Energy Storage Grand Challenge: Energy Storage Market Report

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Disclaimer

Foreword

As part of the U.S. Department of Energy's (DOE's) Energy Storage Grand Challenge (ESGC), DOE intends to synthesize and disseminate best-available energy storage data, information, and analysis to inform decision-making and accelerate technology adoption. The ESGC Roadmap provides options for addressing technology development, commercialization, manufacturing, valuation, and workforce challenges to position the United States for global leadership in the energy storage technologies of the future.[1] This report provides a baseline understanding of the numerous dynamic energy storage markets that fall within the scope of the ESGC via an integrated presentation of deployment, investment, and manufacturing data from the best publicly available sources.

This report covers the following energy storage technologies: lithium-ion batteries, lead–acid batteries, pumped-storage hydropower, compressed-air energy storage, redox flow batteries, hydrogen, building thermal energy storage, and select long-duration energy storage technologies. The user-centric use cases laid out in the ESGC Roadmap inform the identification of markets included in this report. In turn, this market analysis provides an independent view of the markets where those use cases play out. Future versions of this report could continue to develop this alignment of the market data and characterization with the use case framework.

Not all energy storage technologies and markets could be addressed in this report. Due to the wide array of energy technologies, market niches, and data availability issues, this market report only includes a select group of technologies. For example, thermal energy storage technologies are very broadly defined and cover a wide range of potential markets, technology readiness levels, and primary energy sources. In other areas, data scarcity necessitates a greater understanding of future applications and emerging science. Future efforts will update data presented in this report and be expanded to include other energy storage technologies.

This data-driven assessment of the current status of energy storage markets is essential to track progress toward the goals described in the Energy Storage Grand Challenge and inform the decision-making of a broad range of stakeholders. At the same time, gaps identified through the development of this report can point to areas where further data collection and analysis could provide an even greater level of understanding of the full range of markets and technologies.

Finally, numerous complementary analyses are planned, underway, or completed that will provide a deeper understanding of the specific technologies and markets covered at a high level in this report.

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[1] View the ESGC roadmap at https://energy.gov/energy-storage-grand-challenge/downloads/energy-storage-grand-challenge-roadmap.

Acknowledgments

The Energy Storage Grand Challenge (ESGC) is a crosscutting effort managed by the U.S. Department of Energy's Research Technology Investment Committee. The *Energy Storage Market Report* was developed by the Office of Technology Transfer (OTT) under the direction of Conner Prochaska and Marcos Gonzales Harsha, with guidance and support from the Energy Storage Subcommittee of the Research Technology Investment Committee, co-chaired by Alex Fitzsimmons, Deputy Assistant Secretary in the Office of Energy Efficiency and Renewable Energy (EERE), and Michael Pesin, Deputy Assistant Secretary in the Office of Electricity Delivery and Energy Reliability (OE).

Development of the *Energy Storage Market Report* was led by Margaret Mann (National Renewable Energy Laboratory [NREL]), Susan Babinec (Argonne National Laboratory), and Vicky Putsche (NREL), with guidance and direction from Stephen Hendrickson (OTT), Hugh Ho (EERE), and Paul Spitsen (EERE). Data gathering was supported by the following NREL staff: David Feldman, Spencer Gilleon Madeline Gilleran, Chad Hunter, Michael Penev, Genevieve Saur, and Dustin Weigl.

The report would not have been possible without the input and guidance of the Market Report Steering Committee, whose members include: Craig Anderson (Science), Briggs White (National Energy Technology Laboratory), Peter Faguy (EERE), Joe Cresko (EERE), Andrew Dawson (EERE), Vinod Siberry (OE), Karma Sawyer (EERE), and Eric Miller (EERE).

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Acronyms

ARPA-E	Advanced Research Projects Agency – Energy
BNEF	Bloomberg New Energy Finance
CAES	compressed-air energy storage
CAGR	compound annual growth rate
C&I	commercial and industrial
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
ESGC	Energy Storage Grand Challenge
EV	electric vehicle
FCEV	fuel cell electric vehicle
FERC	Federal Energy Regulatory Commission
IEA	International Energy Agency
IHA	International Hydropower Association
LDES	long-duration energy storage
LHV	lower heating value
Li-ion	lithium-ion
NREL	National Renewable Energy Laboratory
OE	Office of Electricity Delivery and Energy Reliability
OTT	Office of Technology Transfer
PSH	pumped-storage hydropower
PV	photovoltaics
ReEDS	Regional Energy Deployment System
RFB	redox flow battery
ROA	rest of Asia
ROW	rest of the world
SLI	starting, lighting, and ignition
STEPS	Stated Policies (IEA)
TES	thermal energy storage
UPS	uninterruptible power source
xEV	electric vehicle (light-, medium-, and heavy-duty classes)

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Executive Summary

As part of the U.S. Department of Energy's (DOE's) Energy Storage Grand Challenge (ESGC), this report summarizes published literature on the current and projected markets for the global deployment of seven energy storage technologies in the transportation and stationary markets through 2030. This work focuses on collecting the best-available estimates of how energy storage is projected to grow, both in the United States and internationally. Thus, the purpose of this report is to summarize available data rather than to provide new analyses of the current and future markets for energy storage.

By 2030, stationary and transportation energy storage combined markets are estimated to grow 2.5–4 terawatt-hours (TWh) annually, approximately three to five times the current 800-gigawatt-hour (GWh) market. Electrified powertrains (i.e., onboard energy storage) have gained greater acceptance and have transitioned mobility to the largest single demand for energy storage, representing approximately five to ten times greater usage by energy capacity than stationary energy storage. The convergence of electrified transportation, a rapid decrease in battery storage costs, and increased variable renewable generation has led to a surge in research and market deployments of energy storage across the global electric and transportation sectors. Although once considered the missing link for high levels of grid-tied renewable electricity, stationary energy storage is no longer seen as a barrier, but rather a real opportunity to identify the most cost-effective technologies for increasing grid reliability, resilience, and demand management. This report seeks to capture the latest projections for energy storage markets.

The growth seen over the last few years in electric vehicle (EV) adoption is expected to continue as central and local government incentives for consumers remain in place in many major world markets, and as manufacturers increase the size of manufacturing platforms. Analysts project mobility storage demands in 2030 of 0.8 to 3.0 TWh, with the demand for light-duty EVs dominating near-term markets. China is expected to be the largest medium-term mobility storage market; however, quite unexpectedly, in July 2020, the European xEV market (with "x" representing electric vehicles across light-duty, medium-duty, and heavy-duty classes) exceeded China's, and is expected to exceed 1 million xEVs this year.

The existing capacity in stationary energy storage is dominated by pumped-storage hydropower (PSH), but because of decreasing prices, new projects are generally lithium-ion (Li-ion) batteries. By 2030, annual global deployments of stationary storage (excluding PSH) is projected to exceed 300 GWh, representing a 27% compound annual growth rate (CAGR) for grid-related storage and an 8% CAGR for use in industrial applications such as warehouse logistics and data centers. China has announced the development of greater than 35-GW PSH from 2020–2026 through development of several multi-gigawatt projects, and although not currently in the development phase, the United States is exploring avenues for PSH growth as well. The largest markets for stationary energy storage in 2030 are projected to be in North America (41.1 GWh), China (32.6 GWh), and Europe (31.2 GWh). Excluding China, Japan (2.3 GWh) and South Korea (1.2 GWh) comprise a large part of the rest of the Asian market. Much of the expansive growth is 4-hour-duration hybrid configurations coupled to utilities, commercial and industrial (C&I), and residential renewables (generally photovoltaics [PV]).

Report Methodology and Scope

This report, supported by the U.S. Department of Energy's Energy Storage Grand Challenge, summarizes current status and market projections for the global deployment of selected energy storage technologies in the transportation and stationary markets. Published projections, derived with different assumptions, are presented to provide the current outlook of how energy storage is expected to develop through 2030. To further inform expectations, recent and current activities expected to have a large impact are included, including research advances in nascent technologies and storage applications. Tracking how projections evolve and how markets actually develop can help inform government and industry research and deployment strategies.

Within this overall framework, the report begins with a summary of each market by sector and region. Then, each technology is discussed individually and their current and expected demand in the applicable markets are presented. Where available, global manufacturing capacities are presented to characterize the current size of the market and dominant locations.

Technologies and Markets

Seven energy storage technologies were selected for inclusion in this first report:

- Lithium-ion batteries
- Lead–acid batteries
- Pumped storage hydropower
- Compressed-air energy storage (CAES)
- Redox flow batteries (RFBs)
- Hydrogen (H_2)
- Building thermal energy storage (TES) – Ice.

The technologies covered in this report are addressed in both the stationary and transportation markets. Although some technologies (primarily Li-ion) are also used in the consumer electronics market, this market is not covered in depth. The report looks both at the historical deployments and projected demands of these technologies over the 2015–2030 time period. In some cases, important information was available prior to 2015 and is included for context. On the other hand, in some cases, information was not available to project the deployment of certain energy storage technologies through 2030. Where available, projections based on differing assumptions are offered for comparison, such as with the total energy storage global market.

The report looks at global deployment of all the technologies. Whenever possible, the information is disaggregated into the following regions:

- China
- United States
- Europe
- Rest of Asia (ROA)
- Rest of the world (ROW).

Deeper dives into the domestic market for several technologies (CAES, PSH, lead–acid) are also presented.

The two primary markets covered in this report are stationary and transportation, and each is further broken down into its sectors. Transportation has two major sectors: (1) mobility as either electric vehicles (xEVs) or fuel cell electric vehicles (FCEVs) and (2) starting, lighting, and ignition (SLI). The applications associated with each sector are further described in Table 1. The stationary storage market, much of which is related to grid and commercial resilience, is described in Table 2.

Table 1. Transportation Application Descriptions

Application Sector	Application Description
Mobility – battery storage	Electric vehicles (light-duty, medium-duty, and heavy-duty)
	Battery electric vehicle
	Plug-in hybrid electric vehicle
	Hybrid electric vehicle
Mobility – hydrogen storage	Hydrogen storage on FCEVs (light-duty, medium-duty, and heavy-duty)
SLI – starting, lighting, and ignition	Batteries in cars, trucks, boats, and other internal combustion motorized vehicles

Table 2. Stationary Application Descriptions

Sector Category	Application	Application Description
Grid-related – utility	Ancillary services	Provision or absorption of short bursts of power to maintain supply and demand and thus the frequency of the grid; frequency regulation and reserves
	Peaking capacity	Provision of capacity to meet system maximum demand
	Energy shifting	Uptake is driven by increasing system flexibility needs. Energy storage is charged during low prices and surplus supply and discharged to meet demand. Batteries can be charged from surplus renewable energy or from assets that, along with battery, become dispatchable
	Transmission-level	Use of an energy storage system as an alternative to traditional network reinforcement, such as to meet an incremental increase in transmission capacity instead of an expensive transmission line upgrade
	Distribution-level	Use of an energy storage system as an alternative to traditional network reinforcement such as to meet an incremental increase in distribution capacity instead of an expensive distribution line upgrade

Sector Category	Application	Application Description
Grid-related – residential		
Grid-related – C&I	C&I energy storage	Energy storage that is used to increase the rate of self-consumption of a PV system from a commercial or industrial customer
Grid-related – utility/residential and C&I	EV charging infrastructure	
LDES	Long-duration energy storage	
Industrial, including military use	Uninterruptible power source (UPS) + data centers	Use of batteries for uninterruptible power and data centers
	Telecom backup power	Telecommunications towers require UPS and backup power and are a significant demand in the stationary sector
	Air conditioning/ refrigeration	
	Hydrogen refueling stations	Refueling stations for FCEVs
	Motive (forklifts)	Commercial and industrial use of battery systems on forklifts for motive power

Literature Sources

An extensive literature search was conducted to identify available market data for the selected technologies. Relevant DOE sources were used to underpin the analysis and were augmented with private and public market data sources. Although more than 50 information sources were used in the development of this report, several sources contributed significantly:

DOE and National Labs

- U.S. Department of Energy, "DOE OE Global Energy Storage Database." DOE. https://www.sandia.gov/ess-ssl/global-energy-storage-database/ (Accessed July 8, 2020).
- U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office, "Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source," U.S. DOE, Washington, D.C., DOE/GO-102016-4869, 2016. Available: https://www.energy.gov/sites/prod/files/2018/02/f49/Hydropower-Vision-021518.pdf
- M. Brown *et al.*, "Regional Energy Deployment System (ReEDS) Model Documentation: Version 2019," National Renewable Energy Laboratory, Golden, CO, NREL/TP-6A20-74111, 2020. Available: https://www.nrel.gov/docs/fy20osti/74111.pdf.

Bloomberg New Energy Finance

- Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/
- Bloomberg New Energy Finance, "2019 Long-Term Energy Storage Outlook," BloombergNEF, New York, 2019. Available: https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/

International Energy Agency

- International Energy Agency, "Global EV Outlook 2020: Entering the decade of electric drive?" IEA, Paris, June 2020. Available: https://www.iea.org/reports/global-ev-outlook-2020.

Avicenne Energy

- C. Pillot, "Lead Acid Battery Market," Avicenne Energy, Paris, 2019, unpublished.
- C. Pillot. (May 2019). The Rechargeable Battery Market and Main Trends 2018-2030. Presented at Advanced Automotive Battery Conference. Available: https://niobium.tech/en/pages/gateway-pages/pdf/technical-briefings/the-rechargeable-battery-market-and-main-trends-2018-2030.

International Hydropower Association (IHA)

- IHA, "The world's water battery: Pumped hydropower storage and the clean energy transition," IHA, London, December 2018. Available: https://www.hydropower.org/publications/the-world-e2-80-99s-water-battery-pumped-hydropower-storage-and-the-clean-energy-transition
- IHA, "Pumped Storage Tracking Tool." IHA. https://www.hydropower.org/hydropower-pumped-storage-tool (Accessed Sep. 20, 2020).

Assumptions and Data Quality

This report is a compilation of a wide range of technologies and markets to provide a high-level snapshot of the markets for the selected technologies. It is out of the scope of this report to determine the "best" source or that the assumptions among reports were consistent. Rather, reputable and reliable sources of information were compiled, including high-level summaries of the underlying assumptions, to show the breadth of potential market outcomes.

Report Limitations

Another important component of this broad summary is to help identify those areas where information is lacking or incomplete. Although the overall objective of this report was to report on the deployment, future projections, and manufacturing of each technology, in many cases—especially with respect to manufacturing—information was simply not available. In most cases, this is because some technologies (e.g., CAES) are not based on a specialized unit such as a battery, but instead are technology systems made up of common components (e.g., compressors). These common components can be sourced from multiple companies and can be used in multiple applications, including non-storage applications. Thus, tracking the manufacturing and development of these systems is difficult. Other technologies (e.g., RFBs) are relatively new and so manufacturing information is sparse or nonexistent.

High-Level Energy Storage Market Summary

This section summarizes the current global deployment and projected demand across both markets and by sector within each market. Due to the availability of information, the grid-related sector within stationary storage is examined in the greatest detail, with summaries by application and global region, including a summary of domestic regions and applications.

The global stationary and transportation combined annual energy storage market projections are summarized in Figure 1.[2] *Market is projected to increase fourfold by 2030 to more than 2,500 GWh, from a 2018 baseline.* The vast majority of this growth is due to the adoption of xEVs; in fact, aggressive adoption (i.e., 30% of vehicle sales) of xEVs could result in up to a 4-TWh market [2]. Transportation annual storage deployments are 2–10 times that of stationary, including PSH, depending upon the assumptions for the transportation deployment. Lower deployments (2 times) generally assume only current policies, whereas higher deployments (10 times) assume policies favoring mobility electrification. These scenarios are described in more detail in the Li-ion section.

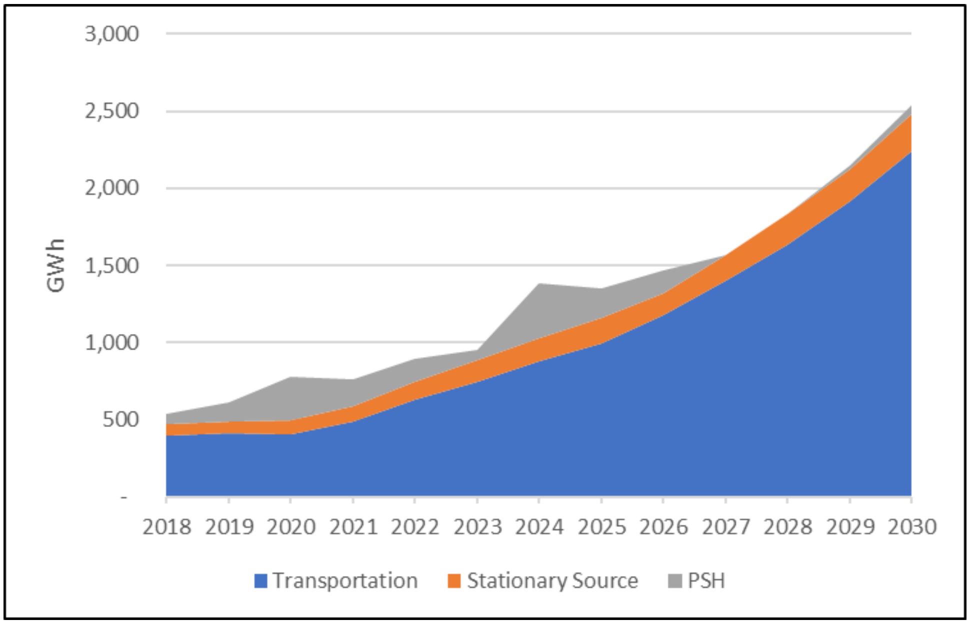

Figure 1. Global energy storage market

Sources: [3] Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.
[4] C. Pillot, "Lead Acid Battery Market," Avicenne Energy, Paris, 2019.
[5] Bloomberg New Energy Finance, "2019 Long-Term Energy Storage Outlook," BloombergNEF, New York, 2019. Available: https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/
[6] International Hydropower Association, "The world's water battery: Pumped hydropower storage and the clean energy transition," IHA, London, December 2018. Available: https://www.hydropower.org/publications/the-world-e2-80-99s-water-battery-pumped-hydropower-storage-and-the-clean-energy-transition.

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[2] PSH is separated from the rest of the stationary storage as it is generally reported in gigawatts, instead of gigawatt-hours, and its storage duration is often is not not available. For this diagram, it was estimated with a 21-h storage duration based on a range of 18–24 h.

Transportation Sector

SLI applications (included in Figure 1), exclusively lead–acid today, currently dominate the transportation market as they are used with all types of vehicles—internal combustion engine vehicles, xEVs, and FCEVs. They are expected to grow slowly through 2030, following global vehicle sales. Annual mobility storage deployments, which are currently a fraction of SLI, will likely exceed SLI for the first time in 2023, with explosive growth expected through 2030. Mobility storage includes both onboard battery and hydrogen storage. Storage on battery electric vehicles and plug-in hybrid vehicles is dominated by lithium-ion batteries. Hybrid electric vehicles can employ other battery chemistries such as nickel metal hydride. Figure 2 summarizes the projected growth of the transportation sector.

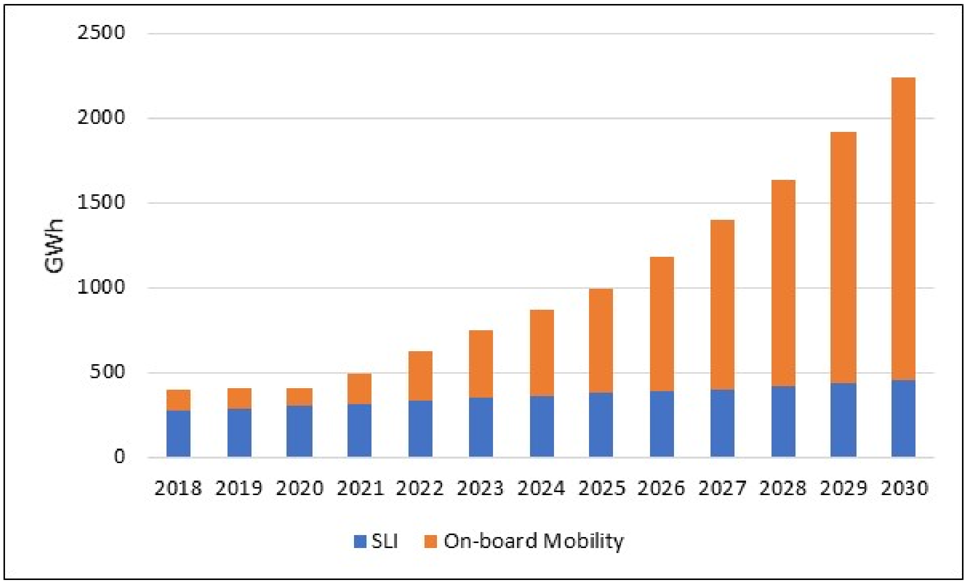

Figure 2. Projected global annual transportation energy storage deployments

Sources: [2] International Energy Agency, "Global EV Outlook 2020: Entering the decade of electric drive?" IEA, Paris, June 2020. Available: https://www.iea.org/reports/global-ev-outlook-2020.
[4] C. Pillot, "Lead Acid Battery Market," Avicenne Energy, Paris, 2019, unpublished.

Stationary Market

Figure 3 offers a more detailed breakdown of the global stationary market, showing ~150 GWh/yr in 2018 growing to 380 GWh/yr by 2030, with a peak at 535 GWh/yr in 2024 [4], [5], [6]. PSH is generally deployed as large-sized singular projects with long lead times, and so these deployments do not follow a smooth curve. Currently, industrial applications are significantly higher than grid-related deployments with an 8% CAGR. Industrial motive storage (e.g., forklifts) are a large segment of this market, followed by UPS and telecom applications. By 2030, however, grid-based applications surpass industrial applications due to its significant growth (27% CAGR).

