The most applicable batteries for industrial energy storage include Li-ion, lead acid, and flow batteries; Li:Sulfur (Li-S) and organic batteries need additional research to lower costs and increase productivity before they could be applied in industrial settings (Kebede et al. 2022).

The academic research community has demonstrated scientific advances in recent decades to improve battery performance. However, most of the development efforts have been driven by applications requiring small-scale systems due to their commercialized status (Frith 2021). For example, technological targets for light-duty vehicles will not lead to batteries that meet industrial storage requirements (Frith 2021). Industrial use requires economic solutions to achieve energy management and arbitrage (Zafirakis et al. 2014). Additionally, the requirements for industrial-use batteries differ from the space and volume constraints in light-duty vehicles. However, Li-ion battery technology continues to advance in production methods for increasing scale and cost-competitiveness that could make this technology more attractive for industrial applications.

Figure 3 shows a bottom-up analysis of various battery technologies over time associated with their chemical cost of energy storage. Interestingly, the costs for new technologies have increased over time. This development can be attributed to the higher energy densities of new technologies that are speculated to compensate for the cost increases. Li-ion batteries, for example, have higher energy and power density than lead acid batteries, which allows their integration into applications as light-duty vehicles or portable devices that justify the cost increase (Li et al. 2017).

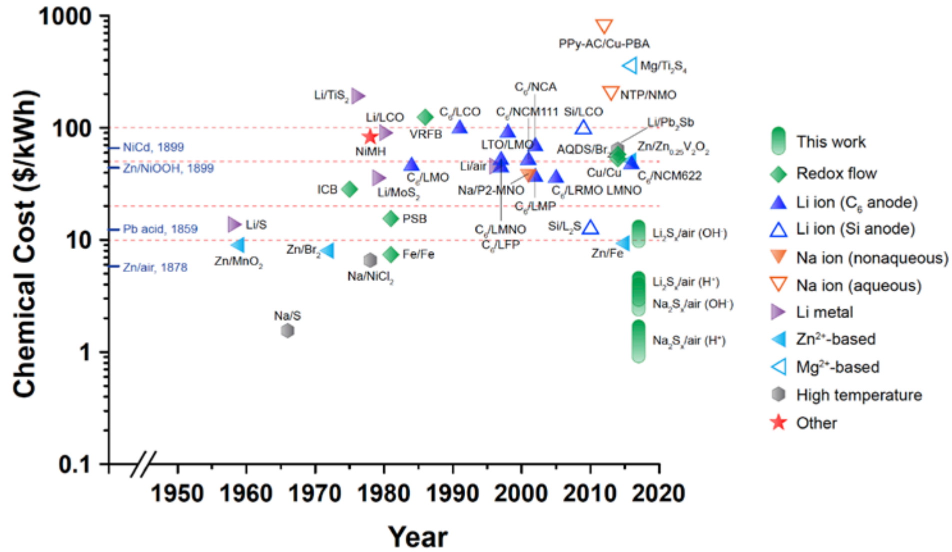


Figure 3. The chemical cost of storage (US$/kWh)

Illustration from *Joule* (Li et al. 2017)

Lead acid batteries are commonly used in large backup power supplies for telephone and computer centers, grid energy storage, and off-grid household electric power systems. Lead acid batteries are a mature technology that is inexpensive and simple in nature, supplying high current with low self-discharge (Kebede et al. 2022). However, these batteries show poor suitability for deep discharge conditions, low numbers of charging-discharging cycles over their lifetimes, and slow charging rates lifetimes (Marańda 2015; El Haj Assad et al. 2021; "Battery Storage for Renewables Market Status and Technology Outlook" 2015).

Li-ion batteries established themselves as the preeminent battery chemistry by their high gravimetric energy density, high electrochemical potential, and low cost, supporting the expectation that they will dominate industrial energy storage in the 10- to 15-year time horizon ("H2@Scale" n.d.). Li-ion batteries have up to 95% round trip efficiency, falling to only 78% when other factors are taken into account (Kebede et al. 2022). Technical improvements are sought to all components—anode, cathode, electrolyte, and separator to increase performance. The current leading cathode candidates are nickel, manganese, and cobalt materials, which are trending toward high nickel concentrations and cell voltages of up to 4.2 V (Holland 2022; Dose et al. 2020). Limitations in the stability of cells with high nickel at these voltages represent an important research challenge (Holland 2022). The most common anode alternatives are carbon, silicon (and alloys), or lithium metal (Miao et al. 2019). Other barriers include identifying solutions to address Si volume expansion, as well as the expansion, loss, and reformation of the solid electrolyte interphase.