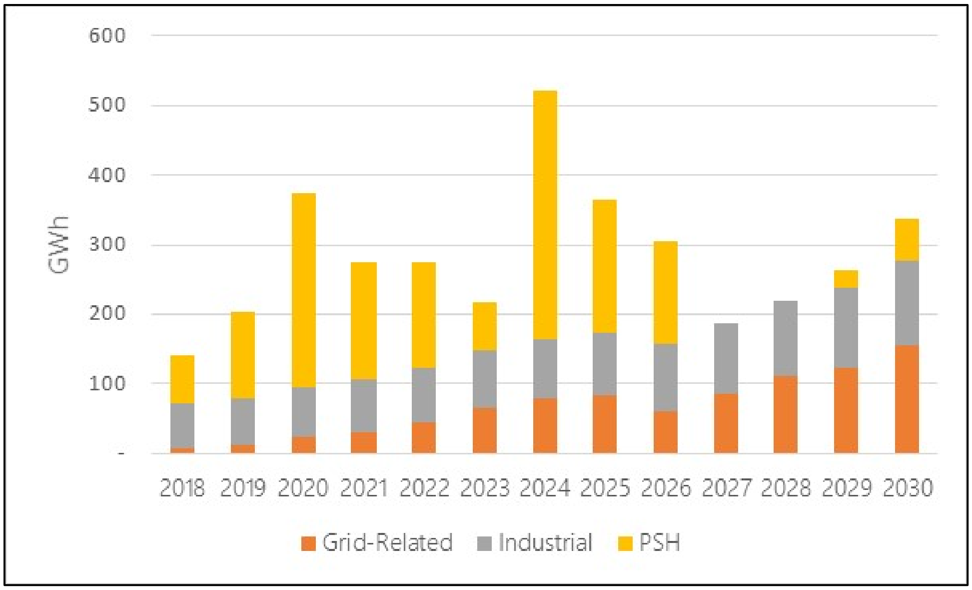

Figure 3. Global annual stationary-source projections by sector

Sources: [4] C. Pillot, "Lead Acid Battery Market," Avicenne Energy, Paris, 2019, unpublished.
[5] Bloomberg New Energy Finance, "Energy Storage Outlook 2019," BloombergNEF, New York, 2019. Available: https://about.bnef.com/
[6] International Hydropower Association, "The world's water battery: Pumped hydropower storage and the clean energy transition," IHA, London, December 2018. Available: https://www.hydropower.org/publications/the-world-e2-80-99s-water-battery-pumped-hydropower-storage-and-the-clean-energy-transition.

Grid-Related

Grid-related global deployment, segmented by region, is summarized in Figure 4 [5]; it was about 10 GWh in 2019 and is projected to increase 15 times, to almost 160 GWh, in 2030.[3] All regions show significant growth over this period, with China showing the largest increase at 8.6 times, increasing from 3.8 GWh in 2020 to 32.6 GWh in 2030. Europe, the United States, and ROA increase 5–7 times over this same period, with the United States deploying 34.3 GWh in 2030 and Europe and ROA reaching 31.2 and 11.4 GWh, respectively. Grid-related transformations, which require energy storage, are global in scope; this is illustrated by the fact that ROW is the region showing the greatest deployments (45 GWh) by 2030.

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[3] The drop in deployment in 2026 is an artifact of Bloomberg New Energy Finance's (BNEF's) models due to a drop in the projections of power plant retirements. They would expect deployments to be more evenly spread out (email from J. Frith, BNEF, to V. Putsche, National Renewable Energy Laboratory [NREL], September 25, 2020).

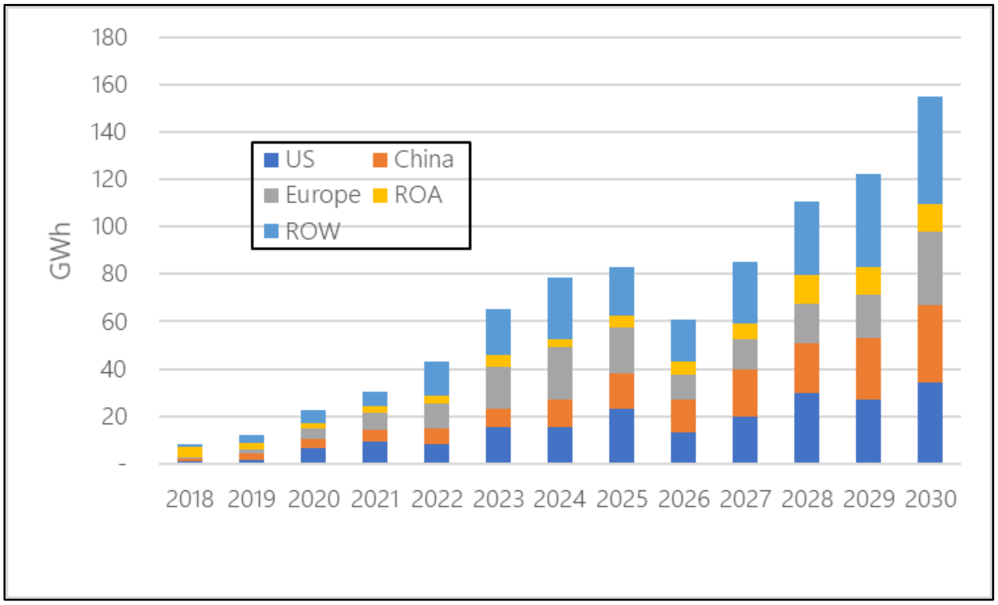

Figure 4. Global projected grid-related annual deployments by region (2015–2030)

Source: [5] Bloomberg New Energy Finance, "2019 Long-Term Energy Storage Outlook," BloombergNEF, New York, 2019. Available: https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/

Bloomberg New Energy Finance (BNEF) also looked at the deployment of grid-related applications in its 2019 long-term energy storage outlook [5], summarized in Figure 5. C&I PV plus storage, often known as hybrid systems, as well as energy-shifting applications, show the most growth over the period. BNEF [5] expects annual expenditures in this sector will increase 3.5 times, from $8.6 billion in 2020 to $30.1 billion in 2030.

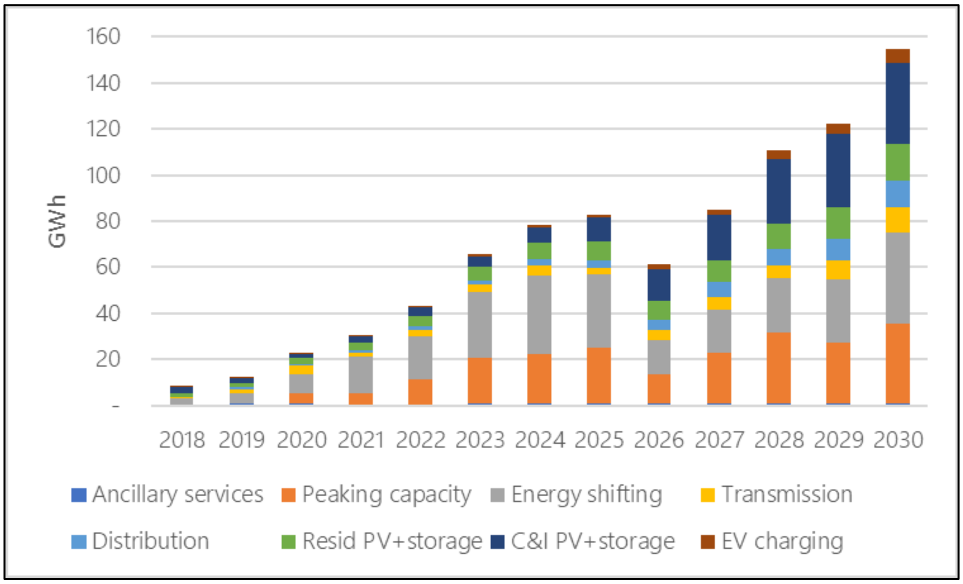

Figure 5. Global projected grid-related annual deployments by application (2015–2030)

Source: [5] Bloomberg New Energy Finance, "2019 Long-Term Energy Storage Outlook," BloombergNEF, New York, 2019. Available: https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/

BNEF [5] also looked at the projected domestic market for grid-related applications. They expect annual U.S. stationary storage deployment to more than quadruple from 2019 to 2022 [5], as shown in Figure 6 (regional) and Figure 7 (application). Much of the growth is expected as energy-shifting applications[4] in California. Peaking capacity and residential applications will show strong growth as well.

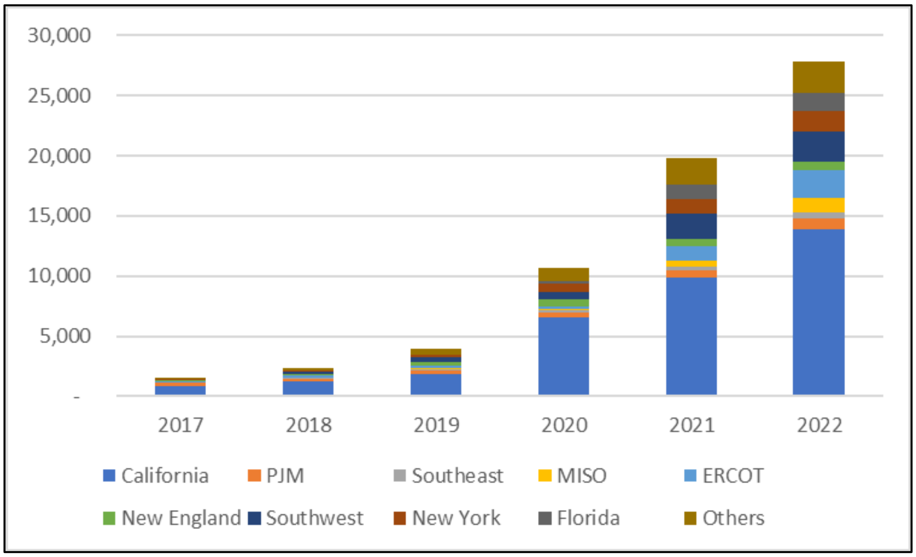

Figure 6. Projected cumulative U.S. grid-related deployment by electric power region[5] (2015–2022)

Source: [5] Bloomberg New Energy Finance, "2019 Long-Term Energy Storage Outlook," BloombergNEF, New York, 2019. Available: https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/

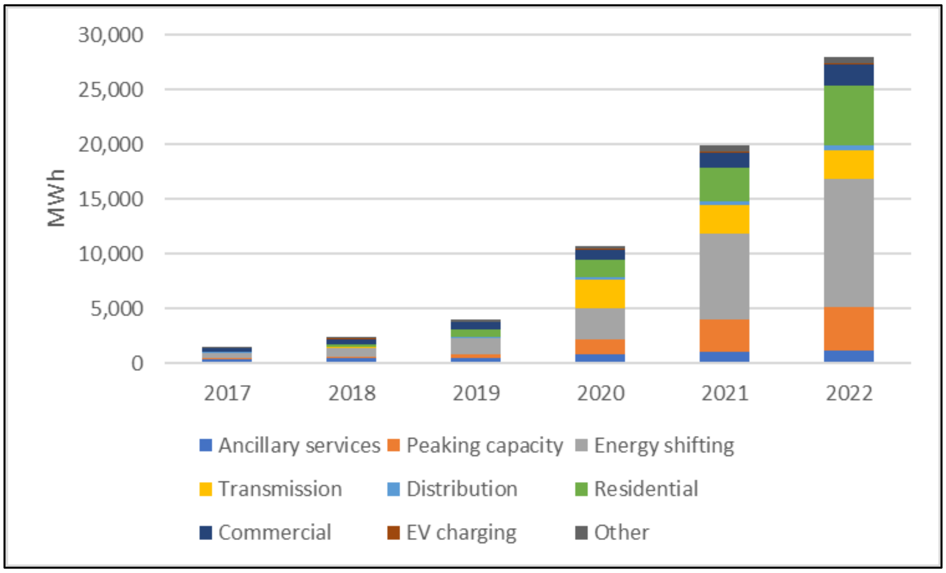

Figure 7. Projected cumulative U.S. grid-related deployment by application (2015–2022)

Source: [5] Bloomberg New Energy Finance, "2019 Long-Term Energy Storage Outlook," BloombergNEF, New York, 2019. Available: https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/

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[4] Energy-shifting applications use surplus renewable energy or other assets to charge batteries and that, along with the batteries, becomes dispatchable [5].

[5] Electric power regions: California (CA), New England (CT, ME, MA, NH, RI, and VT), Midcontinent Independent System Operator (MISO) (all or part of MT, ND, SD, MN, WI, MI, IA, IL, IN, IA, MO, AR, LA, MS, and TN), Northwest (WA, OR, ID, WY, MT, UT, British Columbia, Alberta, and small portion of Northern CA), PJM (all or part of DE, IL, IN, KY, MD, MI, NJ, NC, OH, PA, TN, VA, and WV), Southeast (all or part of GA, AL, MS, NC, SC, MO, and TN), Southwest (AZ, NM, southern NV, CO, and small parts of WY, SD, and NE), Electric Reliability Council of Texas (ERCOT) (most of TX), and Others (Southwest Power Pool [SPP] – KS, OK, and parts of MT, ND, SD, MO, AR, LA, and NM).

Industrial

Global industrial energy storage segments are detailed in Figure 8 [4]. This sector includes applications such as telecom industry backup power, UPS, data centers, FCEV refueling, and forklifts. Global industrial energy storage is projected to grow 2.6 times, from just over 60 GWh to 167 GWh in 2030. The majority of the growth is due to forklifts (8% CAGR). UPS and data centers show moderate growth (4% CAGR) and telecom backup battery demand shows the lowest growth level (2% CAGR) through 2030.

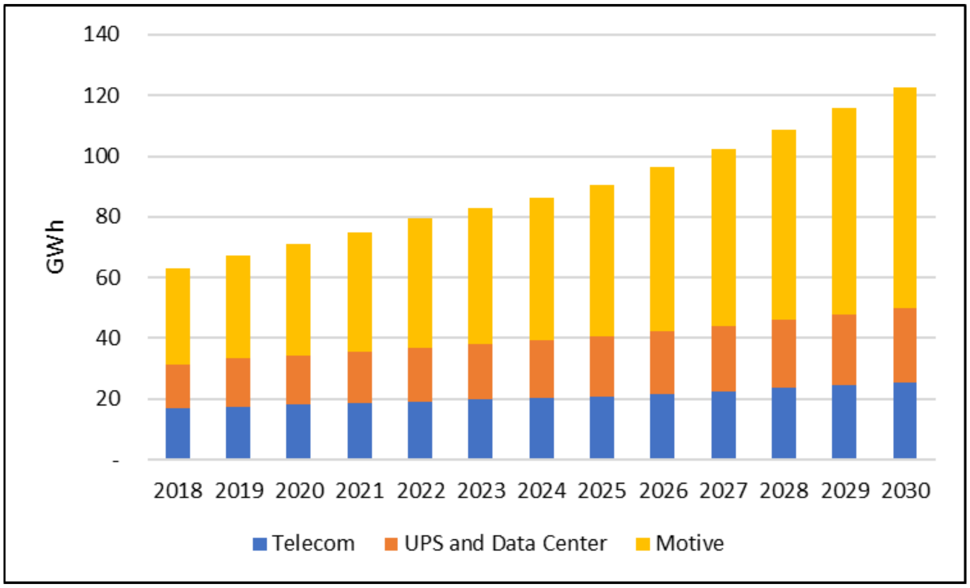

Figure 8. Projected global industrial energy storage deployments by application

Source: [4] C. Pillot, "Lead Acid Battery Market," Avicenne Energy, Paris, 2019, unpublished.

Data center energy demand is important in estimating the size of the DC backup market. It is a mixed function of true demand, including overcapacity for mission-critical needs. Data center annual energy consumption estimates for 2020 cover a range of 200–1,000 TWh [7], [8]. Assuming that the data centers would need to meet the average load of 600 TWh for up to 20 minutes once per day would require 23 GWh of energy storage. Energy storage needs would increase if the time for backup or the DC load required is higher.

DC energy storage technology is transitioning away from primarily lead–acid to alternatives that have longer cycle and calendar life, such as Li-ion. Li-ion flammability, however, is an issue that requires some system engineering. Another new storage chemistry that provides both high power and very long cycle life, Prussian blue chemistry, can meet the demanding DC market performance requirements. DOE funded a startup with this chemistry and their 2020 launch exceeds 50,000 kW [9].

Lithium-Ion Batteries

Li-ion batteries are deployed in both the stationary and transportation markets. They are also the major source of power in consumer electronics. Most analysts expect Li-ion to capture the majority of energy storage growth in all markets over at least the next 10 years [2], [3], [4], [5], [10].

Li-Ion Market

Li-ion is the *fastest-growing* rechargeable battery segment; its global sales across all markets more than doubled between 2013 and 2018. The transportation sector dominates the Li-ion market and is also the fastest growing, with just 1% of automotive sales consuming 60% of Li-ion batteries [10]. Christophe Pillot of Avicenne reports [10] that the Li-ion market was $40 billion in 2018, and as shown in Figure 9, this corresponded to a global deployment of 172 GWh, rising to 195 GWh in 2019 [3].

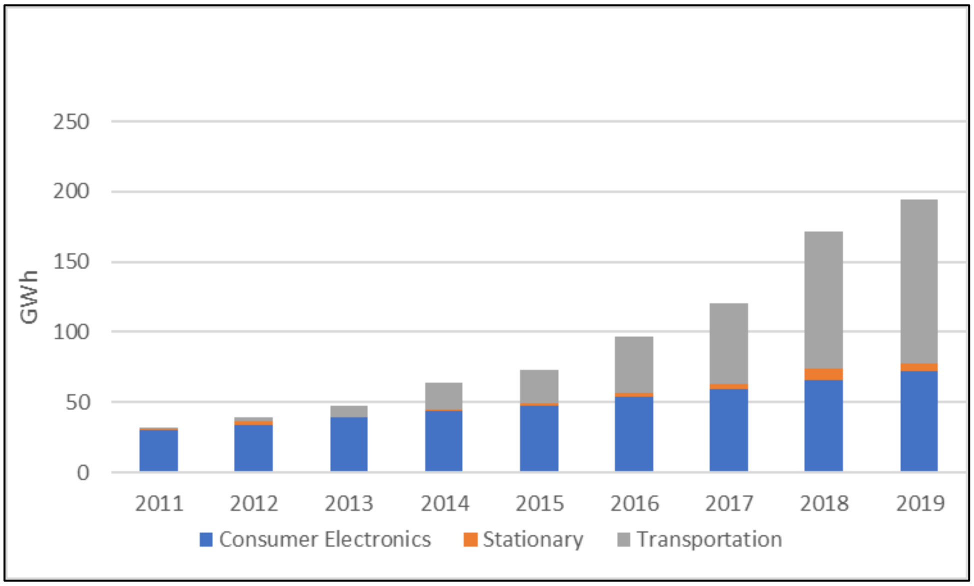

Figure 9. Historical annual global Li-ion deployment – all markets

Source: [3] Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.

Several analysts have projected the Li-ion markets to 2030. The underlying assumptions, as well which markets are included in the analyses, depend upon the specific source. This section provides a high-level summary of these analyses and assumptions.

BNEF [3] and Pillot [10] projected Li-ion deployment for 2030 for all markets, as shown in Figures 10 and 11, respectively. BNEF developed a single scenario and projects just over 2 TWh across consumer electronics, stationary storage, and transportation. Avicenne's projections included these markets as well as an "other" market (e.g., medical devices and power tools) for two scenarios: Base (0.9 TWh) and Realistic (1.2 TWh).[6] All three scenarios over both studies project the transportation sector to dominate

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[6] Avicenne does not present detailed descriptions of either scenario, but both are presented here to show potential options.

(i.e., comprise >90%) Li-ion deployment over the study period. BNEF projects 1.8 TWh of Li-ion for transportation in 2030, whereas Avicenne projects 0.7–1.0 TWh.

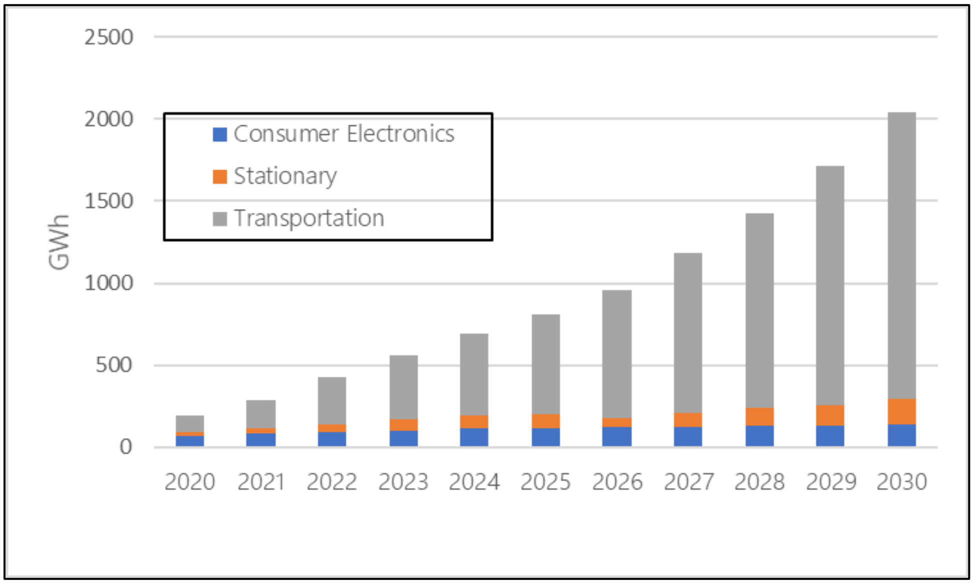

Figure 10. BNEF projected global Li-ion deployment – all markets

Source: [3] Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.

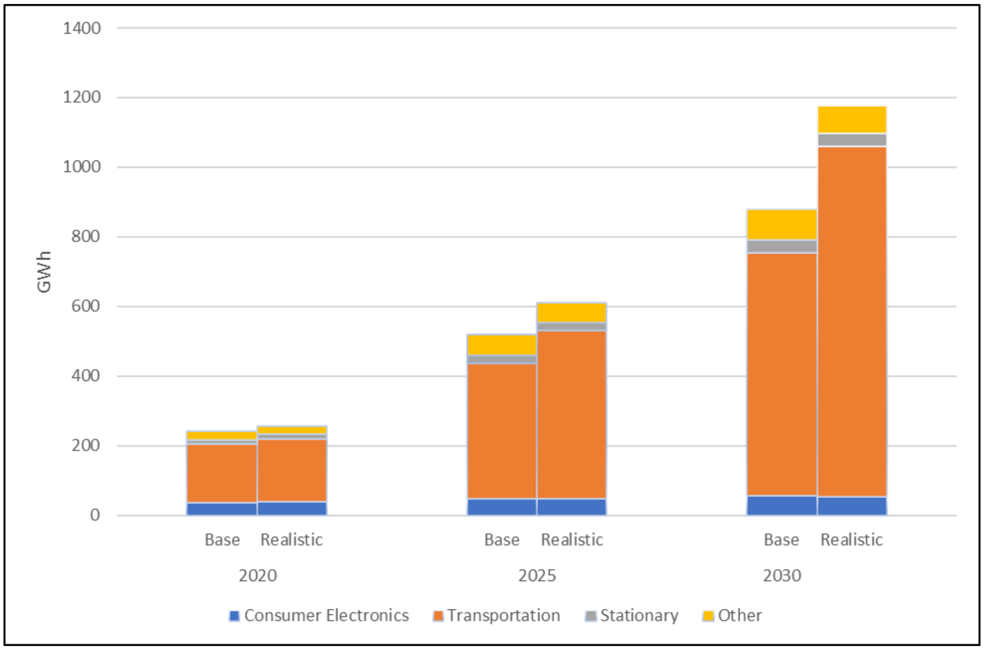

Figure 11. Avicenne global Li-ion projections – all markets

Source: [10] C. Pillot. (May 2019). The Rechargeable Battery Market and Main Trends 2018-2030. Presented at Advanced Automotive Battery Conference. Available: https://niobium.tech/en/pages/gateway-pages/pdf/technical-briefings/the-rechargeable-battery-market-and-main-trends-2018-2030.