Other challenges for large-scale Li-ion battery integration remain, such as fire safety, recycling, battery cycle life, Coulombic inefficiency in long-term storage, as well as mining and manufacturing challenges (Huang and Li 2022). Li-ion batteries used at large scale must be abuse tolerant, and manufacturing defects should not lead to uncontrolled temperature increase in a cell or propagation into a pack (Huang and Li 2022). Importantly, Li-ion batteries use flammable electrolyte and reactive cathodes and anodes (including Si); therefore, safety hazards must be addressed (Holland 2022).

Redox flow batteries are well suited for stationary applications. They have a fast response, are made with low-cost materials, and can have a lifetime of up to 20–25 years without capacity fade (Kebede et al. 2022; "Vanadium Flow Battery Energy Storage" n.d.). However, the energy density is sacrificed with scalability. The primary applications of redox flow batteries include off-peak storage, peak shaving, time shifting, frequency regulation, and grid stability (Kebede et al. 2022). Vanadium redox flow batteries use the multiple oxidation states of vanadium to store and release charges (He et al. 2020). They suit large stationary applications, with long lifetimes (approximately 15,000 cycles), full discharge, and low cost per kWh compared with Li-ion when cycled daily or more frequently (Yin and Fu 2017; Luo et al. 2015). On cost and scale, vanadium flow batteries are attractive for major grid and industry applications (admin 2020). Other chemistries for redox batteries are under investigation. The use of iron as a low-cost active material may solve some of the cost issues with vanadium-based electrodes common to redox flow batteries ("Iron Flow Battery Maker ESS Expands into Europe" n.d.). Zinc-air batteries avoid the need for cobalt and lithium, raw materials that are becoming increasingly expensive as demand for Li-ion batteries grows ("How Zinc-Air Batteries Are Taking On the Long-Duration Storage Market | GTM Squared" n.d.). Aqueous-flow cells, based on organic active materials instead of inorganic actives, are potentially cost-effective and viable for widespread adoption as they are not limited by natural earth abundance (Cao et al. 2020). Several organic chemistries have shown promise and are receiving much interest as next-generation redox flow chemistries (Cao et al. 2020). Despite the attributes of redox flow batteries, the current dominance of Li-ion battery technology remains a large hindrance to adoption (Perathoner and Centi 2018). The current demand for large-scale long-duration energy storage capacity is not large enough to drive current production ("Flow Batteries Struggle in 2019 as Lithium-Ion Marches On" n.d.).

Li-S batteries employ a metallic lithium (anode) and elemental sulfur (cathode) and have very a high theoretical capacity of 1,675 mAh/g (Perathoner and Centi 2018). In addition, Li-S batteries have a theoretical energy density of ~2,600 Wh/kg, which is greater than traditional Li-ion batteries (Perathoner and Centi 2018). However, over many cycles, electrochemical dissolution of the redox intermediates (polysulfides) causes Li anode corrosion, poor electronic conductivity, and significant volume change, which limits energy density and lifetime (Zhu et al. 2019). Importantly, Li metal anodes are subject to dendrite formation, which can lead to short circuits and catastrophic fires (Marańda 2015). Sulfur also undergoes a series of compositional and structural changes during cycling, which compromises electrode structure stability, prevents full utilization of the active material, and yields insufficient cycle life and system efficiency (Manthiram, Fu, and Su 2013). Beyond prototyping, there are no commercial Li-S batteries on the market (Tidblad et al. 2021).

Organic batteries could yield sustainable, low-cost energy storage solutions that reduce GHG emissions in the battery production process and enable increased penetration of renewable power into the grid and could have eventual use in transportation (Kim et al. 2023). Recently, researchers reported a new family of air- and water-stable organic Li-ion cathode materials with high redox potential and specific capacity that are competitive compared with commercial inorganic materials (Jiande Wang et al. 2021). This development could provide a new platform for the Li-ion battery design with organic electrode materials for eco-friendly and sustainable energy storage and conversion systems (Xie and Lu 2021). Additionally, new Li-ion (and other) battery chemistries are being tried out every year, and some might yield a mix of characteristics suitable particularly for the industrial sector. One candidate technology could be sodium-sulfur batteries that operate at high temperatures and need advanced thermal management strategies that could be used in conjunction with industrial applications (Vudata and Bhattacharyya 2021).