The International Energy Agency (IEA) *Global EV Outlook 2020* [2] evaluated the transportation sector only and projected xEV (hybrid and plug-in hybrid electric vehicle) sales by country. The first scenario evaluated was “Stated Policies,” or STEPS, and is based on current goals, plans, and policy measures. Included in this scenario are the effects of achieving national xEV deployment targets, internal combustion engine vehicle phase-out plans, purchase incentives, and current and announced policies for seven major markets (Canada, Chile, China, European Union, India, Japan, and the United States). It also considers announcements from original equipment manufacturers regarding plans to expand the range of xEV models offered and plans for scaling up their production [2].

The Li-ion storage required in 2030 for the vehicles in the STEPS scenario was estimated[7] at 1.6 TWh, which is similar to BNEF’s [3] 1.8-TWh estimate. Figures 12 and 13 detail the IEA STEPS scenario by mobility segment and region, respectively. As shown in the figures, light-duty vehicles comprise the largest class of mobile Li-ion storage and China has the largest market for mobile Li-ion storage.

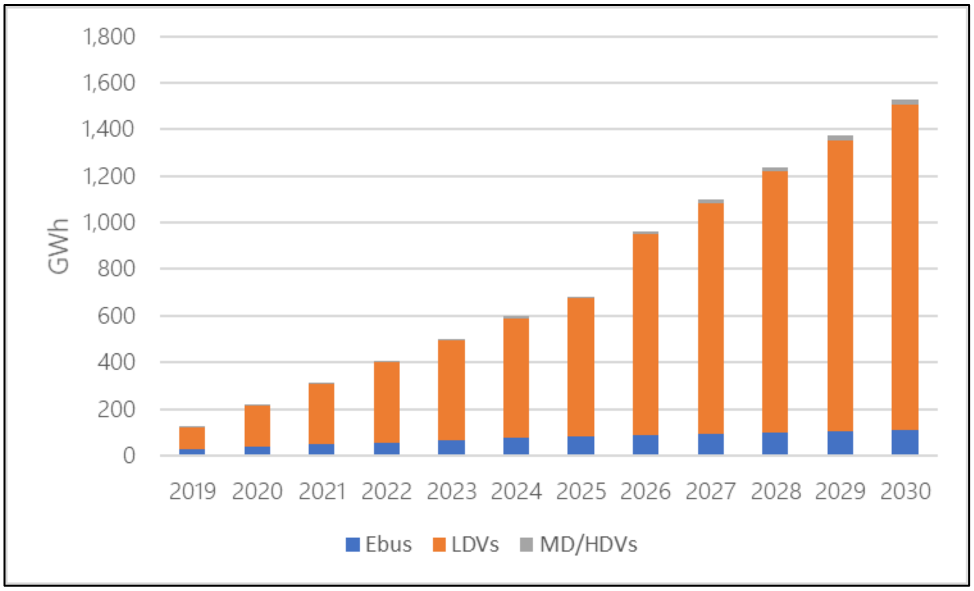

Figure 12. Projected global Li-ion deployment in xEVs by vehicle class for IEA STEPS scenario (Ebus: electric bus; LDVs: light-duty vehicles; MD/HDVs: medium- and heavy-duty vehicles)

Source: [2] International Energy Agency, "Global EV Outlook 2020: Entering the decade of electric drive?" IEA, Paris, June 2020. Available: https://www.iea.org/reports/global-ev-outlook-2020.

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[7] Li-ion storage was estimated from the global vehicle sales by class and typical onboard battery sizes for each vehicle class.

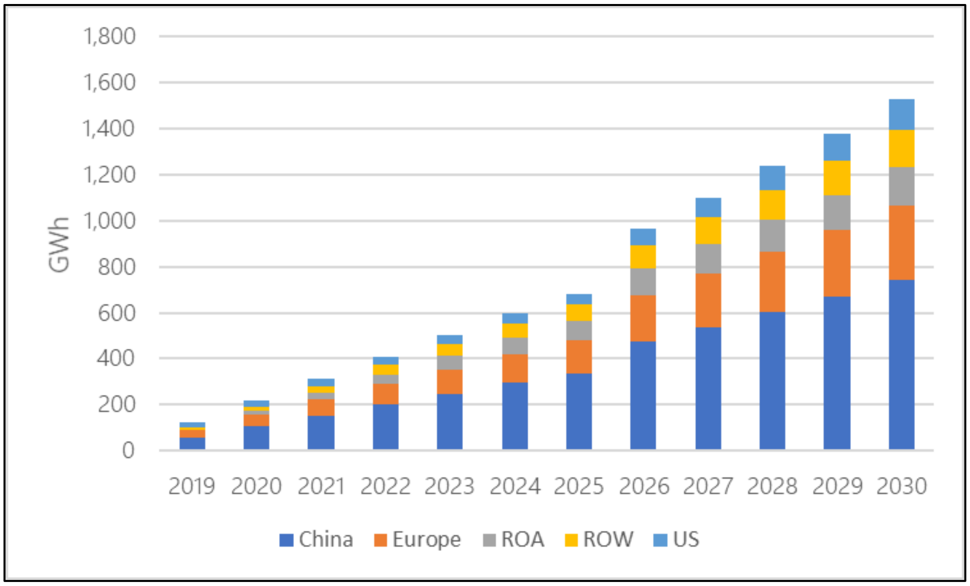

Figure 13. Projected Global Li-ion Deployment in xEVs by Region for IEA STEPS Scenario

Source: [2] International Energy Agency, "Global EV Outlook 2020: Entering the decade of electric drive?" IEA, Paris, June 2020. Available: https://www.iea.org/reports/global-ev-outlook-2020.

IEA [2] also evaluated a second scenario, the "Sustainable Development Scenario," which assumes that the xEVs capture 30% of vehicle sales share for light-, medium-, and heavy-duty vehicles and buses globally [2]. Under this scenario, up to 3 TWh of Li-ion mobility capacity could be added by 2030. Figure 14 compares the two IEA scenarios.

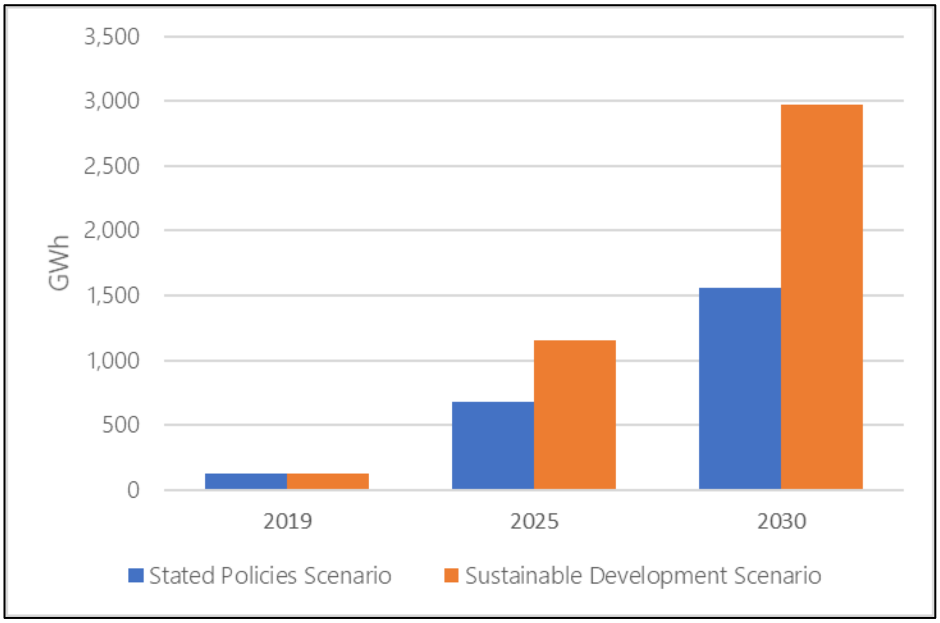

Figure 14. Projected Global Annual Li-ion Deployments in xEVs for IEA Scenarios

Source: [2] International Energy Agency, "Global EV Outlook 2020: Entering the decade of electric drive?" IEA, Paris, June 2020. Available: https://www.iea.org/reports/global-ev-outlook-2020.

Despite many projections otherwise, the European electric-car market exceeded China for the first time in 2020; further, it is expected to reach over 1 million xEVs in 2020 [11]. This growth is related to Europe's sustained policies and subsidies, whereas China has reduced their EV subsidies. Germany, for example, has set targets of 7–10 million xEVs by 2030, and is offering up to €9,000 for new EVs and hybrids [12]. Germany is also investing greater than €1.5 billion in battery cell research and production, targeting initial 2020 manufacturing, which will transition to production scale by the mid-2020s [12].

To support the rapid expansion of the EV market, numerous companies, countries, and municipalities are investing in EV charging infrastructure. Global EV charging ports recently surpassed 1 million, which is a doubling over last 3 years. Europe leads in the expansion, increasing its EV charging infrastructure fivefold between 2017 and 2020. Over the same period, China's growth expanded by 158% and U.S. growth was 65%. Japan, which has invested heavily in hydrogen fuel cell vehicles, saw only a 30% expansion [13].

In contrast to growth in transportation, the United States is a leader in global stationary storage deployments. This is usually because renewables are often the lowest-cost generation source, but require storage to mitigate variability. For example, the California grid is estimated to need 12 GW of energy storage for balancing after solar replaces 9 GW of retired gas generation [14]. The California Public Utilities Commission has thus far approved a total of 5.1 GW, which is planned out to 2022.

Li-Ion Manufacturing

The majority of global Li-ion cell manufacturing is in China, the United States, Asia, and Europe, as shown in Figure 15 [15]. China dominates today with nearly 80% of the global manufacturing capacity (~525 GWh); additionally, it has over 60% of near-term (2025) 1,400 GWh, which is either planned or under construction (Figure 16). For comparison, the Rocky Mountain Institute projects a 2023 global Li-ion manufacturing capability of 1,300 GWh, with half of that in China [16].

The United States is the second-largest manufacturer of battery cells at 8% of current global capacity, primarily due to the Tesla-Panasonic plants in Nevada. The United States also has 6% (~90 GWh) of the facilities planned/under construction. With aggressive new legislation and government-backed financing, manufacturing in Europe is expected to grow significantly.

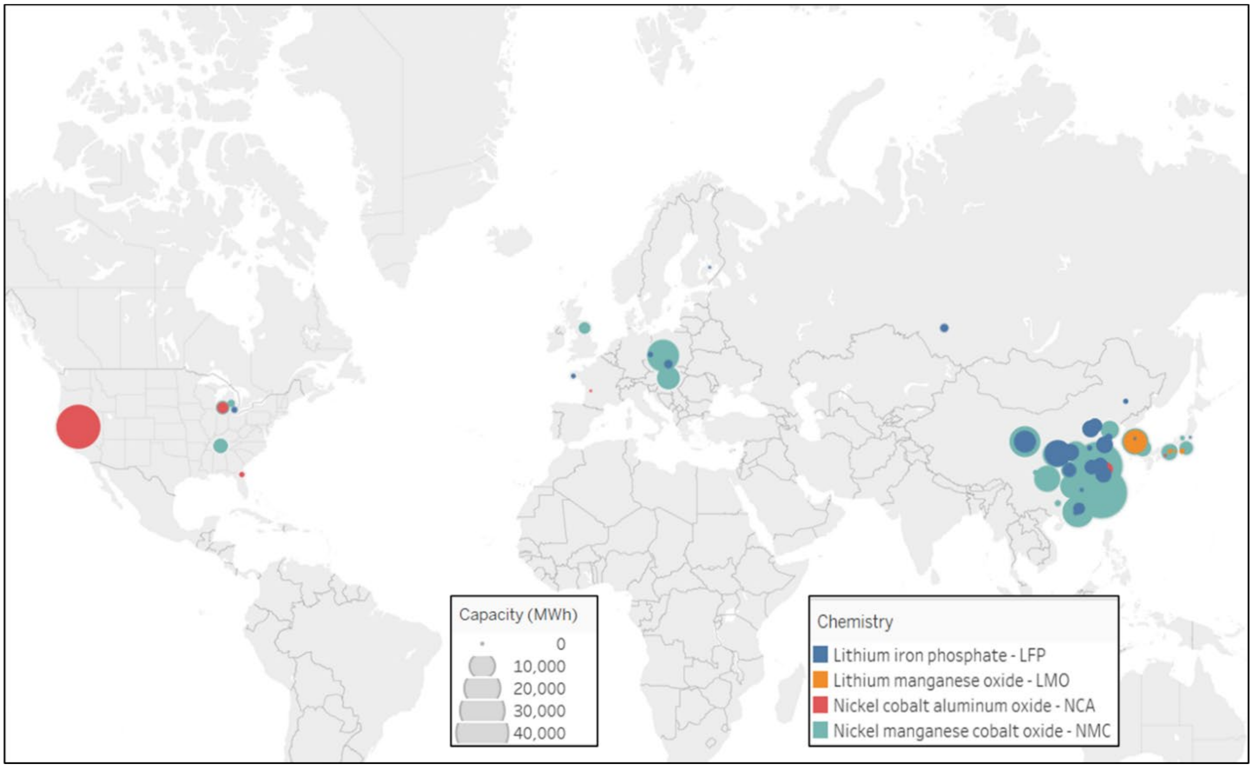

Figure 15. Global Li-ion battery cell manufacturing

Source: [15] Bloomberg New Energy Finance, "Storage Data Hub, Cell Manufacturers," BloombergNEF, New York, 2020. Available: https://about.bnef.com/

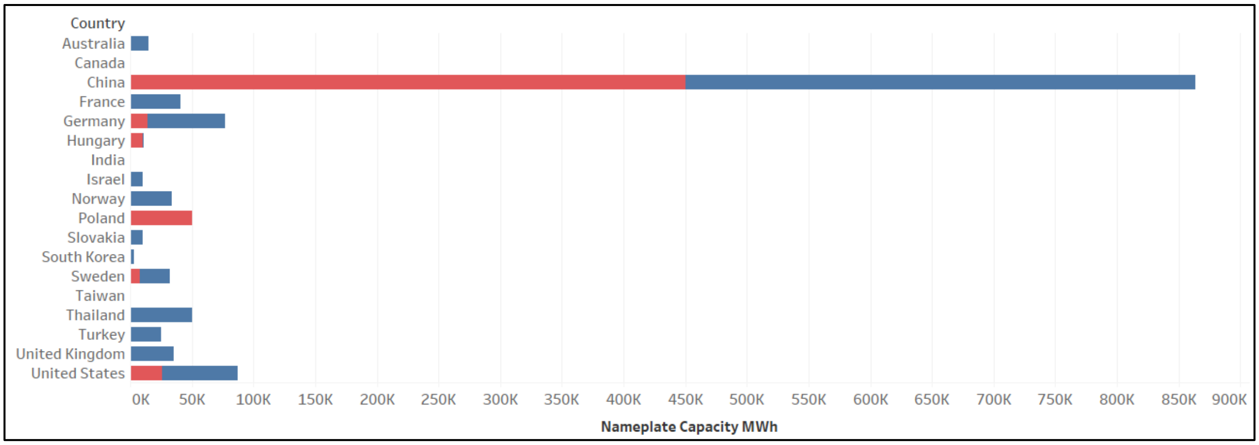

Figure 16. Li-ion battery manufacturing planned (**blue**) or under construction (**red**)

Source: [15] Bloomberg New Energy Finance, "Storage Data Hub, Cell Manufacturers," BloombergNEF, New York, 2020. Available: https://about.bnef.com/

Although China's dominance in manufacturing today is well-established, mobility-fueled growth may change the global footprint in the future. Europe has enacted strong policies and incentives for local and regional growth that supports xEVs. The European Battery Alliance projects that the market for Eureopean-manufactured batteries could be €250 billion by the mid-2020s [11]. Currently, two gigafactories—plants that will produce enough batteries for over one million EVs—are planned in Dourvin, France, and Kaiserslautern, Germany [17], with French and German public investment of €1.5 billion and €3.5 billion, respectively, from private investors.

Figure 17 [18] summarizes the global manufacturing capacity of four of the major components in a lithium-ion battery: anodes, cathodes, electrolyte salts, and electrolyte solutions.[8] Currently, Li-ion anodes are primarily composed of graphite and are manufactured in five countries: China, Japan, the United States, the Republic of Korea, and India, which are responsible for 76%, 13%, 6%, 4%, and 1%, respectively, of global production. Li-ion cathodes, which have varied in composition as new lower-cobalt chemistries have become technically viable, are manufactured in nine countries. Over half (58%) are manufactured in China, followed by Japan and the Republic of Korea, which each have almost 17%. The United States manufactures <1% of global cathodes. China manufactures the majority of electrolyte salts and solutions as well as separators, the fifth major Li-ion component.

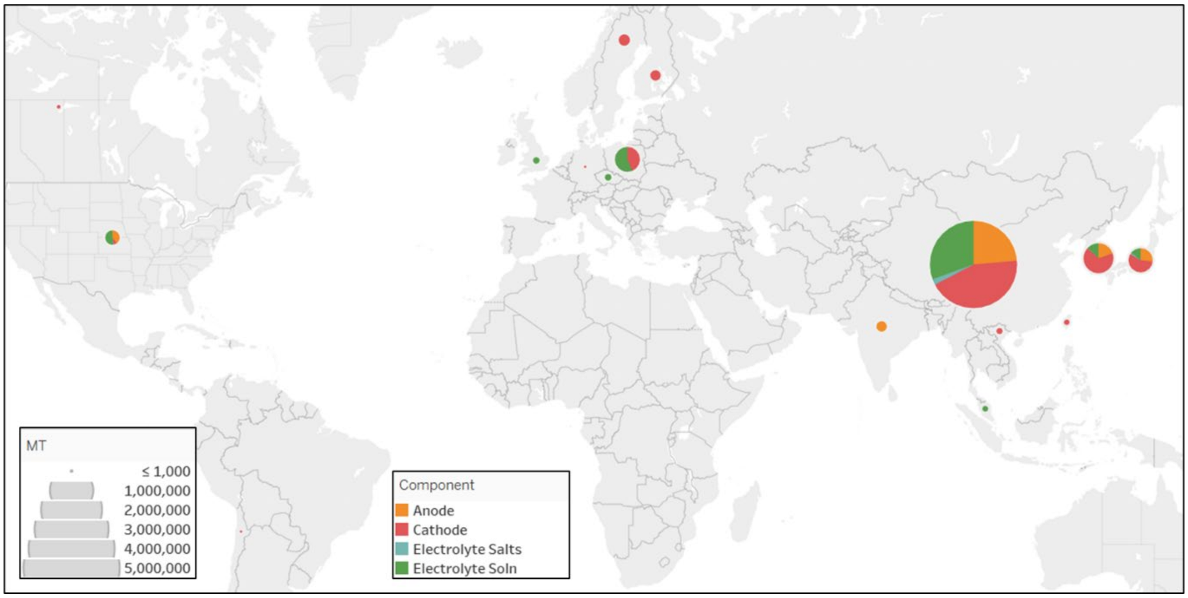

Figure 17. Global Li-ion component manufacturing

Source: [18] Bloomberg New Energy Finance, "Storage Data Hub, Component Manufacturers," BloombergNEF, New York, 2020. Available: https://about.bnef.com/

Li-Ion Research and Development

The U.S. Department of Energy's Vehicle Technologies Office has identified the major remaining challenges to commercializing batteries for xEVs (as well as 12-V start-stop micro-hybrid batteries): cost, performance, life, abuse tolerance, recycling, and sustainability [19]. Key areas of research directed toward these improvements include:

- Fast-charge capability
- Si anodes
- High-energy, low-cobalt cathodes
- High-voltage cathodes
- High-voltage electrolytes
- Lithium metal anodes

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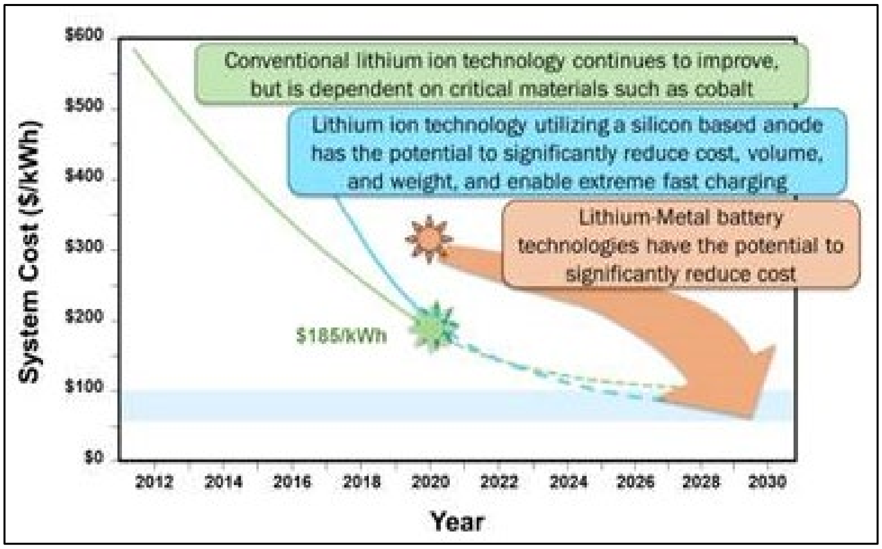
[8] Raw material (e.g., metals) supply and refinement and the distribution of various Li-ion chemistries are important considerations in the market for Li-ions but are outside the scope of the current document. See: D. Steward, A. Mayyas, and M. Mann, "Economics and Challenges of Li-Ion Battery Recycling from End-of-Life Vehicles," *Procedia Manufacturing*, vol. 33, pp. 272–279, 2019. Available: https://www.nrel.gov/docs/fy19osti/71350.pdf

- Solid-state batteries
- Battery recycling.