2.4 Mechanical Energy Storage

Mechanical energy storage systems are based on simple physical principles and typically store energy in the form of kinetic or potential energy. Pumped storage hydropower uses the pumping and release of water between two reservoirs at different elevations to store and retrieve potential energy (Saulsbury 2020). Flywheel energy storage systems store electric energy in the form of kinetic energy by spinning a rotor in a nearly frictionless enclosure. The final example discussed in this section is compressed air energy storage systems that work similarly to pumped storage hydropower plants but instead of water use air or another gas to store potential energy ("Mechanical Electricity Storage Technology" n.d.).

2.4.1 Pumped Storage Hydropower

In 2020, 23 GW of pumped hydro storage capacity existed in the United States (Augustine and Blair 2021). This energy storage type originates from pumping water to a reservoir at higher elevation using electricity when consumer demand—and thus price—is low. When additional electricity is needed in the grid, water is released through turbines to create power. These plants can have round trip efficiencies of 80%. It is difficult to build new plants due to their large-scale, massive upfront capital investment, as well as the disruption to existing water resources and ecosystems. Pumped storage hydropower is often paired with wind power and integrated into an electric grid system to address variability, rather than the industrial sector.

2.4.2 Flywheel Energy Storage

Flywheel technology is well established to store excess energy by converting it into motion of a high-speed rotating disc connected to an electric motor. The stored momentum can then be used to generate on-demand electric energy. This technology is scalable in terms of the amount of designed energy storage, and applications range from low-level machine drive, load levelers, emergency devices, all the way to utility grid scale (Olabi et al. 2021). Flywheels are best suited for high-power, short-duration applications. Excess renewable energy can be stored and released on-demand, with efficiency of 95% (Amiryar and Pullen 2017). Active research to increase the amount of energy that a flywheel can store includes development of inexpensive lightweight materials with high tensile strength, such as laminated steel (Olabi et al. 2021).

2.4.3 Compressed Air Storage

Compressed air energy storage (CAES) is a large-scale storage system using pressurized air to store potential energy, similarly to how pumped storage hydropower employs water. When electricity costs are low, air is pumped into a natural, continuous cavern and is compressed up to 70 bar. When energy is needed, the high-pressure air flows through a pathway that turns a turbine and drives a generator. CAES has a smaller footprint than pumped storage hydropower, but also a 20% lower efficiency due to temperature changes associated with the air compression and expansion. To overcome this efficiency loss, in 2010 General Electric and RWE began efforts to create an adiabatic CAES power station ("ADELE to Store Electricity Efficiently, Safely and in Large Quantities | GE News" n.d.). By coupling compression technology with sensible thermal heat storage, the energy associated with temperature changes can be retained. On-demand electricity can be produced by extracting the stored thermal energy to heat the air and powering a turbine with simultaneous heat recovery ("ADELE to Store Electricity Efficiently, Safely and in Large Quantities | GE News" n.d.). Currently, there is only one 110-MW commercial-scale CAES plant (Macintosh, Alabama) in operation in the United States (Augustine and Blair 2021).

2.5 Other Energy Storage

Supercapacitor or ultracapacitor energy storage could be another type of energy storage used for industrial applications in the future. Supercapacitor energy storage materials store electricity directly through static charge. This energy storage technology is used for frequent charge and discharge cycling, and short time scales. Supercapacitors are a relatively new development compared to Li-ion batteries. They have found applications in back-up power batteries and pulse power applications. Recent application of supercapacitors include hybrid vehicles and smart phones (Muzaffar et al. 2019). In the industrial sector, combined battery-supercapacitor energy storage systems have promise for new uses in power-related applications.

3 Industrial Energy Storage Applications

New energy technologies that support industrial energy storage can be integrated into manufacturing processes and can help manage the shift to renewably sourced energy. There are several applications where large-scale energy storage integration can shift energy demand, which could facilitate this transition. Industrial energy storage technologies each have unique parameters for capacity, time scale, energy density, location, and size, and thus could be better matches for different types of industrial applications. Here, we discuss a number of influential industrial configurations that could benefit from increased integration of energy storage.

Overall, the applications of energy needed in U.S. manufacturing vary, and we explore some of the more common applications. The manufacturing and energy footprint analysis based on 2018 data reported that 95% of the energy used in diverse U.S. manufacturing industries is derived from direct combustion or steam produced by fuel combustion ("Manufacturing Energy Consumption Survey" 2018). Furthermore, 51% of this fuel was used to produce manufacturing process heat. A striking 34% of energy used in manufacturing process heat is wasted. The next largest use of energy is for industrial machine drive (mainly from electricity) at 73%, and 7% for the facility heating, ventilating, and air conditioning (HVAC) ("Manufacturing Energy Consumption Survey" 2018).