Figure 18 offers cost and technology trends for lithium-based xEV batteries [20]. Figure 19 offers an overview of the candidate battery technologies and their likely ability to meet the DOE cost goals [19]. Because of the large variation in different battery technologies, battery research also includes multiple activities focused on addressing the remaining high-cost areas within the entire battery supply chain [19], [20].



Conventional lithium ion technology continues to improve, but is dependent on critical materials such as cobalt

Lithium ion technology utilizing a silicon based anode has the potential to significantly reduce cost, volume, and weight, and enable extreme fast charging

Lithium-Metal battery technologies have the potential to significantly reduce cost

Figure 18. Cost and technology trends for lithium-based EV batteries

Source: [20] S. Boyd, "Batteries and Electrification R&D," in *2020 DOE Vehicle Technologies Office Annual Merit Review about Batteries and Electrification Technologies*, Washington DC, 2020. Available: https://www.energy.gov/node/4523480.

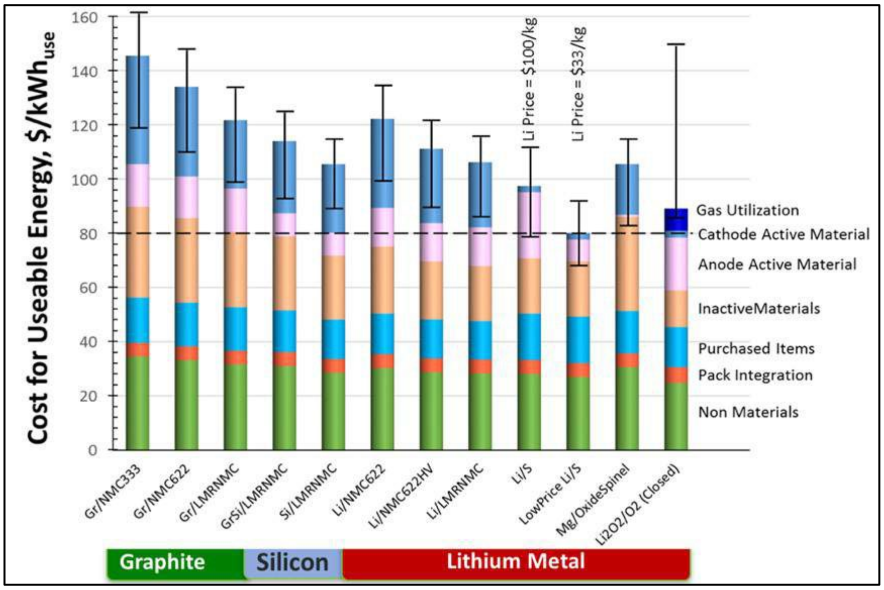


Figure 19. Potential for future battery technology cost reductions

Source: [19] U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office, “Batteries: 2019 Annual Progress Report,” U.S. DOE, Washington, D.C., DOE/EE-1987, 2020. Available: https://www.energy.gov/eere/vehicles/downloads/2019-annual-progress-report-batteries.

Lead–Acid Batteries

Lead–acid batteries are deployed in both the transportation and stationary markets, primarily providing SLI for all types of on- and off-road vehicles. Additionally, they provide a significant amount of energy storage for the industrial sector, including telecom battery backup, UPS and data centers, and forklifts. Lead–acid battery storage for grid-related applications is relatively minor today.

Lead–Acid Market

Annual global lead–acid battery sales grew by over 20% from 2013–2018 to $37 billion [10]. Currently, they provide >70% of all rechargeable markets; 75% of lead–acid sales are in the automotive SLI sector. Johnson Controls dominates this automotive sector with $23.3 billion; Enersys leads in industrial sales with $14.2 billion [10]. Figures 20 and 21 present the current global market for lead–acid in terms of percentage of storage capacity (GWh) by application and industry sales ($ billion), respectively.

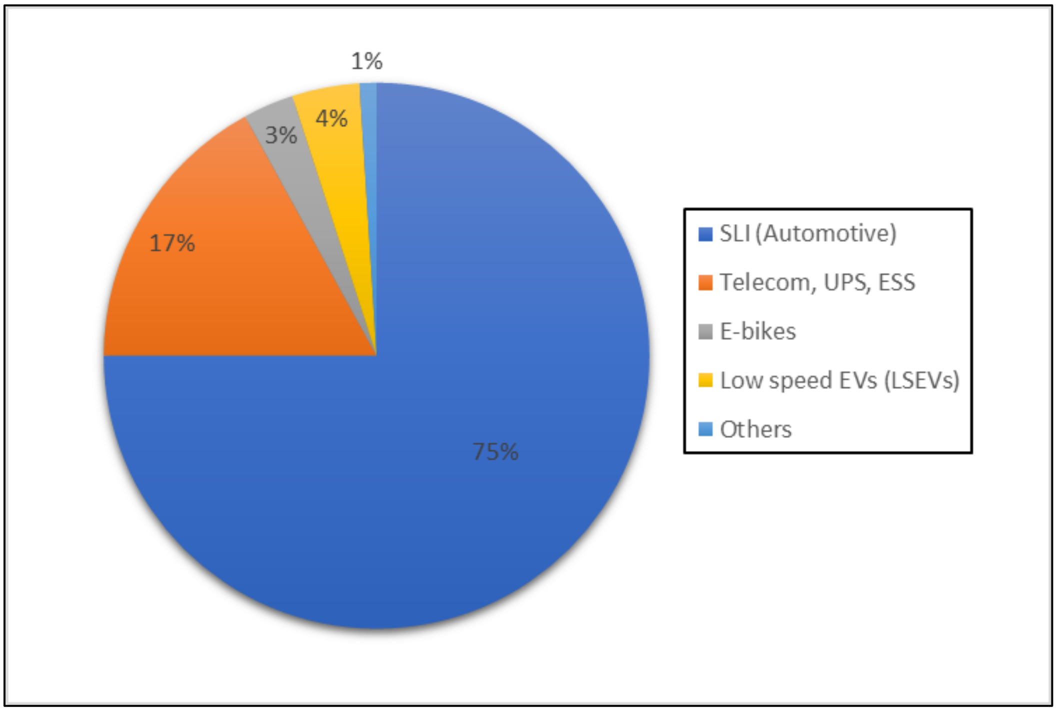


Figure 20. 2018 global lead–acid battery deployment by application (% GWh)

Source: [10] C. Pillot. (May 2019). The Rechargeable Battery Market and Main Trends 2018-2030. Presented at Advanced Automotive Battery Conference. Available: https://niobium.tech/en/pages/gateway-pages/pdf/technical-briefings/the-rechargeable-battery-market-and-main-trends-2018-2030.

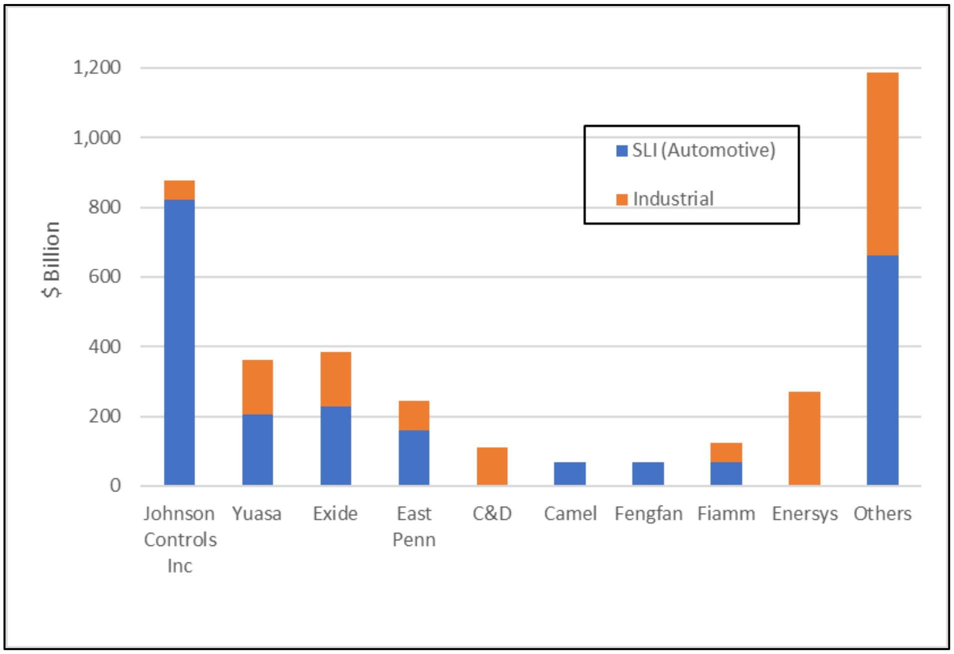


Figure 21. 2018 lead–acid battery sales by company

Source: [10] C. Pillot. (May 2019). The Rechargeable Battery Market and Main Trends 2018-2030. Presented at Advanced Automotive Battery Conference. Available: https://niobium.tech/en/pages/gateway-pages/pdf/technical-briefings/the-rechargeable-battery-market-and-main-trends-2018-2030.

Pillot [10] projects 5% annual growth in lead–acid battery demand through 2030 (Figure 22). Although lead–acid batteries are currently the most common battery in both stationary and transportation applications (for SLI), they are expected to still lead in capacity (GWh) by 2025, but may lag in sales dollars. The hope is that mild and start-stop hybrids will be a growth area for advanced lead–acid batteries in 2020 and beyond [4].

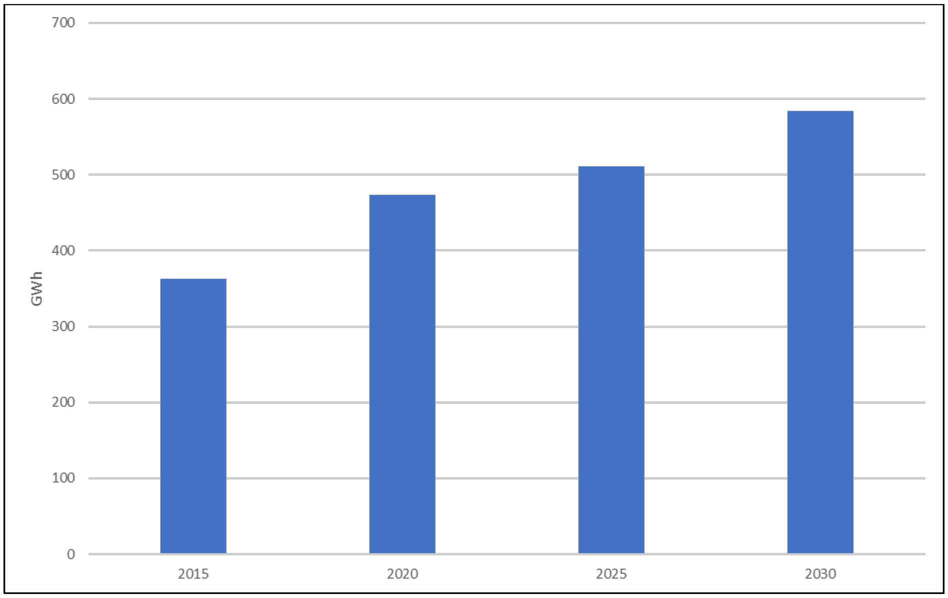


Figure 22. Projected global lead–acid battery demand – all markets

Source: [10] C. Pillot. (May 2019). The Rechargeable Battery Market and Main Trends 2018-2030. Presented at Advanced Automotive Battery Conference. Available: https://niobium.tech/en/pages/gateway-pages/pdf/technical-briefings/the-rechargeable-battery-market-and-main-trends-2018-2030.

New vehicle sales will create small increases in lead–acid battery SLI demand until the mid-2020s, at which point they are expected to level off (Figure 23). The total vehicle market for lead–acid batteries is ~5 times greater than that based on new vehicles due to battery replacements (3-yr life). Although batteries are larger in medium- and heavy-duty vehicles, over 70% of all of the SLI energy storage (GWh) is in light-duty vehicles due to their significant advantage in total sales (Figure 24).

Advanced lead–acid batteries for micro (48-V) and start-stop (12-V) hybrid vehicles are a potential area of growth for lead–acid batteries. Micro-hybrids save 5% fuel over conventional vehicles and are up to 10 times less expensive than a full-hybrid electric vehicle [4].

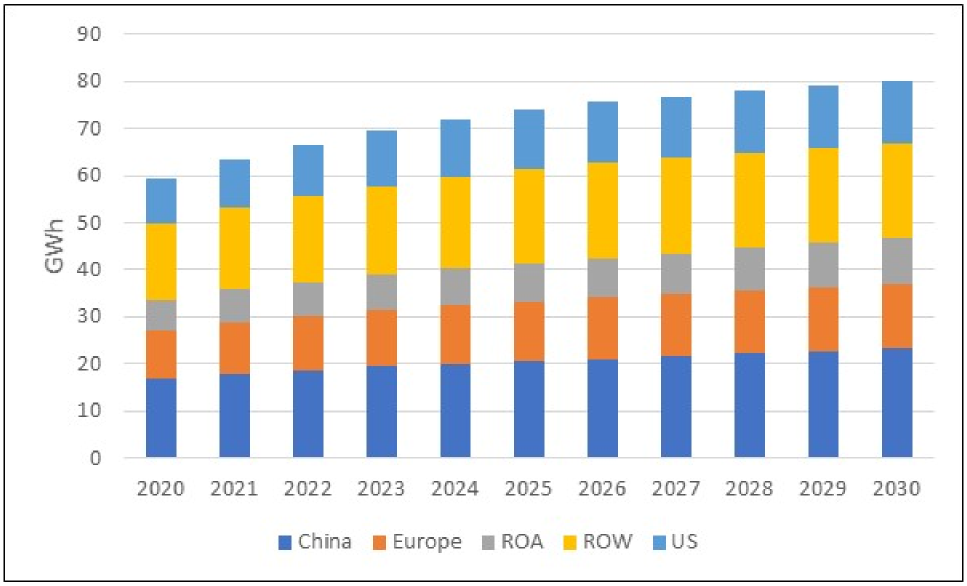


Figure 23. Projected lead–acid capacity increase from vehicle sales by region based on BNEF

Source: [3] Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.

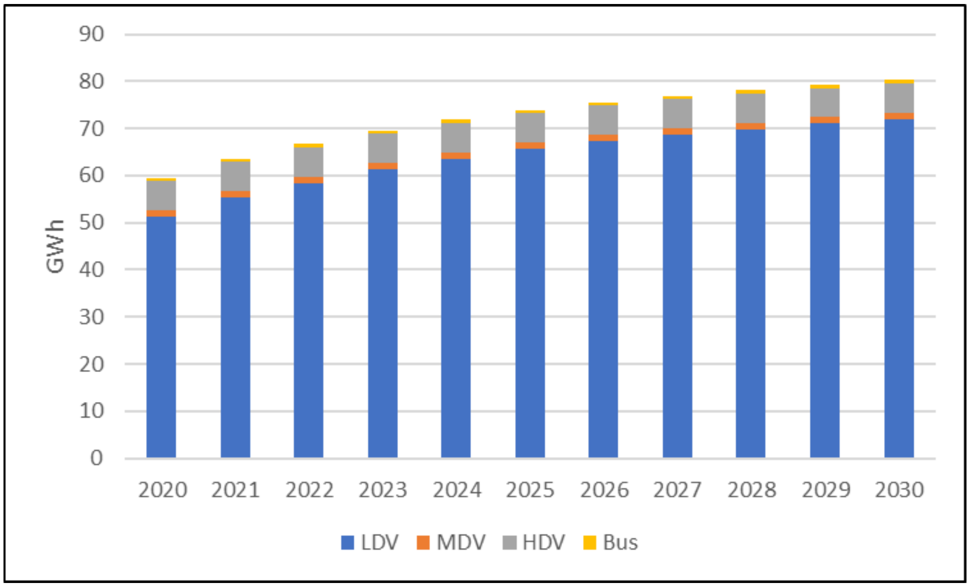


Figure 24. Projected lead–acid capacity increase from vehicle sales by class

Source: [3] Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.

As shown in Figures 25 and 26, 2017 was the start of rapid growth in lead–acid batteries for stationary markets [21]. Figure 25 illustrates that growth is primarily fueled by strong demand in China, some in Europe, and little in the United States. Figure 26 details the application breakdown—stationary markets were primarily grid-related applications prior to 2017, after which industrial uses also fuel the explosive growth.

The lead–acid industry believes that this chemistry has significant future stationary storage market opportunities based in technology advancements and market developments, including:

- Investment in bipolar design to increase energy density and reduce cost
- Behind-the-meter storage and other applications where safety is critical
- Telecom reserve power deployment in developing countries and for 5G deployment.

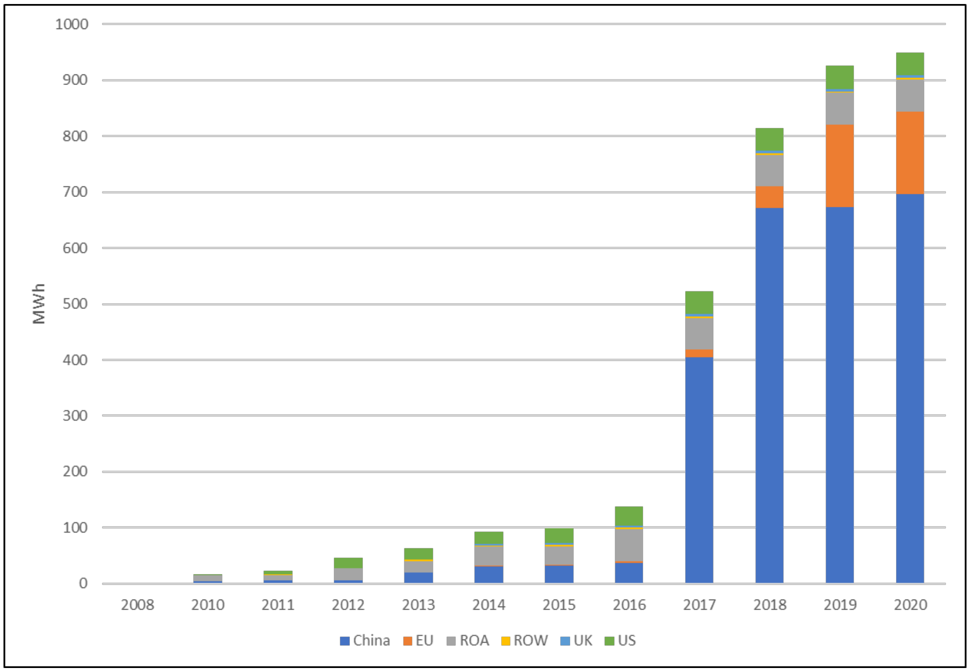


Figure 25. Global cumulative lead–acid stationary storage by region

Source: [21] Bloomberg New Energy Finance, "Storage Data Hub - Storage Assets," BloombergNEF, New York, 2020.Available: https://about.bnef.com/

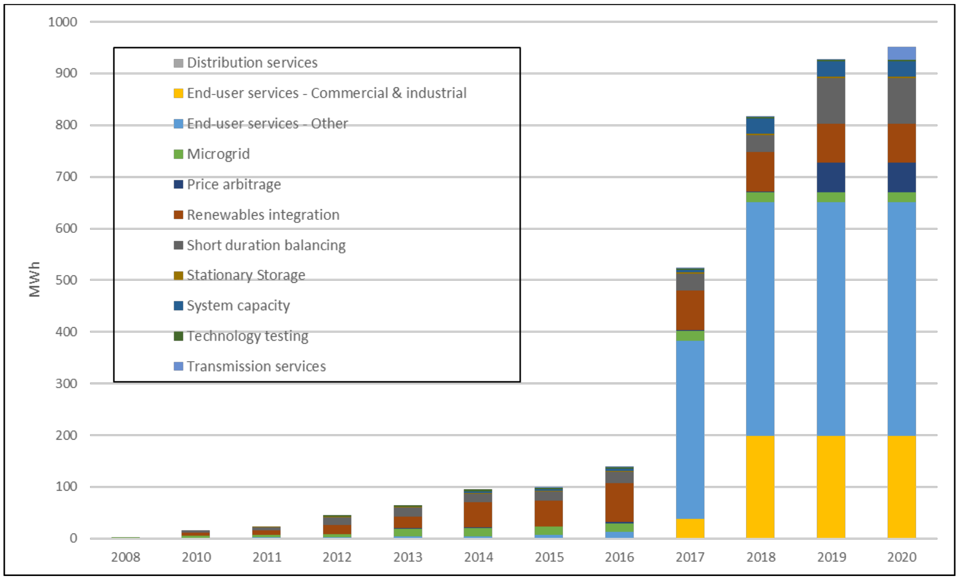


Figure 26. Global cumulative lead–acid stationary storage by application

Source: [21] Bloomberg New Energy Finance, "Storage Data Hub - Storage Assets," BloombergNEF, New York, 2020. Available: https://about.bnef.com/

Lead–Acid Manufacturing

The lead–acid industry has an annual output or economic impact of $26.3 billion in the United States [22]. They are produced domestically and 99% are recycled. Lead–acid batteries are manufactured in 18 states across every region of the country [23]. In addition, 10 states have recycling facilities, 9 have technology development, and 10 have companies that provide supplies (e.g., graphite) or equipment to the lead–acid industry. The lead battery industry has created nearly 25,000 direct jobs (manufacturing, recycling, transport, distribution, and mining) in 38 states [22]. Figures 27 and 28 show the U.S. domestic manufacturing industry and jobs creation, respectively.

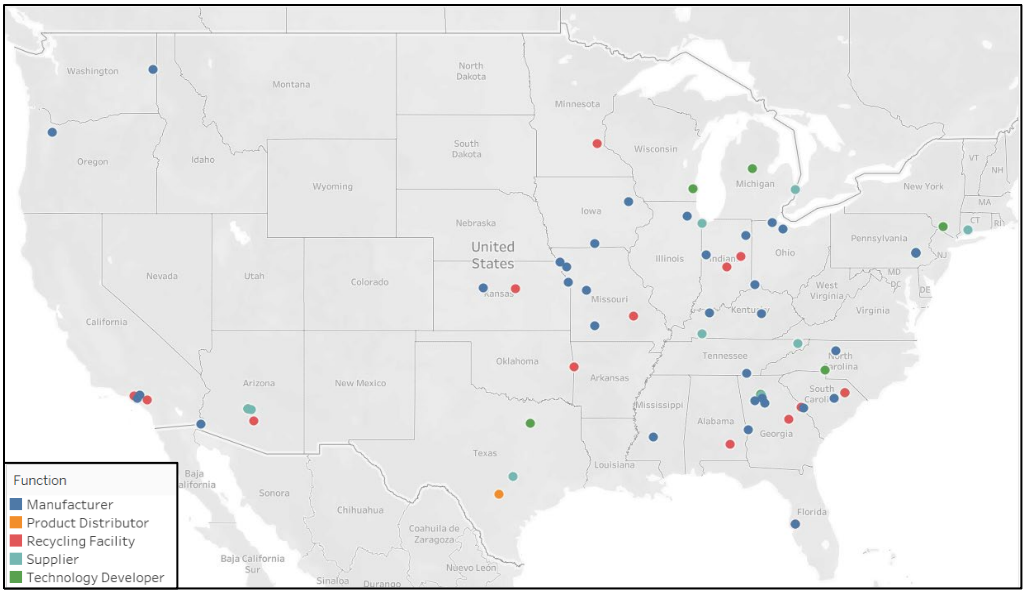


Figure 27. Domestic lead–acid industry and related industries

Source: [23] Battery Council International, "US Lead Battery Industry Business Infrastructure," Battery Council International, Chicago, 2020, unpublished.