3.1 Manufacturing Process Heat

Process heat has been identified as an application that can be integrated with industrial energy storage technologies to decrease overall energy consumption. Figure 4 shows the process heat energy and temperature demand for 14 of the largest GHG-emitting industries in the United States, over a six-year period (McMillan and Ruth 2019). The data show that about half of all processes require process heat at a temperature lower than 300˚C. This low-temperature regime is typically covered through conventional boilers, the combination of heat and power, or cogenerated in a petroleum refining process.

Low temperature requirements can be covered by geothermal or solar thermal technologies, when transitioning to renewable energy sources. Higher temperature requirements could be satisfied through concentrating solar power technologies that allow for process heat temperatures of up to 1,000˚C. However, for large-scale plants with high energy requirements above 100 MW, alternative low-carbon thermal energy generation technologies will need to be established and are a topic of ongoing research (McMillan and Ruth 2019).

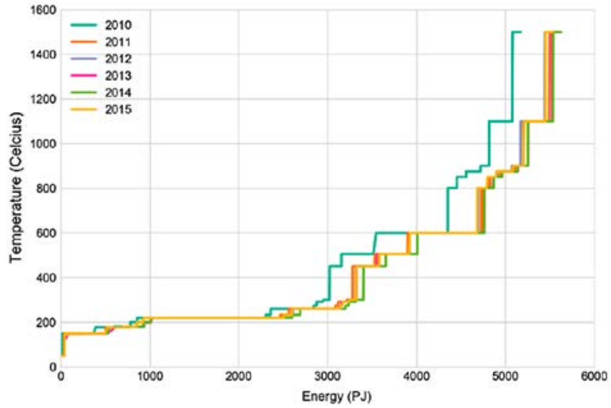


Figure 4. Temperature and energy demand for 2010–2015 across the 14 largest GHG emitting industries

Illustration from ***Applied Energy*** (McMillan and Ruth 2019)

There are a number of challenges to developing thermal energy storage (Alva, Lin, and Fang 2018; H. Zhang et al. 2016) for the industrial sector, as any application of thermal energy storage is highly heterogeneous and each integration strategy must be engineered specifically for an individual system or process. Storage solutions need to be able to store and deliver the right amount of energy (or more) at the correct temperature in a designated time. In order to use waste heat recovery, detailed knowledge of the individual processes and required process temperatures are important. Incorporation of thermal heat into industrial processes requires the engineering design challenge of simultaneously determining the amount of energy needed, the amount of energy available, and the system required to achieve a synergistic energy balance.

Determining which thermal generation and storage configuration is best suited can be approached from different perspectives that encompass fuel-driven process heat (e.g., burning natural gas) and electricity-driven process heat (e.g., electric heaters). Either can be supplemented with electrochemical storage and all four configurations are discussed in here. First, fuel-driven heat generation with thermal storage requires no retrofitting of existing facilities and can easily be used to store thermal energy. While point source emissions from fuel combustion may occur, there are practical, inexpensive waste-heat recovery methods and thermal storage options that have high efficiencies, and consequently lower emissions. Fuel-driven heat generation in combination with electrochemical storage does not directly store the thermal heat. This method is subject to efficiency losses during the electrochemical round trip of the heat-to-electricity transformation. There is no practical waste-heat recovery. This method suffers from high cost of electrochemical storage, and it requires heat to electrically power the cycle. Third, electricity-driven heat generation with thermal storage can provide a highly precise temperature and power flux from the electric drive. The process heat is stored, and this method avoids point-source emissions from on-site fuel combustion (although emissions from electricity generation still occur). There are practical waste-heat recovery methods and thermal storage options that are inexpensive and have high efficiencies. Finally, electricity-driven heat generation supported by electrochemical storage produces again highly precise temperatures with minimal power flux. However, this method does not store the thermal heat, and the roundtrip efficiency of the electrochemical transformations is sizable. This configuration also suffers from the high cost of electrochemical storage and there are no practical capabilities for waste-heat recovery. Through a better understanding of process temperatures, heat quality, and energy requirements across various industrial processes, solutions that can address large needs across heterogeneous processes can be identified.

Research and development opportunities in the field of TES include identification and prioritization of low technology readiness level development opportunities in thermochemical storage with potential for high impact. A specific opportunity is improving the cyclability of the thermochemical loop for integrating H_2 and captured CO_2 to produce synthetic hydrocarbons. New designs to couple multiple thermal storage categories are being considered, like sensible and thermochemical or sensible with latent heat storage technologies, to optimize energy efficiencies.

3.2 Industrial Machine Drive

Industrial machine drive is primarily created by electric motors, pumps, and fans. Machine drive accounts for 14% of industrial energy use, of which 73% is derived from electricity (Mai et al. 2012). Currently, batteries offer the most suitable energy storage technology for industrial machine drive applications due to the combination of quick response, durability, energy density, and commercial availability. Continued improvements in battery performance will enhance efficiency in machine drive applications. Since Li-ion batteries are expected to dominate the battery field for the foreseeable future, leveraging the current capital investment and current manufacturing ecosystem of Li-ion batteries is the most sensible approach to industrial machine drive energy storage. While hydrogen fuel cells could support energy storage that could be used for machine drive in the future, the extent and breadth will be dependent upon significant new hydrogen infrastructure development.

3.3 HVAC Systems

The HVAC systems in industrial buildings represent a large opportunity for improved energy efficiency and energy storage. Controlling temperature in a building through HVAC systems can consume large amounts of energy and can be expensive. However, with the integration of thermal energy storage, the energy consumed to control temperatures can be reduced. Thermal energy storage that has been used for centuries includes ice tanks, chilled water tanks, solar hot water tanks, and campus-scale lake source cooling. More recent types of energy storage media also include those incorporated into building construction, the ground, other fluids, specific solids, and PCMs, which can all be used to store energy. Both short-term (daily) and long-term (seasonal) storage are possible. Integration of energy using loads such as chillers, packaged AC, space heating, and domestic water heating storage with existing process heat requirements/waste-heat recovery could provide greatly improved efficiencies and reduced costs for implementation.

Industrial applications have a unique advantage compared to commercial, or even residential buildings: industry typically has heating and cooling needs beyond HVAC. Coupling HVAC with industrial process heat could create unique opportunities for synergy, and if designed well could lower the overall use of energy to heat and cool the industrial buildings. Even if machine drive is deployed in commercial building heating and cooling systems, the HVAC systems will also require electrical energy storage, and residential building HVAC systems are better suited to using batteries.

3.4 Building Systems

Buildings can use electrical, thermal, or virtual storage using a combination of batteries, HVAC-integrated storage, smart appliances, and intelligent controllers. These systems can dynamically shape load profiles to support grid operations. Response time can be extremely fast in the case of utility-controlled water heaters and refrigerators so they can provide frequency regulation, while other systems can provide hourly or longer-term response. Systems can be controlled by customers or aggregators that bid into various electricity markets. Greater use of building-located storage and highly responsive loads could help power system planners and operators increase power system flexibility and accommodate greater amounts of renewable generation.

Future research may include designing and developing a controls network to monitor, characterize, and manage building energy use. For example, a computer control system could analyze building energy use, identify the optimal configuration and control of building energy storage to increase economic value, and improve methods to compare storage technologies for different load management applications that could be of interest. The tradeoffs between individual buildings or storage devices that respond to energy price signals and aggregations that organize that response across multiple buildings, or even a campus, could be analyzed. Different building technologies (controls, storage technologies, smart appliances, etc.) and policy options to increase cost-effective electricity market participation could be analyzed.

3.5 Other Systems

The growth in other global industrial energy storage segments is shown in Figure 5. This includes applications such as telecom industry backup power, uninterrupted power sources (UPS), data centers, fuel cell electric vehicle refueling, and forklifts. Global other industrial energy storage is projected to grow 2.6 times, from just over 60 GWh to 167 GWh in 2030. UPS and data center energy use shows moderate growth, and telecom backup battery demand shows the lowest growth estimates through 2030 (“Energy Storage Grand Challenge: Energy Storage Market Report” 2020).