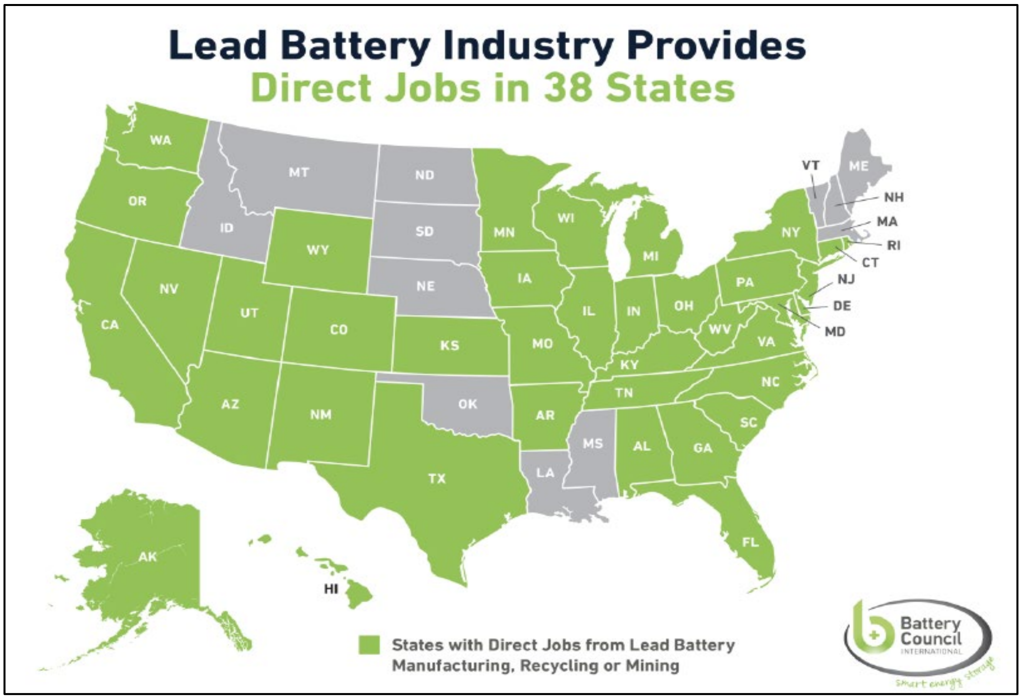


Figure 28. States with direct jobs from lead battery industry

Source: [22] EDR Group, “Economic Contribution of the U.S. Lead Battery Industry,” EDR Group, Boston, 2019. Available: https://essentialenergyeveryday.com/wp-content/uploads/2019/10/Economic-Impact-of-Lead-Batteries-in-the-United-States-Sept-2019.pdf.

Pumped Storage Hydropower (PSH)

PSH Market

PSH is one of the earliest energy storage methods. In fact, the oldest operating PSH system was commissioned in Switzerland in 1909 [24]. Historical *cumulative* global PSH deployment is shown in Figure 29, rising to 160 GW in 2019 [25]. The majority of this capacity is in Europe and Asia. Although the amount of operating PSH is significant, it should be noted that not all of it was designed to meet today’s grid challenges.

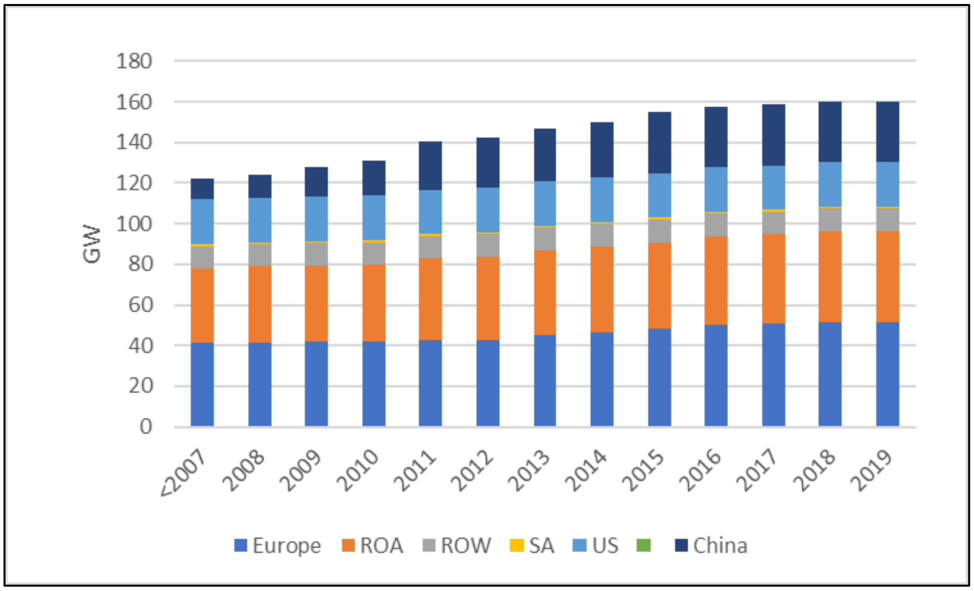


Figure 29. Global cumulative PSH deployment (GW)[9]

Source: [25] U.S. Department of Energy, "DOE OE Global Energy Storage Database." DOE. https://www.sandia.gov/ess-ssl/global-energy-storage-database/ (Accessed July 8, 2020).

IHA reports mid-2020 global operational PSH capacity of 164 GW in 357 installations, with another 124 in the pipeline (under construction, planned, or announced) [24]. They project capacity to increase 50% to 240 GW by 2030, with 65 of the new projects in China, 19 in the United States, and 10 in both Australia and Indonesia. Using the head and reservoir volume, IHA estimates the energy storage rating of these installations >17 TWh with another 0.5 TWh in the pipeline. This value may be underestimated, as many facilities do not report reservoir size or head [24]. Figure 30 is a snapshot of the IHA database (mid-2020) showing the locations and sizes of the PSH installations.

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[9] Storage durations were not provided and so only GW are shown.

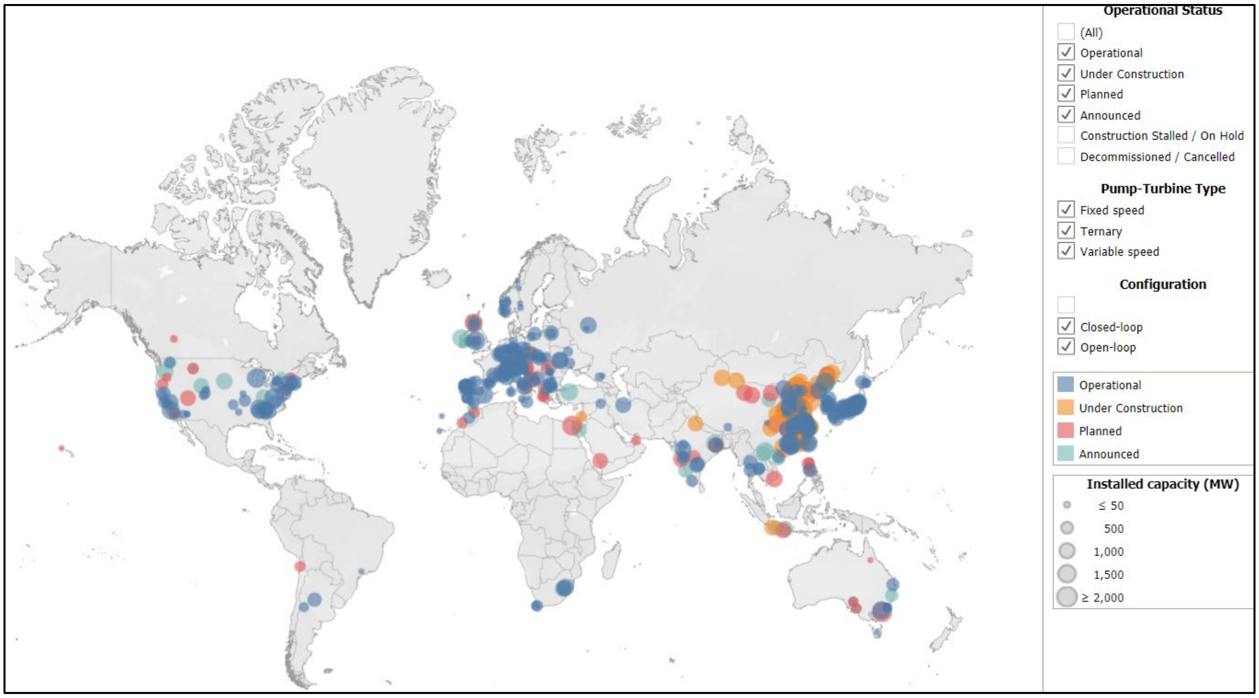

Figure 30. Global PSH installations

Source: [24] International Hydropower Association, “Pumped Storage Tracking Tool.” IHA. https://www.hydropower.org/hydropower-pumped-storage-tool (Accessed Sep. 20, 2020).

Projected installed capacity deployments are shown in Figure 31. These projected deployments include projects that are either under construction or planned for development and have sought or received regulatory approval; announced projects are not included. As shown in the figure, annual PSH deployment can vary significantly, with some years having no projected deployments. This variability is in part related to relatively long project development lead times of the typically large deployments. An example of long lead time is India’s 1.2-GW Pinnapuram PSH project [26], which will be paired with 2-GW solar and 400-MW wind and tied to a 760/400-kV grid. The project was approved in 2018 by the government, and in 2020 a $2.5-million contract was awarded for the next step in the design.

China has the greatest amount of near-term deployment planned. From 2020–2026, China is expected to deploy >35 GW of PSH, typically as very large plants. For example, China’s $2.8-billion Fengning County plant, intended for the 2022 Winter Olympics, is 3.5 GW [27]. In Australia, Genex Power Limited has recently finalized a 250-MW Kidston Australia contract with Energy Australia Pty, Ltd. [28].

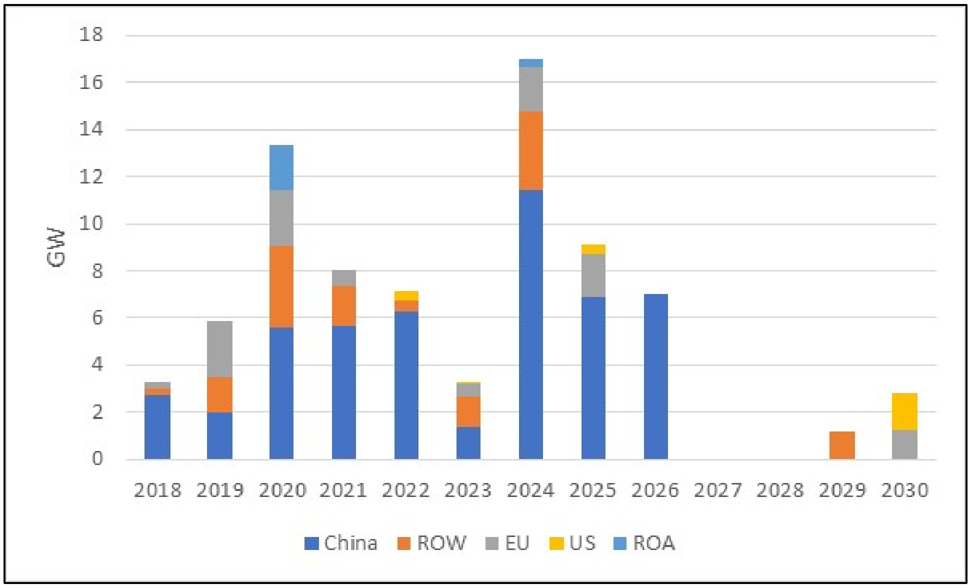

Figure 31. Projected[10] annual global PSH installations

Source: [6] International Hydropower Association, "The world's water battery: Pumped hydropower storage and the clean energy transition," IHA, London, December 2018. Available: https://www.hydropower.org/publications/the-world-e2-80-99s-water-battery-pumped-hydropower-storage-and-the-clean-energy-transition.

In 2016, NREL used the Regional Energy Deployment System (ReEDS) [29] model to develop a set of possible development scenarios of PSH resource availability as part of the U.S. *Hydropower Vision* [30]. These scenarios started with an initial upper-bound estimate based on an assessment of all PSH projects proposed to the Federal Energy Regulatory Commission (FERC) since 1980. This represented only a subset of potential PSH projects because some hydropower owners and developers do not need FERC authorization or have projects defined but have not yet applied to FERC. With these assumptions, the FERC-based PSH estimate was 109 GW across 166 sites. The ReEDS modeling also included one 750 MW[11] "artificial" PSH project in each region to reduce the likelihood of over-constraining PSH expansion in regions without FERC applications, while allowing for consistent growth across all regions [29]. Figure 32 presents the combination of the "artificial" PSH resources of 101 GW and the 109 GW of FERC-based PSH resources. For a potential 12-h duration, this lower bound estimate (210 GW) is 2,500 GWh. Detailed GIS assessment to refine the resource estimates is ongoing and is expected to be complete at the end of 2021.

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[10] Includes planned and under-construction facilities; announced facilities are not included.

[11] 750-MW was selected for the project size because it is an approximate average of the capacity of PSH projects proposed in the decade leading up to the Hydropower Vision [30].

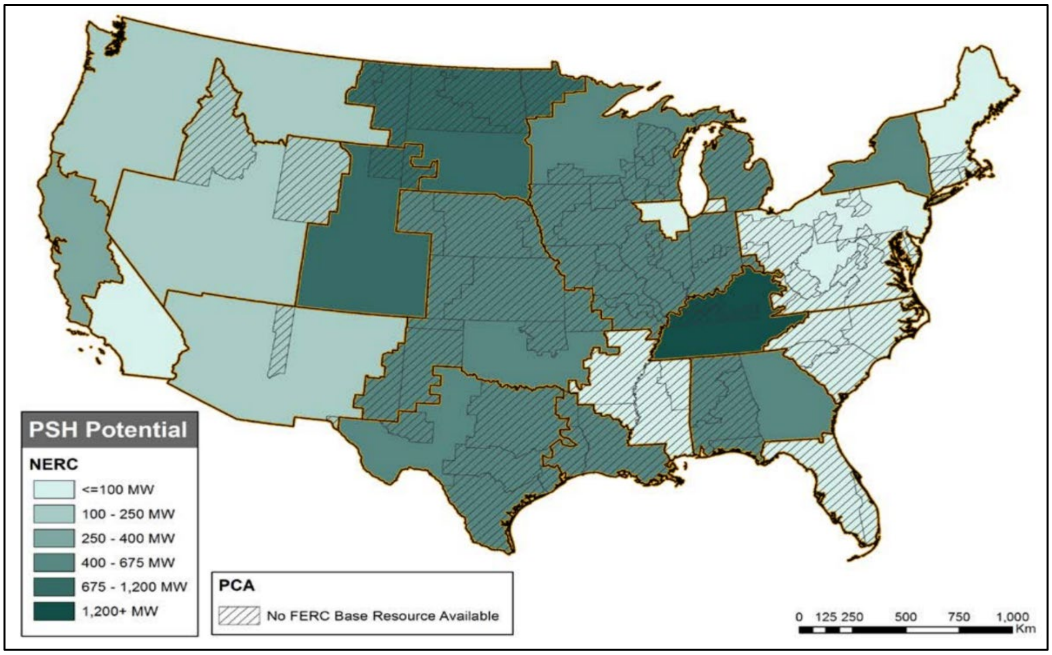

Figure 32. Lower-bound domestic PSH potential based on ReEDS modeling

Source: [29] M. Brown et al., "Regional Energy Deployment System (ReEDS) Model Documentation: Version 2019," National Renewable Energy Laboratory, Golden, CO, NREL/TP-6A20-74111, 2020. Available: https://www.nrel.gov/docs/fy20osti/74111.pdf.

The *Hydropower Vision* [30] also includes results of three scenarios modeled in ReEDS: advanced technology, low-cost finance, and a combination of both that also included sustainable hydropower development. The advanced technology scenario included factors such as lower cost and increased viable geographies, accounting for new technologies such as Obermeyer pumped storage.[12] The low-cost financing scenario considered lending conditions that value the long life of PSH assets. Figure 33 summarizes the results of this analysis, where the combined case results in a capacity increase of 36 GW over business as usual [30]. This result is greater than the sum of either scenario individually, even when including environmental constraints, and as noted earlier is based on modeling with a lower-bound estimate of potential resources.

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[12] Obermeyer pumped storage is an innovative PSH design that does not need an underground powerhouse, which is generally one of the most costly, risky, and environmentally impactful aspects of PSH. For more information: https://www.nrel.gov/news/program/2020/psh-ensures-resilient-energy-future.html.

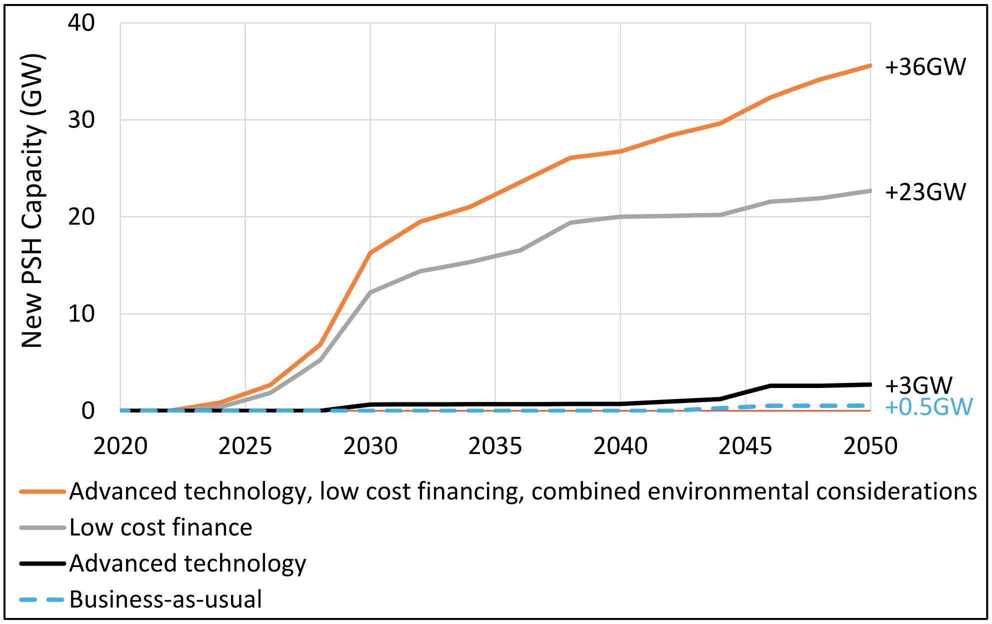

Figure 33. U.S. PSH deployments model ReEDS: tech improvement and financing increase

Source: [30] U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office, "Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source," U.S. DOE, Washington, D.C., DOE/GO-102016-4869, 2016. Available: https://www.energy.gov/sites/prod/files/2018/02/f49/Hydropower-Vision-021518.pdf.

Compressed Air Energy Storage (CAES)

CAES stores energy as compressed air and is generally deployed in large underground caverns. It is used only in the stationary market.

CAES Market

The BNEF *Storage Data Hub* [21] lists seven commissioned CAES facilities worldwide, with four of these in the United States. Although not all facilities report both capacity (MWh) and power (MW), the collected information shows that the United States deployed the largest amount of both from 2011–2019 (Figures 34 and 35). In 2011, a large 300-MWh facility was deployed in Texas. BNEF [21] also notes that three large facilities have secured financing and are under construction in China. The facilities include a 50-MW (300-MWh) facility in Shandong province, a 100-MW facility in Hebei province, and a 60-MW facility in Jiangsu province. All were scheduled for commissioning at the end of 2019 or the beginning of 2020, but no information was found on whether any of these projects were completed.

New approaches are also under consideration; CAES is being explored in hybrid systems, which can potentially balance its cost/performance trade-offs. For example, in the Netherlands, CAES was recently combined with Li-ion for a hybrid system for ancillary services. This approach is expected to both extend the Li-ion life and significantly improve the total lifetime cost [31].