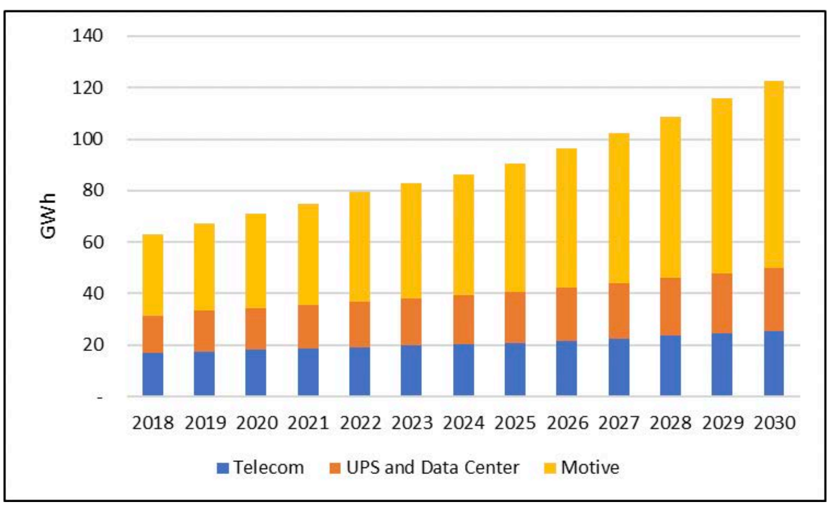


Figure 5. Projected global industrial energy storage deployments by application

Illustration from U.S. Department of Energy (“Energy Storage Grand Challenge: Energy Storage Market Report” 2020)

4 Energy Storage Outlook

Flexible, integrated, and responsive energy storage is essential to transitioning from fossil fuel to renewable energy. The challenge is to balance energy storage technology capabilities with the needs of a particular industrial energy process. Determining the most appropriate storage technology will be dependent on the unique energy needs of that environment. Common drivers for advancing the development and adoption of large-scale energy storage in manufacturing include technology drivers—powered by scientific discovery, engineering advances, and investment—as well as market-based business, regulatory, and policy drivers.

4.1 Technology Drivers

Advances in technologies such as improving manufacturing methods, using earth-abundant raw materials, and identifying ways to recycle storage materials could improve the economic feasibility and reduce the environmental impact of energy storage technologies. Such advances are evidenced by NREL's Storage Futures Study (Blair et al. 2022), which has shown that Li-ion battery pack costs have dropped by more than 80% over the past decade and are expected to further decline based on increasing scale of production and demand. Scientific discovery provides the path forward through efforts to use low-cost materials, develop new manufacturing methods, and develop systems focused on large-scale applications. For example, organic battery chemistries are environmentally friendlier, more sustainable, and less dependent on critical raw material supply than the currently available energy technology (e.g., Li-ion, lead-acid, or flow batteries). Research with a focus on large-scale applications will serve to diminish the current gap between laboratory scale discoveries and pilot-to-commercial scale deployments. For example, in the case of Li-S batteries, performance enhancement seen for lab-scale batteries did not directly translate to industrial scale (Zhu et al. 2019). Since small-scale research is performed using coin cells, clear comparison of performance is not fundamentally possible with large cells (for example, charge and discharge rates). Safety concerns associated with scaling must also be addressed—for example, incorporating $LiNO_3$ additives to Li-S batteries. Additionally, some nanoscale surface treatments for stabilizing Li dendrite growth or the availability of exotic carbons used as electrodes or additives have not been developed for large-scale manufacturing (Zhu et al. 2019). These examples demonstrate some of the obstacles for translating research and development advances into energy savings at the industrial scale.