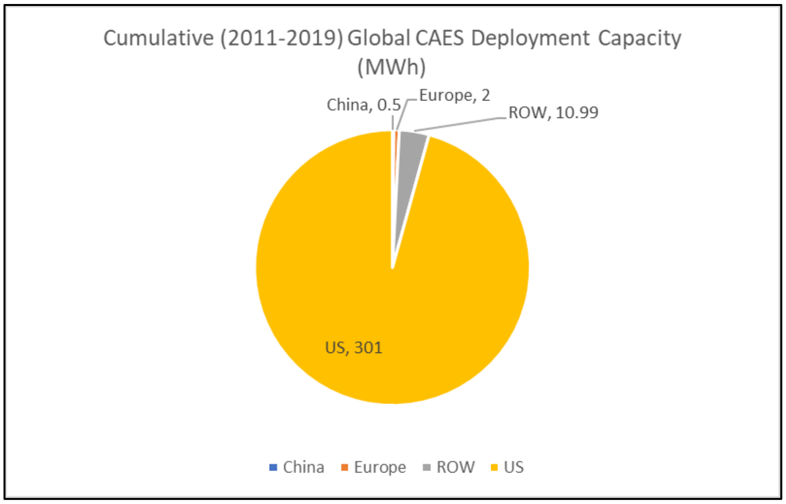

Figure 34. Cumulative (2011–2019) global CAES energy storage deployment

Source: [21] Bloomberg New Energy Finance, "Storage Data Hub - Storage Assets," BloombergNEF, New York, 2020. Available: https://about.bnef.com/

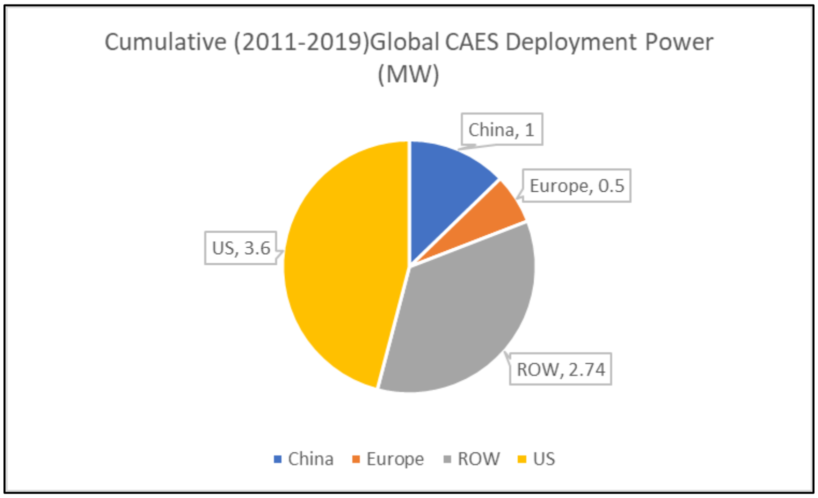

Figure 35. Cumulative (2011–2019) global CAES power deployment

Source: [21] Bloomberg New Energy Finance, "Storage Data Hub - Storage Assets," BloombergNEF, New York, 2020. Available: https://about.bnef.com/

Existing underground formations improve safety and economics, and are critical for future CAES. NREL [29] estimated the U.S. potential domestic CAES resource at 121 GW, considering salt domes (22.6 GW), salt beds (61.6 GW), and aquifers (37 GW), using the descriptions below. Thus far, many sites tested have been shown inadequate due to poor rock porosity, and as such, the estimate should be considered an optimistic and unproven scenario. Figure 36 summarizes the results of the analysis.

Salt dome:
    Thick salt deposits (~1 mile thick) and small geographic spread (~2 miles wide)
    Few locations in United States
    Solution mined caverns
Salt beds:
    Solution mined caverns are wide and vertically thin

Available in many areas

Aquifer:

Nonporous formation forming an "inverted" pocket of gas above water table

Widely used for natural gas storage.

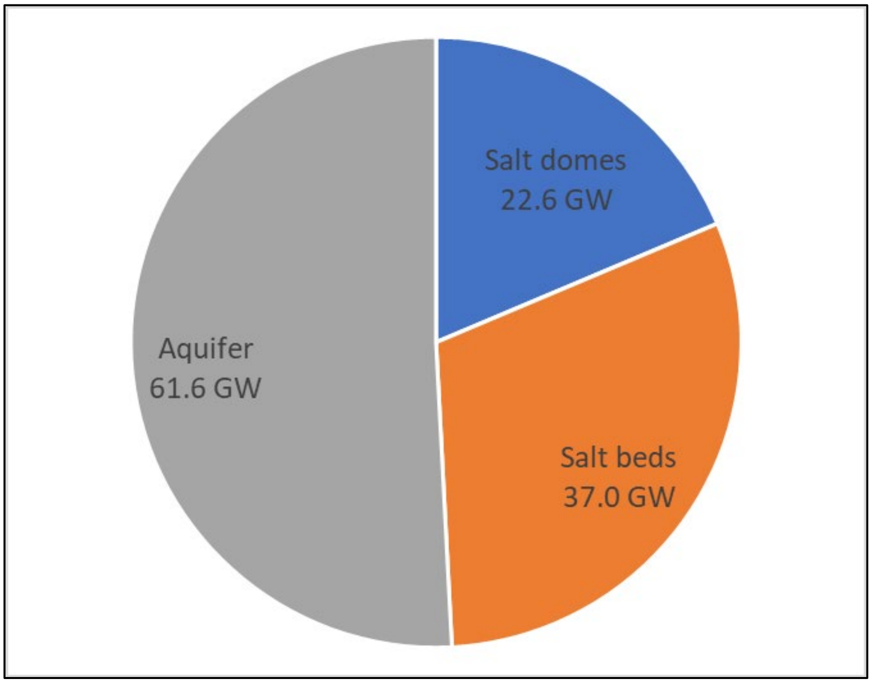

Figure 36. U.S. CAES resource estimate

Source: [29] M. Brown *et al.*, "Regional Energy Deployment System (ReEDS) Model Documentation: Version 2019," National Renewable Energy Laboratory, Golden, CO, NREL/TP-6A20-74111, 2020. Available: https://www.nrel.gov/docs/fy20osti/74111.pdf.

Although the United States leads the world in CAES deployment, not all projects have been successful or were commercial. Below are several examples of demonstrations and unsuccessful projects:

Successful demonstration	
- Alabama:	110 MW, operational, 1991
Not moving forward	
- Ohio, First Energy:	2,700 MW, on hold, 2018, reservoir not suitable
- Iowa, ISEP:	270 MW, scrapped, 2011, low aquifer porosity
- California, PG&E:	300 MW, feasibility ended, 2018, reservoir uneconomic.

CAES was evaluated as a competitor to Li-ion in a BNEF report on emerging stationary storage technologies [32]. Using the parameters noted below as primary metrics, BNEF analyzed the competitiveness of CAES versus Li-ion for each unique grid market application to determine its "addressable market." Addressable market was defined as the market available to that technology when competing with lithium-ion batteries in the grid-related energy storage sector on three parameters: technical and economic feasibility, locational constraints, and system size. Although it did not evaluate specific facility locations, its need for an extremely large footprint for economic viability was included in the assessment.

The analysis predicts that CAES could potentially compete with Li-ion for about 60 GWh of the total 150-GWh projected capacity required in 2030. Figure 37 shows that peaking and energy shifting are the applications where CAES is most competitive.

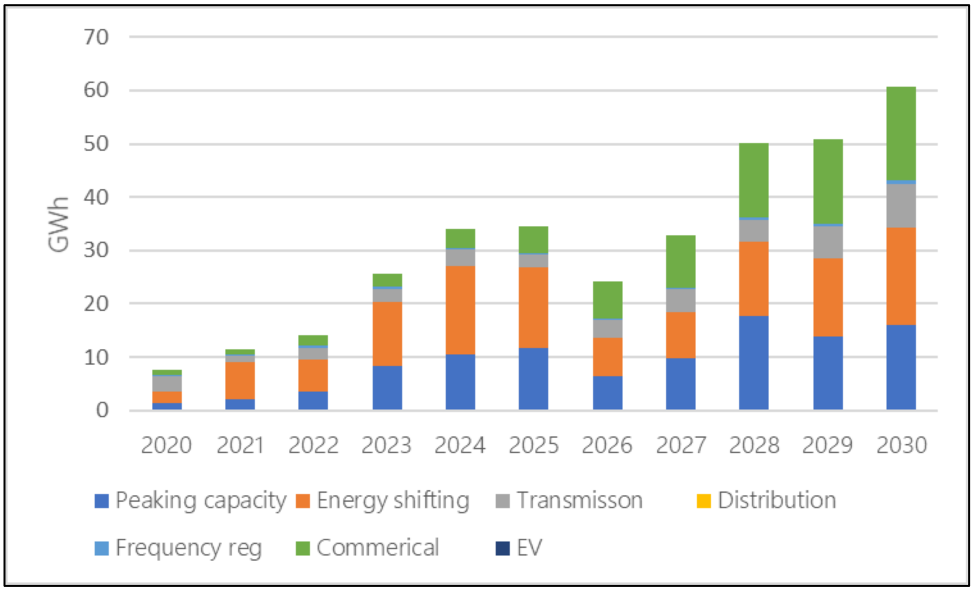

Figure 37. Projected Addressable Market for CAES Technology

Source: [32] J. Frith, “Emerging Energy Storage Technologies,” BloombergNEF, New York, 2020. Available: https://about.bnef.com/

Redox Flow Batteries (RFBs)

RFB Market

RFBs are used exclusively in stationary markets and are typically aqueous-based. Global annual and cumulative deployments are summarized in Figures 38 and 39, respectively; China and the rest of Asia lead in RFB deployment. Of the 800 MWh of RFB projects deployed since 2008, more than 75% were deployed in the last 2 years [21].

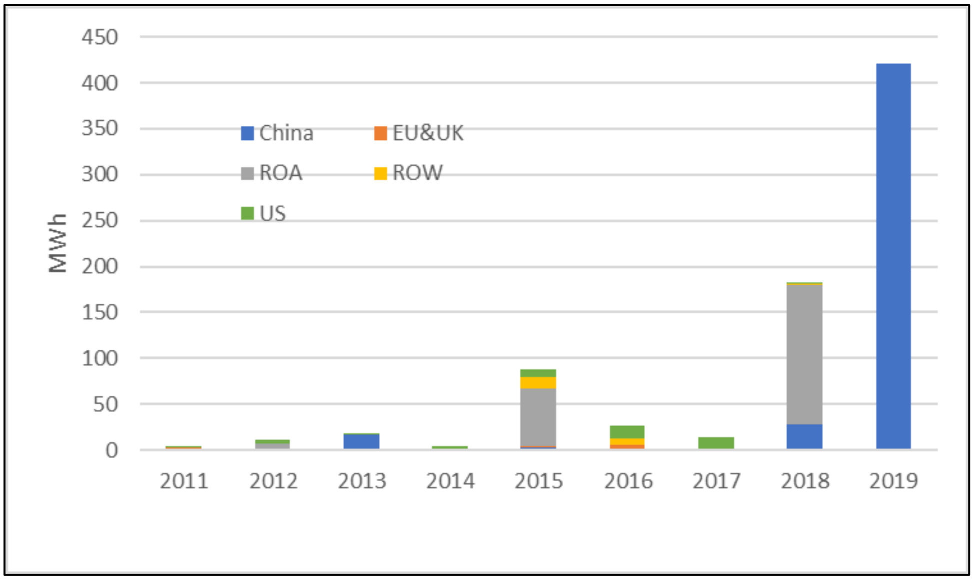

Figure 38. Global annual deployment of RFBs by region

Source: [21] Bloomberg New Energy Finance, "Storage Data Hub - Storage Assets," BloombergNEF, New York, 2020. Available: https://about.bnef.com/

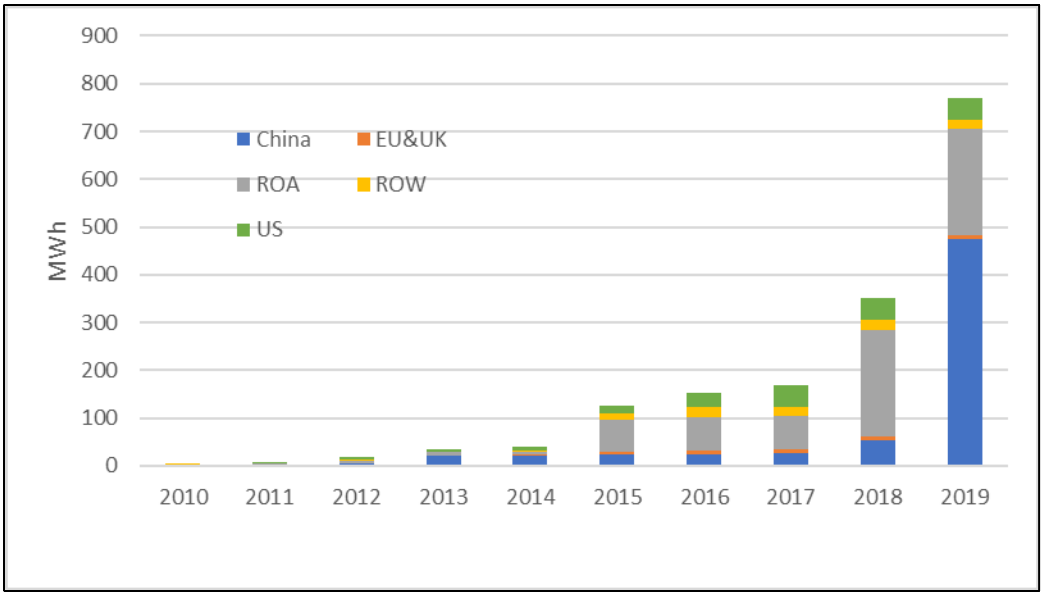

Figure 39. Global cumulative deployment of RFBs by region

Source: [21] Bloomberg New Energy Finance, "Storage Data Hub - Storage Assets," BloombergNEF, New York, 2020. Available: https://about.bnef.com/

In 2016, the largest RFB project ever (200 MW/800 MWh and vanadium-based) was approved for construction in Dalian, China [33]; it is being co-developed by Rongke Power and UniEnergy Technologies. The project was designed for the use cases of black start, peak shaving, and grid stability, and was originally scheduled for completion in late 2019, although no announcement of completion or startup has been found [34].

Figure 40. Largest vanadium redox flow battery facility (under construction)

Source: [33] J. F. Weaver, "World's largest battery: 200 MW/800MWh vanadium flow battery - site work ongoing," *Electrek*, Dec. 21, 2017. Available: https://electrek.co/2017/12/21/worlds-largest-battery-200mw-800mwh-vanadium-flow-battery-rongke-power/.

As noted earlier, BNEF [32] developed an "addressable" market for several emerging stationary storage technologies. Addressable market was defined as the market available to that technology when competing with lithium-ion batteries in the grid-related energy storage sector on three parameters:

- Technical and economic feasibility
- Locational constraints
- System size.

Rating systems were developed for each market application (e.g., energy shifting) and the technology was compared to Li-ions in the same application.

All redox flow battery chemistries were grouped together and were assumed to have an average system duration of 4 hours. If shorter duration systems are feasible, then the addressable market would be larger. BNEF predicts that flow batteries could compete with lithium-ion for up to 69 GWh (46%) of the total 150 GWh of required capacity in 2030. Peaking and energy shifting are the applications most competitive for RFBs, as shown in Figure 41. The emergence of iron-based chemistries to solve some of the cost issues of vanadium-based flow batteries may change the projections.

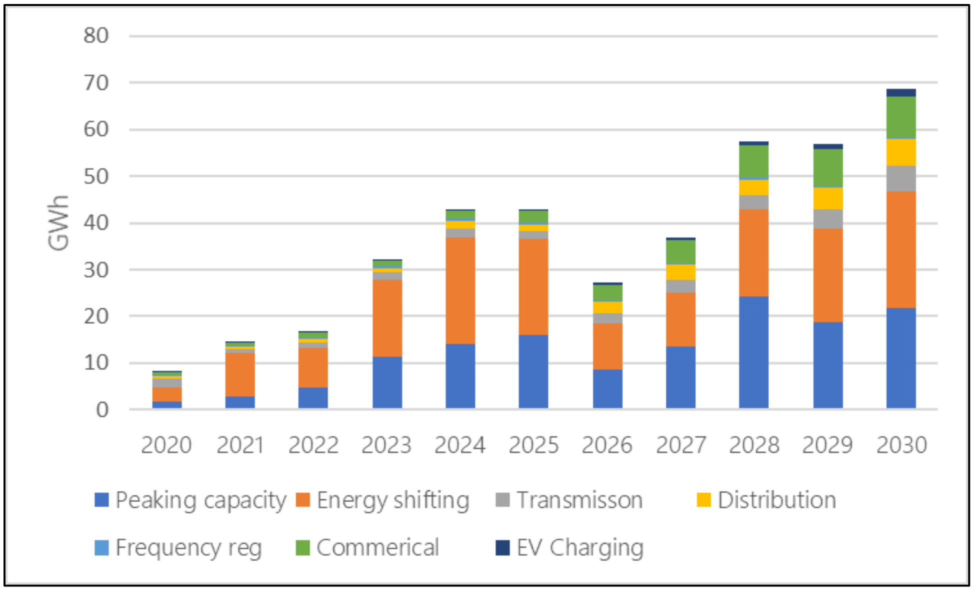

Figure 41. Potential redox flow battery market by application

Source: [32] J. Frith, "Emerging Energy Storage Technologies," BloombergNEF, New York, 2020. Available: https://about.bnef.com/

A summary of the RFBs by deployment date and size is provided in Figure 42 [21]. Similar to other emerging technologies, the deployment of RFBs, specifically vanadium-based, has been increasing significantly in recent years.

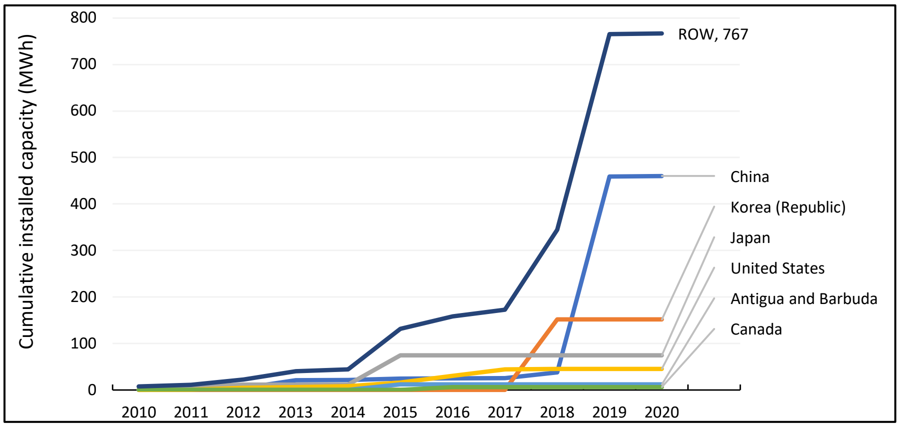

Figure 42. International installations of RFBs

Source: [21] Bloomberg New Energy Finance, “Storage Data Hub - Storage Assets,” BloombergNEF, New York, 2020. Available: https://about.bnef.com/

A large determinant of RFB viability is system cost, which is strongly coupled to the active material choice. Historically, vanadium has been preferred due to several attractive electrochemical properties, including relatively long life. However, as Li-ion prices have dropped, vanadium RFBs can begin to compete economically. Because the RFB’s design fundamentally creates a cost advantage in the 4–6-hour duration segment (which is increasingly important), strategies are evolving to improve active material economics. Several investors and startup companies are demonstrating new RFB technologies, which may impact future deployments, if successful. For example:

- A vanadium producer and an RFB company formed a joint venture to rent vanadium electrolyte to redox flow battery developers [35].
- Iron is an extremely low-cost active material and is seeing some early RFB commercial successes. For example, a young iron RFB company whose device can provide up to 10-hour duration is now scaling to >5 MW and expanding manufacturing capacity. It is receiving support from both investors and its nascent future supply chain [36].
- A zinc-bromide RFB has been designed as a standard 5-hour duration product and is manufactured as a commercial 25-kW design. The California Energy Commission recently awarded this startup a contract for further demonstrations [37]. 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. Several organic chemistries have shown promise and are receiving much interest as next-generation redox flow chemistries.

Hydrogen

Projects like H2@Scale explore hydrogen across the whole economy, as shown in Figure 43 [38]. This report focuses on stationary and transportation energy storage technologies but is also including the use of hydrogen for power generation and heat/distributed power.

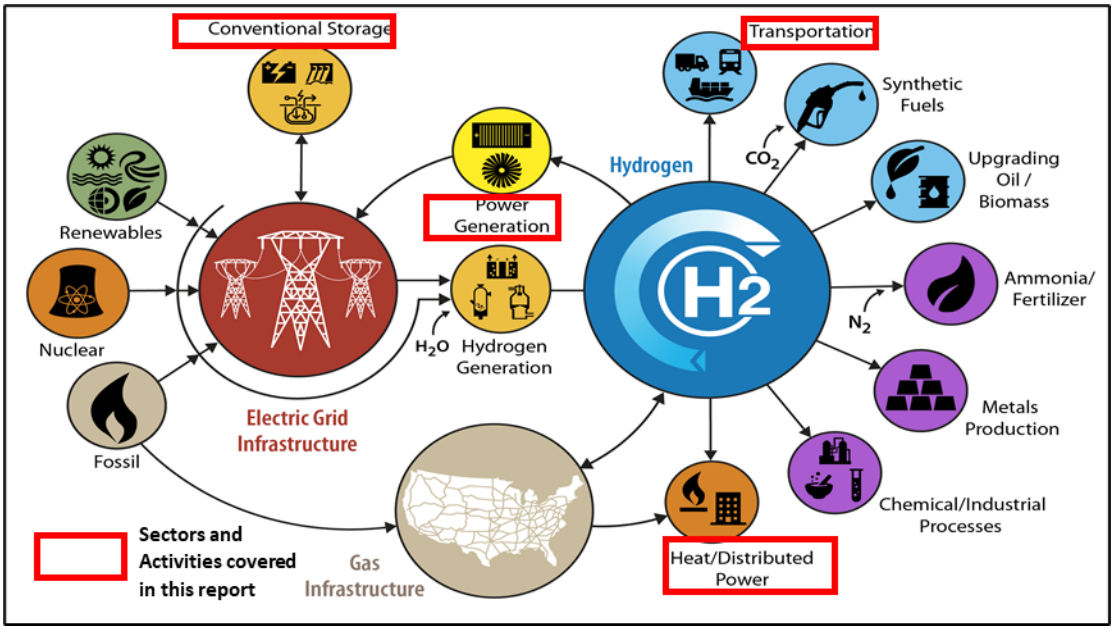

Figure 43. Hydrogen energy economy

Source: [38] U.S. Department of Energy, “H2@Scale Bubble Chart,” DOE, Washington, D.C., 2020. https://www.energy.gov/eere/fuelcells/h2scale

Market – Hydrogen

As an energy storage technology, hydrogen has additional flexibility. Hydrogen can be produced from electricity or other primary energy sources such as natural gas and then used as a fuel or converted back to electricity. Hydrogen can also be used as a molecular building block for the production of other energy carriers and fuels such as ammonia or hydrocarbons.

Total global hydrogen consumption is projected to grow from 70 million metric tons (MMT) in 2017 to 85 MMT (2.83 million TWh[13]) by 2022 [39], [40], with the vast majority produced from natural gas. China consumes about one-third of global hydrogen annually. Currently, the principal drivers of hydrogen consumption are ammonia production, petroleum refining, and methanol production. Hydrogen from renewable-energy-driven water electrolysis continues to gain traction globally, but represents a very small fraction of total hydrogen production.