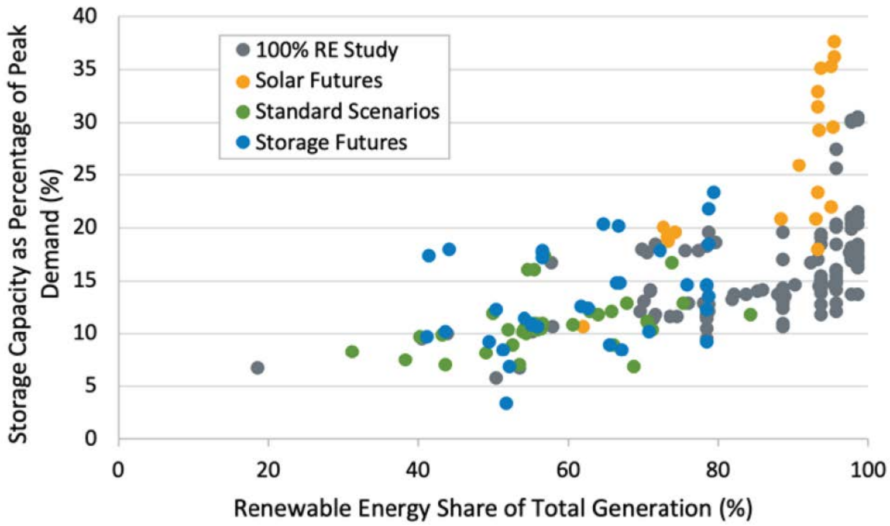
Scientific research on energy storage recycling can also provide pathways to large-scale deployment. As the number of batteries used in industry increases, developing a pathway for a second-use or repurposed batteries will also become important. A significant number of plug-in electric vehicles batteries will be available at the end of a vehicle's service life with ~70% of its initial capacity (Neubauer et al. 2015). Between 2010 and 2021, over 2.1 million plug-in electric vehicles have been sold in the United States. This includes 1.3 million fully electric battery vehicles, and 800,000 plug-in hybrid electric vehicles, which results in an aggregate battery capacity sold of just over 110 GWh (Gohlke et al. 2022). At the end of the vehicle lifetime this storage capacity could be available for industrial grid storage applications. An NREL study showed that the second use of a plug-in electric vehicle battery to support the electric grid has the potential to offset service costs to a vehicle owner, defer premature battery recycling, support grid resiliency and efficiency, reduce variability of solar and wind power, and reduce overall GHG emissions (Neubauer et al. 2015). This study reported that the value of second use could be as high as $20-$30/kWh and plug-in electric vehicle batteries could last up to another 10 years in some second-use applications. The technical barriers include ongoing cost reductions for new batteries, the cost to repurpose, the ability to integrate the plug-in electric vehicle batteries into different designs, the challenge of pairing the batteries with different industrial technologies, the complexity of establishing a battery pack ownership chain, lack of repurposing guidelines at end of vehicle life, and predicting expected life for second use. The industry must also recognize that it can be economic to reuse the batteries and establish efforts for large-scale battery repurposing.

4.2 Market, Business, Regulatory, and Policy Drivers

Scientific advancements in energy storage are necessary but might not be sufficient on their own to realize the progress required to transform our energy dependence away from fossil fuels within the given timeframe. In order to achieve the goal of zero carbon emissions by 2050, large-scale integration of these technologies into existing infrastructure is vital. For industry to decarbonize successfully and economically without forgoing functionality, it will be critical to establish a clear understanding of the market structure, business models, regulatory environment, and policies required for industry to successfully implement these technologies.

Energy storage plays an essential role in the implementation of renewable energy technologies at the industrial scale. Energy storage supports high penetrations of renewable energy by allowing surplus energy to be stored instead of being curtailed. This excess energy can then later be retrieved when needed by the industrial process. According to NREL's Storage Futures Study (Frazier et al. 2021), the United States' grid-level storage capacity is expected to increase more than five-fold from about 23 GW installed in 2020 to more than 125 GW in 2050. Especially high shares of renewable energy generation at the grid level will require a large amount of energy storage capacity to provide the necessary time-shifting potential to manage imbalances between generation and demand, see Figure 6.

Industrial energy storage could be used to capture energy from renewable resources during peak generation times through industrial energy storage technologies that then later provide the stored energy back into the electric grid when renewable electric generation drops. In other words, at the grid scale, industrial energy storage can take advantage of any potentially curtailed energy when generation is plentiful (i.e., daylight for solar) and supply that energy back to the grid when energy is needed. If some or most of the storage comes from large-scale industrial storage applications, the amount of curtailed electricity could be significantly reduced, making the overall U.S. electric grid more efficient.



100% RE Study: Quantifying the Challenge of Reaching a 100% Renewable Energy Power System for the United States (Cole et al. 2021)

Solar Futures: Solar Futures Study (DOE 2021)

Standard Scenarios: 2020 Standard Scenarios Report (Cole et al. 2020)

Storage Futures: Storage Futures Study: Economic Potential of Diurnal Storage in the U.S. Power Sector (Frazier et al. 2021)

Figure 6. Storage capacity as a function of renewable energy contribution in percent

Illustration from NREL's Storage Futures Study (Blair et al. 2022)

Governmental funding provides an important driver to implement renewable energies. For example, hydrogen was noted earlier as a potential key pathway for decarbonizing industry and for long-term industrial energy storage. The U.S. Department of Energy has put forth a vision for large-scale hydrogen use including production, storage, and use, shown in Figure 7. Research and funding are directed at each of these applications. A broad and encompassing appreciation for the scale of systems needed to work together provides realistic pathways to enable the United States to transition away from fossil fuels. The United States is not alone in supporting the growth of hydrogen-fueled economies. Governments around the world are also devoting millions of dollars to research and analysis to facilitate the transition to using hydrogen as a fuel. With increasing adoption of renewable energy, the need for energy storage will increase to provide a solution for the variable nature of energy supply from sources such as wind and solar. In this context, industry can provide or absorb a significant proportion of the deficit or surplus required to smooth out this variability via a wide range of storage options. But this will require a systematic characterization of process heat duties based on process types and temperature ranges. For instance, since waste heat recovery opportunities are highly dependent on process conditions and end use, a comprehensive characterization is needed for waste heat inventory data.