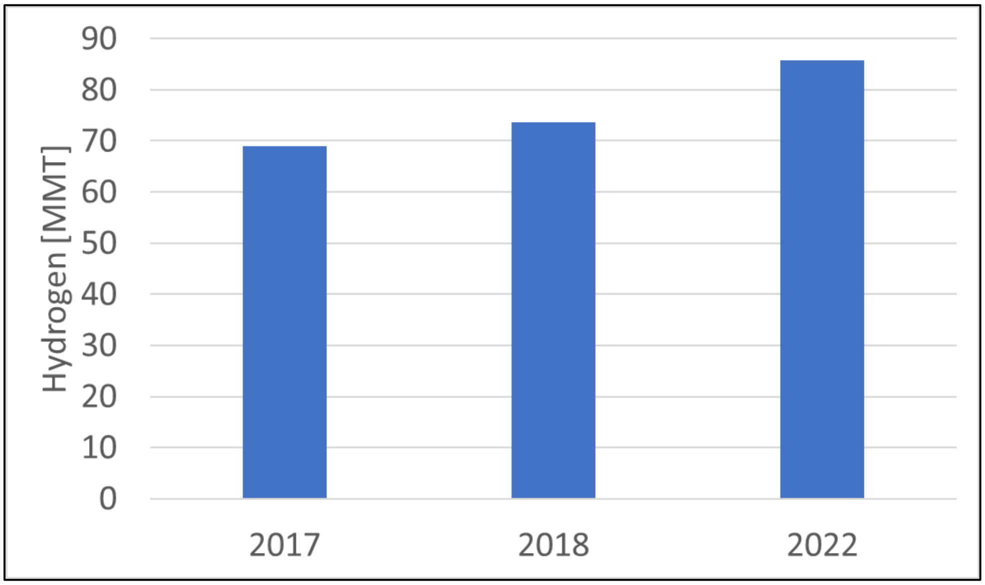

Figure 44. Global hydrogen consumption – all sources

Sources: [39] X. Wang, “Hydrogen Economy Outlook,” in CEC IERP Commissioner Workshop, 2020. Docket 233719, https://efiling.energy.ca.gov/Lists/DocketLog.aspx?docketnumber=20-IEPR-02
[40] B. Suresh, S. Schlag, T. Kumamoto, and Y. Ping, “CEH Marketing Research Report: Hydrogen,” SRI Consulting, Menlo Park, CA, 2010.

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[13] Based on lower heating value (LHV) of 33.3 kWh/kg

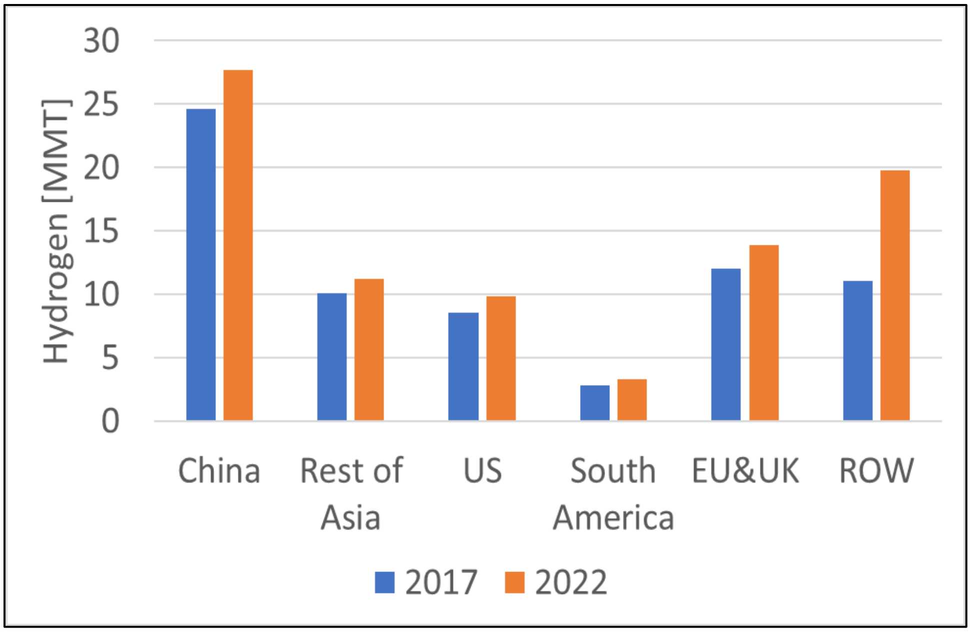


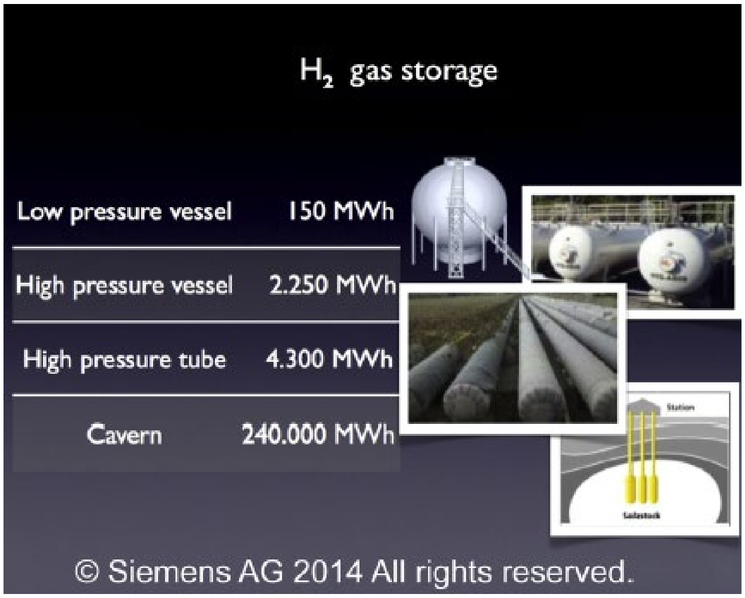
Figure 45. Hydrogen consumption by region

Source: [40] B. Suresh, S. Schlag, T. Kumamoto, and Y. Ping, "CEH Marketing Research Report: Hydrogen," SRI Consulting, Menlo Park, CA, 2010. Docket 233719, Available: https://efiling.energy.ca.gov/Lists/DocketLog.aspx?docketnumber=20-IEPR-02

Hydrogen FCEVs are projected to increase but currently account for less than 1% of new low-carbon vehicles sales [41]. Approximately one-third of the world's FCEVs are operating in the United States, followed by China, Japan, and Korea. The majority of growth in FCEVs over the next decade is projected to be in Asia, although increasing attention is being paid to hydrogen for medium- and heavy-duty vehicles in the United States.

Hydrogen can be stored in a number of ways, employing both physical and chemical methods. Gaseous hydrogen storage includes pressurized vessels in salt caverns, depleted gas fields, and rock caverns; liquid hydrogen is stored at high pressure in cryogenic vessels. Hydrogen can also be converted to molecular energy carriers such as ammonia, methanol, and heavier liquid organics, thus allowing for storage and delivery under lower pressures and higher temperatures.

Figure 46 provides a summary of typical conditions for pressurized gas storage [42]. As noted in the table, caverns can store the largest amount of hydrogen; salt caverns have thus been employed as a near-term option for storing large quantities of hydrogen for extended periods.



H_2 gas storage

Low pressure vessel	150 MWh
High pressure vessel	2.250 MWh
High pressure tube	4.300 MWh
Cavern	240.000 MWh

Figure 46. H_2 gas storage

Source: [42] E. Wolf, “Large-Scale Hydrogen Energy Storage,” in *Electrochemical Energy Storage for Renewable Sources and Grid Balancing*, P. T. Moseley and J. Garche, Eds., Amsterdam, Netherlands: Elsevier, 2015, pp. 129–142.

Salt caverns are a low-cost method for storing very large quantities of hydrogen, which makes them attractive for long-duration storage. Typical technical design parameters of a hydrogen cavern at 1,000-m depth [42] are:

- Volume of 500,000 m^3
- Operational pressure range: 60–180 bar
- Storage capacity:
    - 140 GWh thermal or
    - 85 GWh of electrical energy.

The power output of a cavern depends on thermodynamic limits and well-head configuration but is estimated at 700 MW. Leakage rate for H_2 through salt is negligible and at detection limits.

Figure 47 shows the location of major salt deposits around the world that may be amenable to hydrogen storage [43], [39]. Current large hydrogen storage projects include [43]:

- Teesside, Great Britain (3 caverns, 70,000 m^3 each, 370 m)
- Clemens Dome, Texas (1 cavern, 580,000 m^3, 1,000–1,300 m)
- Moss Bluff, Texas (1 cavern, 566,000 m^3, 335–1,400 m).

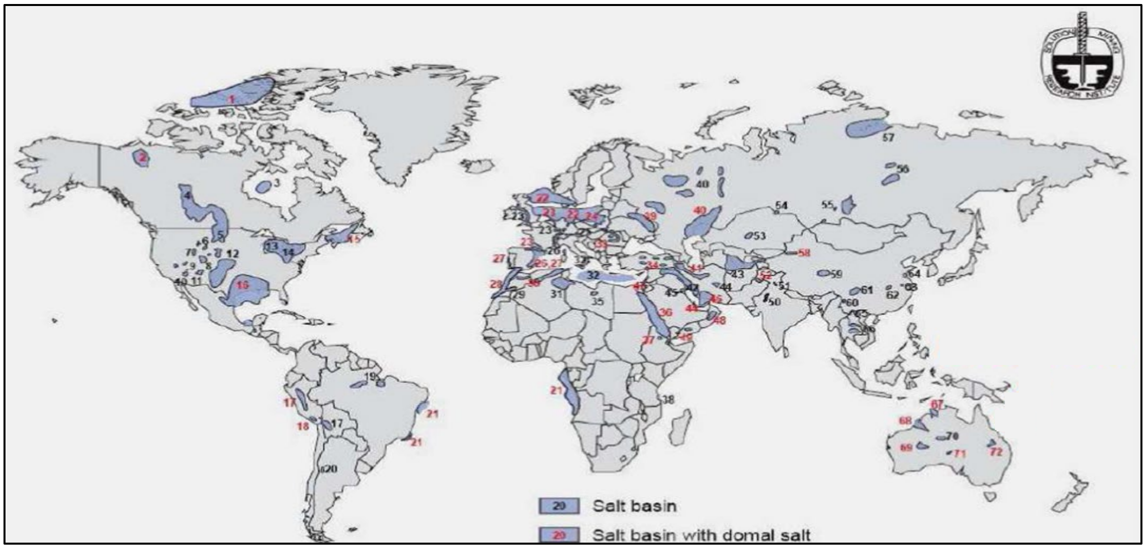


Figure 47. Major salt deposits

Source: [43] H. Blanco and A. Faaji, "A review of the role of storage in energy systems with a focus on power to gas and long-term storage," *Renewable and Sustainable Energy Reviews Journal,* vol. 81, no. 1, pp. 1049-1086, 2018. Available: https://doi.org/10.1016/j.rser.2017.07.062.

Europe, and Germany in particular, have significant salt and cavern resources and many are used for natural gas or hydrogen storage. Germany presently stores 24% of its natural gas in roughly 200 caverns. They plan to develop more for hydrogen storage. Figures 48 and 49 show the resource and development of salt caverns for gaseous storage in Germany and Europe, respectively.

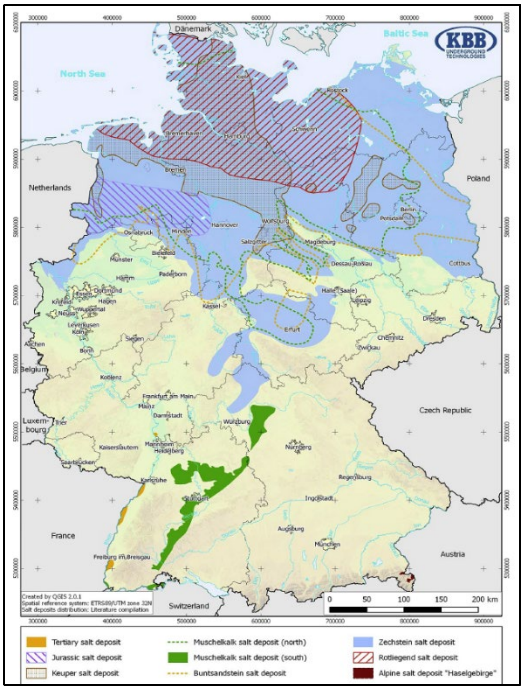


Figure 48. Salt deposits and caverns in Germany

Source: [42] E. Wolf, "Large-Scale Hydrogen Energy Storage," in *Electrochemical Energy Storage for Renewable Sources and Grid Balancing*, P. T. Moseley and J. Garche, Eds., Amsterdam, Netherlands: Elsevier, 2015, pp. 129–142.

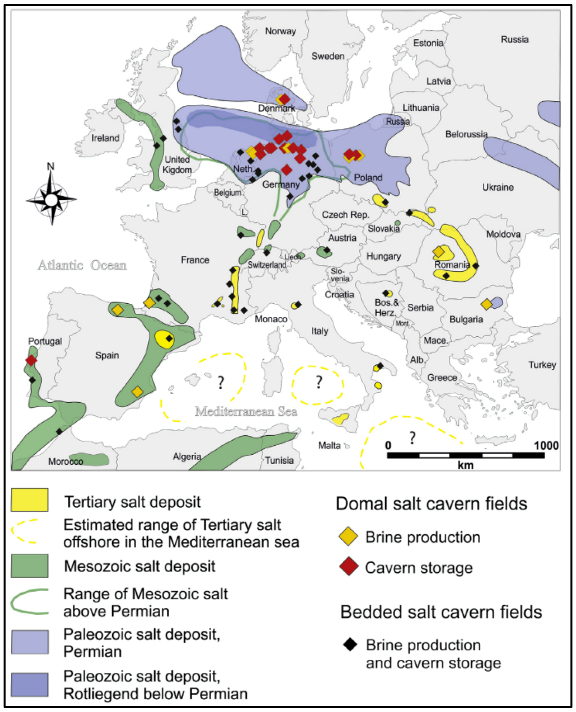


Figure 49. European salt domes and caverns

Source: [43] H. Blanco and A. Faaji, "A review of the role of storage in energy systems with a focus on power to gas and long-term storage," *Renewable and Sustainable Energy Reviews Journal,* vol. 81, no. 1, pp. 1049-1086, 2018. Available: https://doi.org/10.1016/j.rser.2017.07.062.

The United States, Japan, and South Korea are leaders in the deployment of FCEVs [3]. The majority of FCEVs deployed are light-duty vehicles, but recently buses, especially in China, have begun to increase in importance. Using historical FCEV sales [3] and representative onboard storage quantities[14] for each vehicle class, as well as the lower heating value (LHV) of hydrogen,[15] the cumulative energy stored as hydrogen on FCEVs was estimated and is shown in Figures 50 and 51.

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[14] Assumed onboard hydrogen quantities: light-duty FCEV: 5 kg; medium-duty FCEV: 24 kg; heavy-duty FCEV: 80 kg; FCEV bus: 55 kg

[15] 33.3 kWh/kg [55]

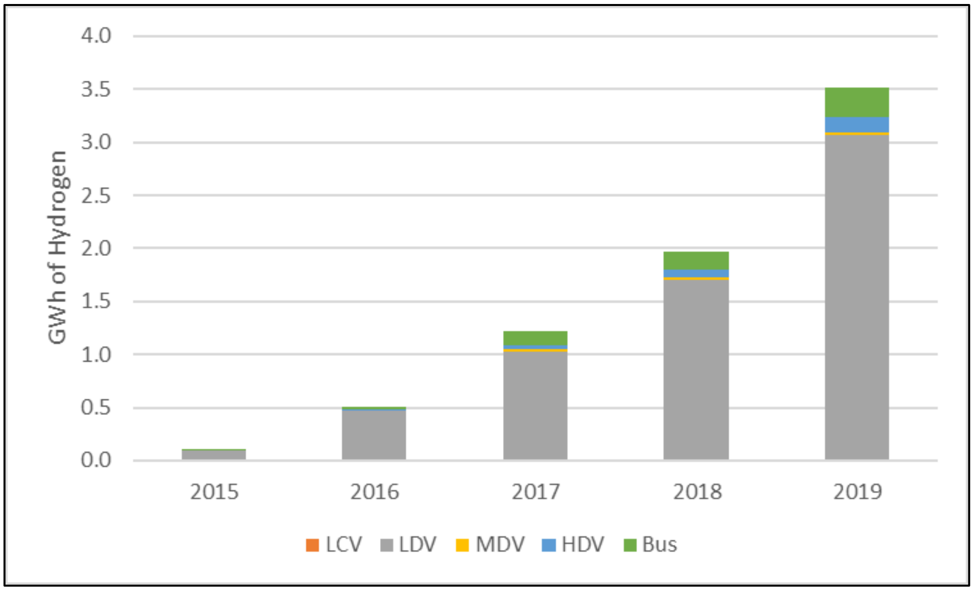

Figure 50. Estimated global cumulative hydrogen storage deployment by vehicle type

Source: [3] Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.

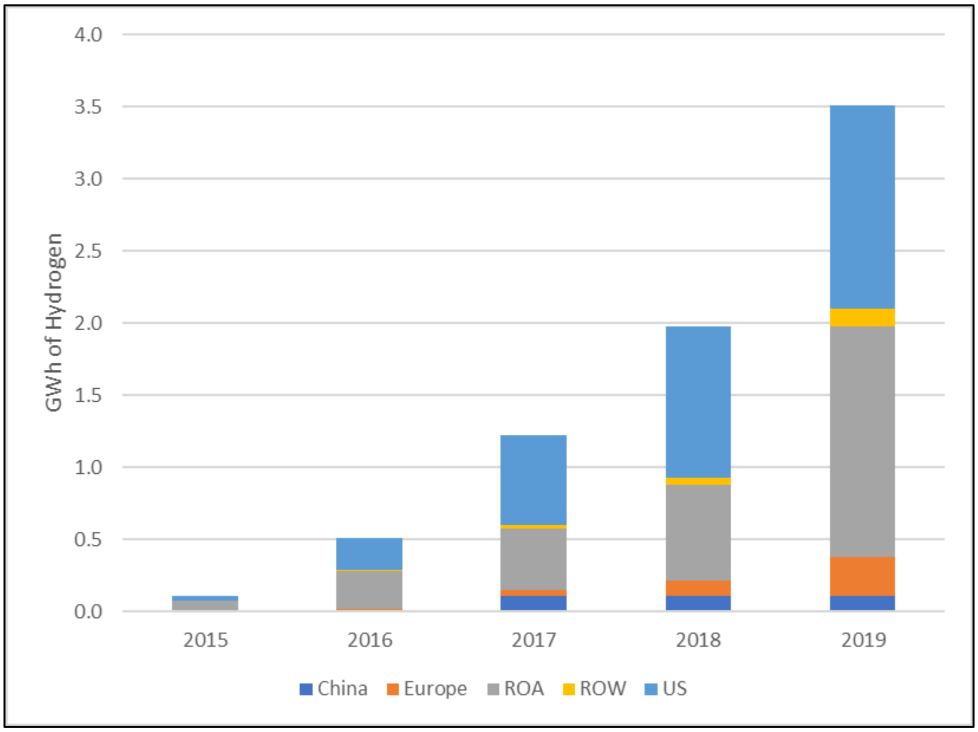

Figure 51. Estimated global cumulative onboard hydrogen storage by region

Source: [3] Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.

Using this same methodology and the projections of FCEVs by BNEF[16] [3], the projected deployment through 2030 is presented in Figures 52 and 53. By 2030, over 35-GWh LHV of onboard hydrogen storage could be deployed annually. China and other Asian countries are projected to deploy the most onboard hydrogen storage, with Europe close behind. Fuel cell buses and passenger light-duty FCEVs are projected to have the greatest demands for onboard hydrogen storage.

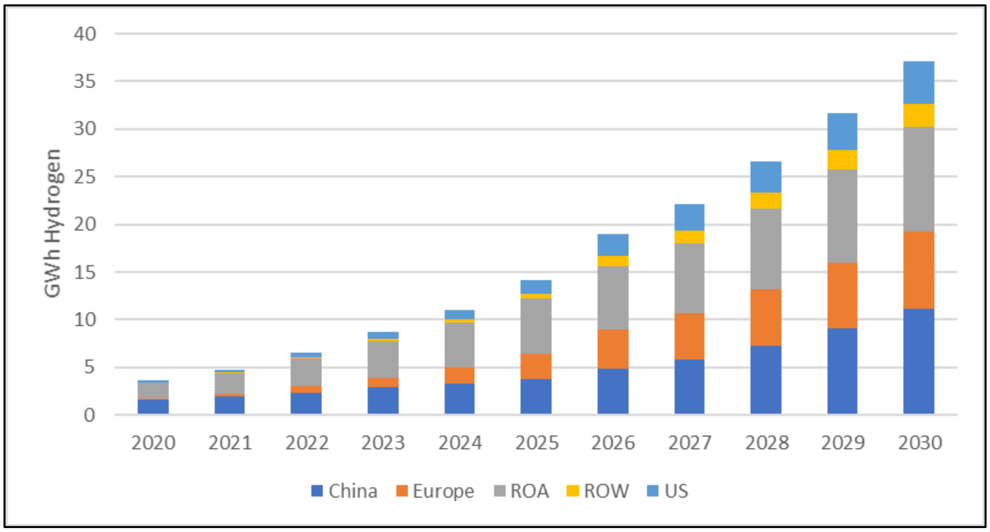

Figure 52. Projected onboard hydrogen storage by region

Source: [3] Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.

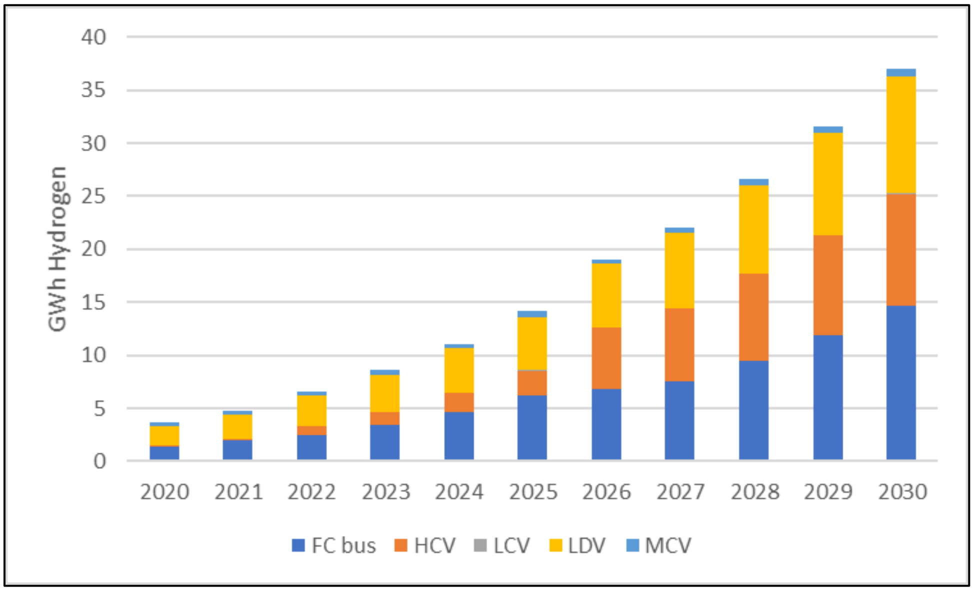

Figure 53. Projected onboard hydrogen storage by vehicle type

Source: [3] Bloomberg New Energy Finance, "Electric Vehicle Outlook 2020," BloombergNEF, New York, 2020. Available: https://about.bnef.com/electric-vehicle-outlook/.

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[16] The BNEF *Electric Vehicle Outlook 2020* included conventional internal combustion engine vehicles, xEVs, and FCEVs.

Globally, there are just over 400 active hydrogen refueling stations, with approximately another 170 planned. Assuming "conventional" refueling stations (39 kg) [44] results in 530-MWh LHV (existing) and 210-MWh LHV (planned) storage. Europe and Asia (excluding China) have the most hydrogen stations (>300) and about 150 in the planning stages. Although the public/private breakdown of the majority of existing infrastructure is unknown, for those stations where we have data, a significant majority are public stations.

Figures 54 and 55 summarize the number of hydrogen refueling stations globally [45], [46].[17]

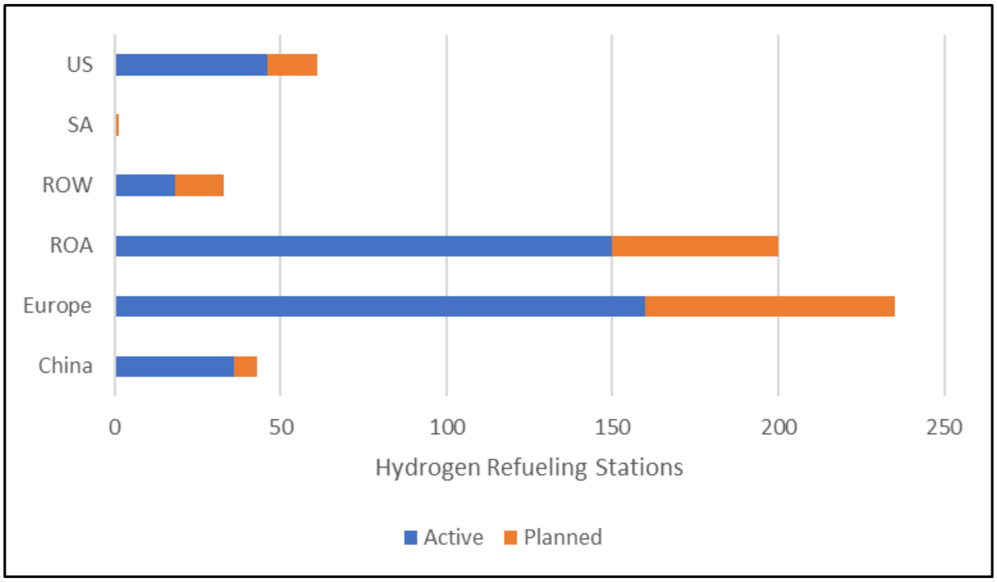

Figure 54. Active and planned hydrogen refueling stations by region

Source: [45] U.S. Department of Energy, "Hydrogen Analysis Resource Center." https://h2tools.org/hyarc (Accessed Aug. 20, 2020).

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[17] Storage for xEV charging stations is included in grid-based stationary-source discussions in the introductory section (based on Li-ion), as well as RFB and CAES. See Figures 5, 7, 38, and 42.

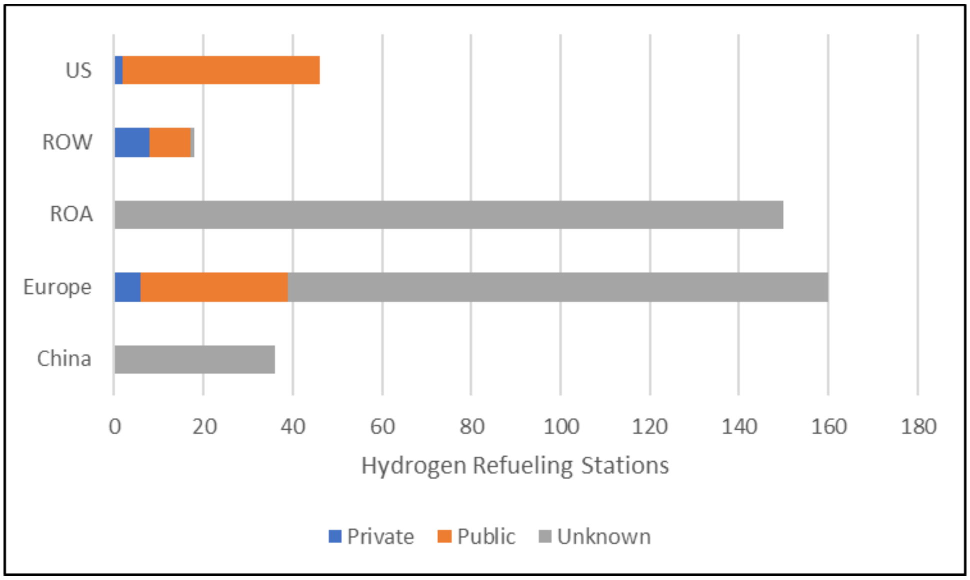


Figure 55. Active public and private hydrogen refueling stations by region

Source: [46] U.S. Department of Energy, "Hydrogen Fueling Station Locations." Alternative Fuels Data Center. https://afdc.energy.gov/fuels/hydrogen_locations.html#/find/nearest?fuel=HY (Accessed Aug. 20, 2020).

Building Thermal Energy Storage (TES) – Ice

Building thermal energy storage is an established technology that shifts heating or cooling energy from an on-peak demand period when rates are highest to an off-peak period, when rates are lower. The two main types of cooling thermal energy storage systems shift night supply with day demand and are either ice-based systems or chilled water systems. Only ice-based systems are considered in this report. Figure 56 provides a typical thermal energy storage cycle [47]. Figure 57 shows a commercial installation at the University of Arizona [48].

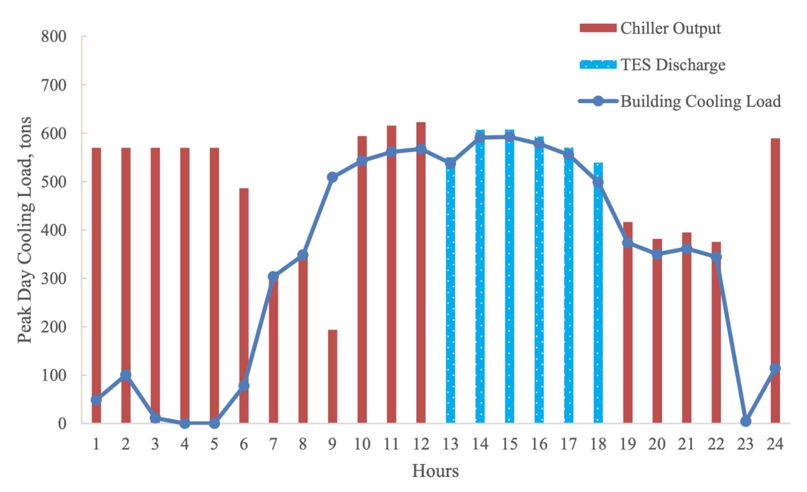


Figure 56. Typical thermal energy storage cycle

Source: [47] R. Yin, D. Black, M. Piette, and K. Schiess, "Control of Thermal Energy Storage in Commercial Buildings for California Utility Tariffs and Demand Response," Lawrence Berkeley National Laboratory, Berkeley, CA, August 2015.

Figure 57. Thermal energy storage installation

Source: [48] CALMAC, “University of Arizona,” 2020. Available: http://www.calmac.com/large-energy-storage-project-university-of-arizona.

TES Ice Market

Current U.S. deployment was nearly 100 MW of TES (ice) in 2017 [25]. There was a significant jump in deployment in 2014, but it has otherwise remained fairly constant. New York and Pennsylvania have deployed the greatest amount of TES (ice) in the United States.

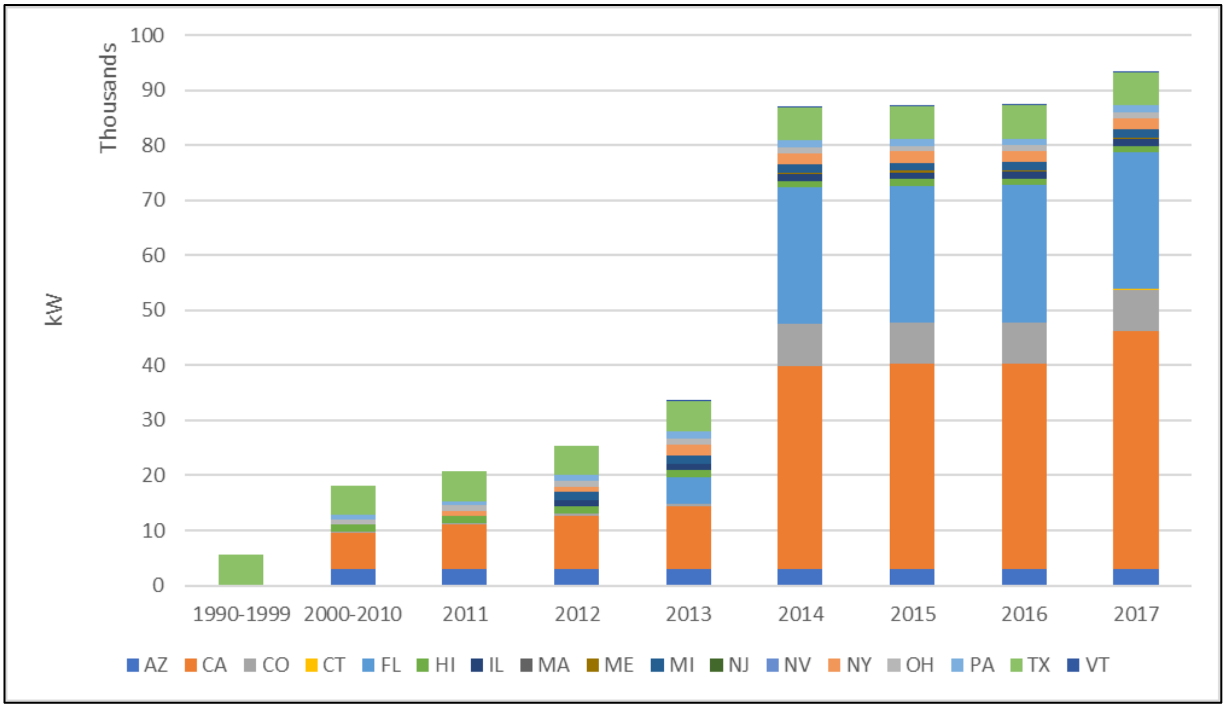


Figure 58. Domestic cumulative TES (ice) deployment

Source: [25] U.S. Department of Energy, "DOE OE Global Energy Storage Database." DOE. https://www.sandia.gov/ess-ssl/global-energy-storage-database/ (Accessed July 8, 2020).

Global TES (ice) annual vendor revenue projections were obtained from two analysts: Navigant (now Guidehouse) [49] and Grand View [50] and are summarized in Figures 59 and 60.

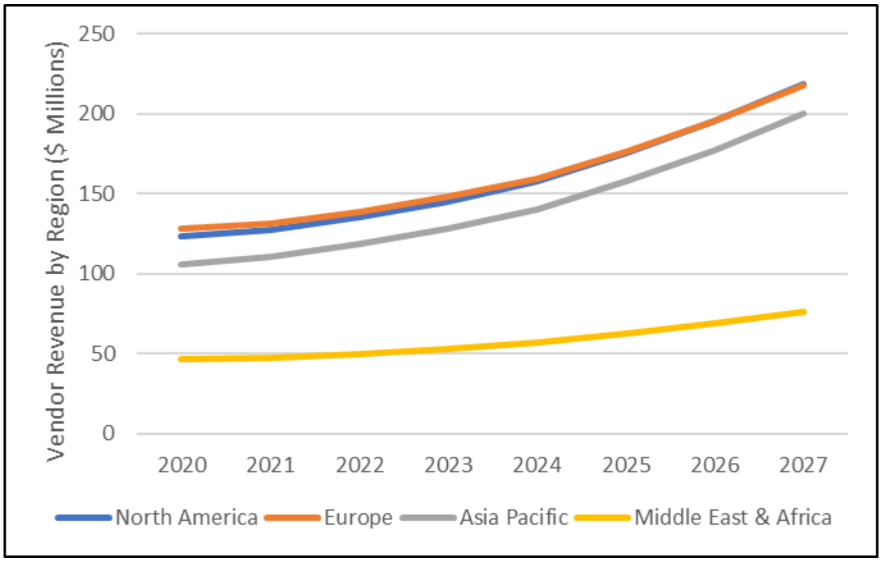


Figure 59. TES vendor revenue by region – market study 1

Sources: [49] R. Rodriguez and A. Eller, "Thermal Energy Storage Systems for Residential and C&I Applications: Global Market Analysis and Forecasts," Navigant Research, Boulder, CO, 2018.
[50] Grand View Research, Inc., "Thermal Energy Storage Market Size, Share & Trends Analysis Report," Grand View Research. Inc., San Francisco, 2020.

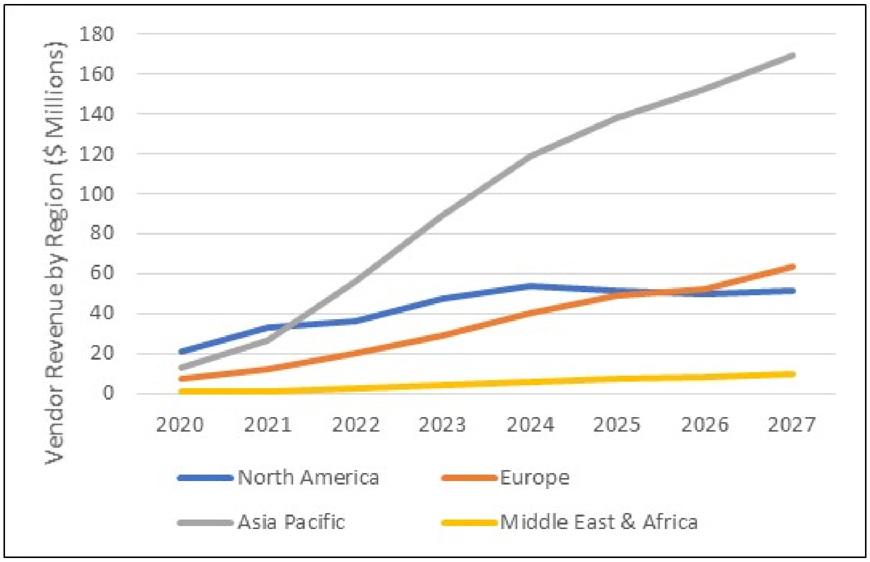


Figure 60. TES vendor revenue by region – market study 2

Sources: [49] R. Rodriguez and A. Eller, "Thermal Energy Storage Systems for Residential and C&I Applications: Global Market Analysis and Forecasts," Navigant Research, Boulder, CO, 2018.
[50] Grand View Research, Inc., "Thermal Energy Storage Market Size, Share & Trends Analysis Report," Grand View Research. Inc., San Francisco, 2020.

Discrepancies between these two market studies are related to differences in the basis for vendor revenue and different assumptions regarding areas for growth. Figure 60 includes maintenance charges in their revenue projections and assumes very similar growth rates in all regions. Figure 61 predicts high growth in Asia Pacific, specifically Japan, Australia, South Korea, China, and India, and only includes new deployments for vendor revenue.

The very high growth rate in the Asia Pacific region shown in Figure 62 is due to the following assumptions made in that market study:

- Rising demand for cooling in warm climates (air-conditioning demand has grown significantly in China over the last decade, reaching around one-third of the global air-conditioning stock in 2017)
- Government policies to reduce energy consumption are growing, including green building certificate programs and deployment of energy-efficiency solutions.

Ice-based TES adoption is generally assumed to be dependent on the presence of time-of-use tariff schemes, which provide cost saving opportunities for consumers, and the relative cost of batteries because TES can only impact thermal electric loads and generally occupies a larger footprint than a lithium-ion battery.

Figure 61 presents the regional deployment in terms of storage capacity.

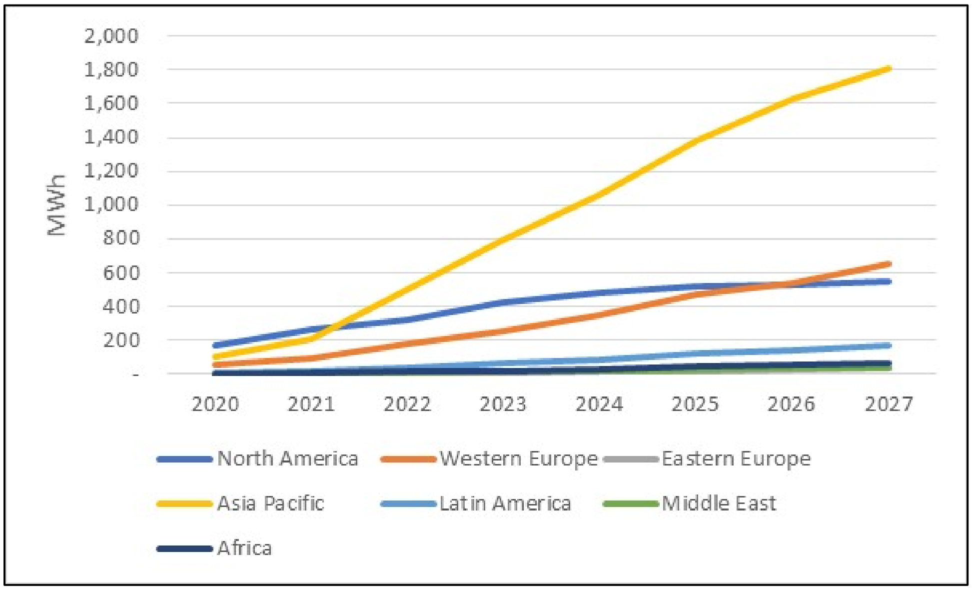


Figure 61. TES energy capacity deployments by region

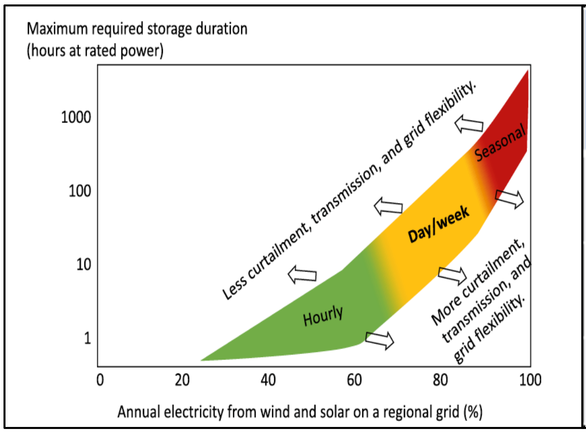
Sources: [49] R. Rodriguez and A. Eller, "Thermal Energy Storage Systems for Residential and C&I Applications: Global Market Analysis and Forecasts," Navigant Research, Boulder, CO, 2018.
[50] Grand View Research, Inc., "Thermal Energy Storage Market Size, Share & Trends Analysis Report," Grand View Research. Inc., San Francisco, 2020.

Nascent Application – Long-Duration Energy Storage (LDES) [51], [52]

The ESGC addresses not only well-established technologies and applications, but also those which are emerging. Long-duration energy storage (LDES) is one example of an emerging market included in this report. Below is a high-level description of LDES that portrays its evolving profile and opportunity to fill an important storage need.

As renewable content on the grid increases, the duration of storage needed to provide reliability also increases. The relationship between the grid renewable content and storage duration is complex and dependent on the details of the particular use scenario. Figure 62 illustrates this relationship and shows the estimated length of storage required versus grid renewable penetration. As the national grid transitions away from fossil fuels to renewables, the amount of LDES (>10 hours of storage) will be needed. For very high (i.e., >80%) of renewables, storage durations of >120 hours, often called seasonal storage, will be needed [53].

As duration increases, the marginal value of storage decreases and, therefore, so does the affordable total capital. The competitiveness of a technology will thus depend on the required hours of duration. Total capital is defined here as the fully installed cost, including both the device and complete balance of plant.



Duration (hrs)	Capital Cost Target ($/Kwh - fully installed)
~10	40
~50	7
~100	3

Figure 62. LDES targets[18]

Source: [51] P. Albertus, J. Manser, and S. Litzelman, "Long-Duration Electricity Storage Applications, Economics and Technologies," *Joule,* vol. 4, no. 1, pp. 21–32, 2020. Available: https://doi.org/10.1016/j.joule.2019.11.009.

Several technologies are available or are under development to address the emerging LDES needs, including PSH, RFBs, chemical and thermal storage, and electrochemical couples. PSH is an existing low-cost technology that can serve LDES; it is reported to offer the lowest-cost storage base on a 12-hour duration [53]. It is broadly deployed today in locations that are naturally well-suited to its siting requirements and sites for future capacity expansions are under evaluation.

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[18] Capital estimates assume a storage round-trip efficiency >50%.

RFBs are projected to be cost-effective for durations greater than 6–8 hours, depending on the particular chemistry. Vanadium-based RFB costs depend substantially on the cost of vanadium, which is historically variable and often high. Other chemistries using earth-abundant materials may be more competitive for LDES [53]. For example, as noted earlier, a company with an iron-based RFB designed for up to 10-hour duration is now scaling to >5 MW and expanding manufacturing capacity [36].

Chemical storage (e.g., H_2, ammonia, and certain hydrocarbons) for LDES applications typically require cavern storage to be economical. Exploration for suitable formations is thus underway. Ammonia may be the exception to this general rule due to its existing large infrastructure in the commodity chemical industry. For seasonal storage (120 hours), hydrogen systems with geologic storage and natural gas with carbon capture provide the lowest current and future projected capital costs [53].

Thermal storage can be viable for long-duration needs of both industrial processes and for the grid. It will likely remain focused on thermal-to-thermal cycles, but not thermal-to-electrical cycles, due to increased capital costs and efficiency issues for the electrical conversion.

Electrochemical couples (e.g., Na/S and Fe/Fe flow cells), often using novel concepts for low-cost containerization, remain in research and development. For these systems, the energy density should be >100 Wh/L as a guideline. One startup company recently indicated it has an “aqueous air” battery that can meet the cost targets of >50-hour duration [54].

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