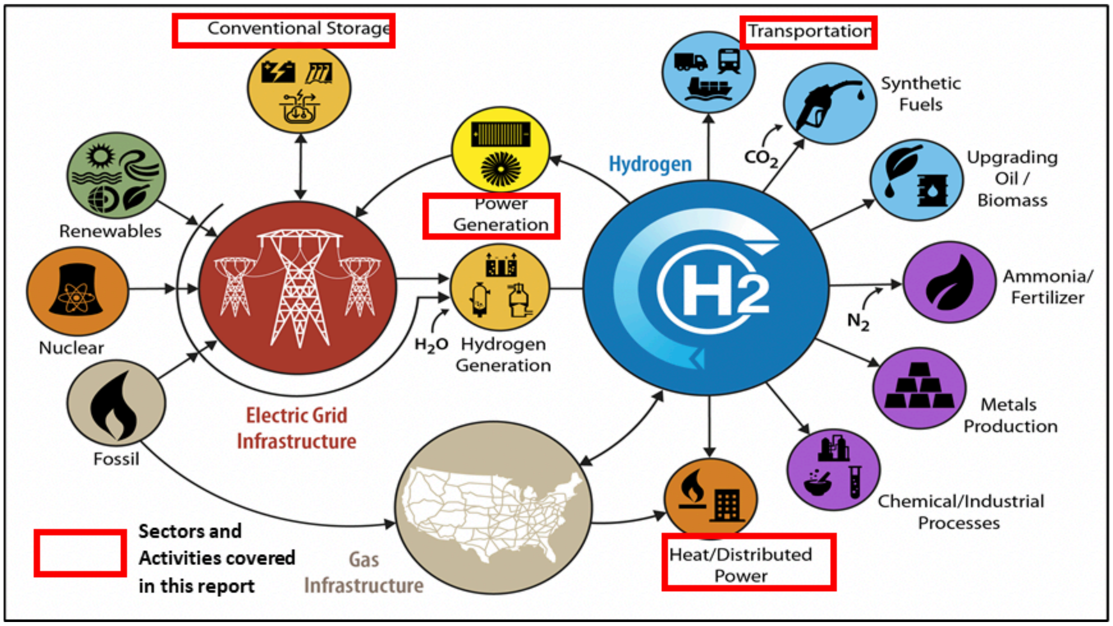


Figure 7. The U.S. Department of Energy H2@Scale vision

Illustration from U.S. Department of Energy ("H2@Scale" n.d.)

There is a need to establish a process to define policy and regulatory requirements and set targets for energy storage technologies for various applications and scenarios via analysis, modeling, and validation. This process may identify what should be the characteristics of energy storage devices required to meet particular grid applications and scenarios. Policy makers could then introduce incentives that allow for economic benefits for participating industries through establishing market mechanisms such as peak shaving (Zimmermann and Sauer 2020; Chua, Lim, and Morris 2016) or arbitrage in a dynamic-pricing market (Telaretti, Ippolito, and Dusonchet 2016). This will involve analyzing the tradeoffs between different industrial storage options responding to price signals and aggregators organizing that response. This effort should also include analyzing potential benefits of electrical, thermal, and virtual storage on energy and industrial systems resilience. Test protocols and procedures also have to be established to evaluate various energy storage devices against the targets.

5 Summary

As the world increasingly adopts renewable energy to achieve the net-zero carbon emission goal by 2050, energy storage capacity is expected to increase significantly to support integrating, stabilizing, and balancing the variable nature of renewable energy generation. A broad vision and knowledge of energy losses and demands is needed to determine efficient and cost-effective strategies. Adoption of emerging energy storage technologies, as well as the associated benefits, will ultimately be determined by industry goals. For the status quo where fuel combustion continues to produce process heat following the load requirements, energy savings can be achieved via heat recovery and other efficiency driver technologies such as combined heat and power. In the near term, this approach will rely on efforts to address heterogeneous industrial and site processes, with costs, energy densities, and temperature profiles tuned to individual process/location needs. If industrial goals include reducing emissions, advances in energy storage and integration will become more prominent. This will require innovation and technical improvements to develop a dynamic, wide-ranging integrated energy storage and distribution network.

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