ELECTRIC POWER
RESEARCH INSTITUTE

Overview of Emissions Impacts from Grid-Connected Battery Energy Storage

Technical Brief — *Environmental Aspects of Fueled Distributed Generation and Energy Storage*

Energy Storage Landscape

Energy storage may be used to provide ancillary[1], energy[2] and/or capacity[3] services to the electrical grid (Forrester, 2017). Use of energy storage may also contribute to grid infrastructure investment deferral through mitigation of congestion and improvements to power quality. Globally, capacity is now expected to grow rapidly for the next decade, culminating with 741 gigawatt-hours of cumulative capacity in 2030 (Wood Mackenzie(1), 2020) In the U.S., 168 MW were deployed in the second quarter of 2020, driven in part by a very large front-of meter project that accounted for more than 2/3 of the total MW deployed. Residential behind-the-meter energy storage experienced a record quarter, while commercial and industrial storage had its third strongest quarter ever (Wood MacKenzie(2), 2020). Expectations for strong future growth remain, with a forecasted growth in the U.S. from 523 MW in 2019 to 7.3 GW in 2025 (Wood MacKenzie(2), 2020). Lithium ion batteries controlled more than 90% of the grid-scale battery storage market by 2019 (EESI, 2019). About 60% of grid-scale batteries were nickel-manganese-cobalt (NMC) blends, also the technology of choice for electric vehicles, (EIA, 2020). This is followed by lithium iron phosphate (LFP), lithium cobalt oxide (LCO) and other chemistries. Battery energy storage (BES) technologies such as flow batteries, sodium sulfur batteries (NaS) and hydrogen fuel cells are alternative storage technologies gaining attention.

Figure 1. Common configuration for a stationary grid-connected lithium ion battery system in a container.

Short-Term Emissions Impacts of Energy Storage

Responding to the growing interest for grid-connected BES to support the integration of renewable generation, many researchers have investigated how emissions of greenhouse gases (GHG) and criteria air pollutants (e.g., NOx, CO)[4] would be affected. Criteria pollutants affect human health and ecosystems both directly, due to exposure, and indirectly due to their transformation into other pollutants and deposition on vegetation or waterbodies.

Initial studies assessing grid-connected energy storage generally relied on dispatch modeling tools and found that emissions tend to increase under basic operating conditions, such as energy arbitrage in which operations are set to reduce electricity costs.

The first driving factor is the round-trip efficiency of the battery, which quantifies the energy loss during charge-discharge cycles due to battery internal inefficiencies. Round-trip efficiency depends critically on the battery's internal components driven by the battery technology, such as type of electrodes, electrolyte and/or other components (e.g., internal pumps for flow batteries), and balance of plant components (e.g., thermal management, power conversion systems).

The second driving factor is the timing of the BES charge-discharge. Generation fuel mix and corresponding emissions vary during the day. Most studies found that, unless batteries are charged with cleaner generation than the generation they displace (to account for those round-trip energy losses), short-term GHG and air pollutant emissions will increase[5] (Hittinger, 2015) (Hittinger, 2017) (Craig, 2018) (Vandepaer, 2018). For example, Hittinger et al. estimated the amount of renewable energy needed to offset the emissions produced by a 25 MW/100 MWh storage device when used for energy arbitrage, depending on location and operational mode. The results ranged between 0.03-4 MW of wind and 0.24-17 MW of solar generation. Arciniegas et al. further investigated

[1] Services necessary to support the transmission of electric power from seller to purchaser to maintain reliable operations of the interconnected transmission system. They can be divided into balancing and contingency services.

[2] Services providing energy arbitrage by charging during lower-cost off-peak hours and discharging during higher-cost on-peak hours.

[3] Services providing capacity similar to traditional generators, reducing the need for new generation investments.

[4] The National Ambient Air Quality Standards (NAAQS) define criteria pollutants; https://www.epa.gov/criteria-air-pollutants

[5] Not applicable if the battery is fully charged with renewable energy that would be otherwise curtailed.

what energy storage operations would be required to reduce emissions while maximizing revenue. They concluded energy storage could reduce CO_2 emissions up to 25-50% in some areas, with a minimum loss of revenue of 1-5%, mostly by shifting the timing of operations to reduce marginal emissions. Yet, the results varied considerably by region and the authors recognized would be difficult to achieve in a profit-seeking market unless enforced through regulatory intervention (Arciniegas, 2018).

Similar conclusions have been reached by studies focused on behind-the-meter residential/commercial applications. Operating these batteries to minimize electricity prices led to increased emissions (Fisher, 2017) (Babacan, 2018) (Olivieri, 2020). One study suggested that internal energy losses associated to battery round-trip efficiency may increase emissions regardless of the timing of the charge/discharge cycles (Fisher, 2017). The studies also demonstrated batteries can be operated to minimize emissions, though tariffs or incentives for certain operational regimes may be required.

Dispatch modeling serves an important purpose, though by its nature is historical and not prospective. Emissions changes resulting from future capacity investments in the electrical grid, such as those due to changes in fuel price and the generation mix that storage deployments may influence, are unable to be incorporated. In recent years more complex analyses have been performed that account for multiple operational cycles and the important long-term structural changes to the grid that storage can facilitate. These will be reviewed next.

Emission Insights from Real-World Experience

Insufficient installation of grid-connected BES systems exists to clearly determine impacts to emissions. However, there are lessons to be learned from real-world installations of behind-the-meter storage.

The California Public Utility Commission (CPUC) Self-Generation Incentive Program (SGIP) provides economic incentives to install behind-the-meter self-generation technology to reduce peak grid demand. In the last few years, most of the program funding has supported BES. Terms for consideration of GHG emissions were introduced in 2010 (CPUC, 2010), and in 2015 a minimum round-trip efficiency eligibility metric of 66.5% was required for all storage projects (CPUC, 2015). The assumption was that the storage systems would charge with excess renewable energy and release it during peak times. Instead, successive evaluations of the program in through 2018 generally showed GHG emissions were actually increasing as the BES were primarily operated for profit maximization, charging during off-peak times with higher-emitting energy sources than the lower-emitting sources displaced when discharging. To correct this issue the CPUC issued a rule in January 2020 (CPUC, 2020) requiring new commercial installations to demonstrate emission reductions of 5 kg CO_2 per kWh of storage capacity during 5 years to receive full funding. Residential customers are required to have a single-cycle round-trip efficiency of at least 85% and enroll in a time-varying rate program. Residential developers must submit GHG emissions reduction data twice per year on kWh charged/discharged in every hour, in order to demonstrate their fleet reduces emissions in aggregate (Fosterling, 2020). Software by WattTime[6] that provides 24-hour forecasts of carbon intensity of the grid is available to facilitate the choice of optimal operational cycles. CPUC annual program performance assessments will assess if the new requirements were effective.

Insights from Long-Term Modeling Approaches

Growth of energy storage in the grid will influence investments and/or retirement of other assets in future years via its impact on wholesale prices and thus asset revenues. Bistline et al. (Bistline, 2020) evaluated scenarios with growing energy storage using EPRI's capacity planning and dispatch model, US-REGEN[7], across the lower 48 states in the United States. Their analysis considered both investment and dispatch costs to find the storage and generation mix that minimized net present value of U.S. electric sector costs. The authors note that, although adding more storage while holding other generation capacity fixed may lead to an increase in CO_2 emissions, deployment of more energy storage may increase the ability of the grid to support greater amounts of zero-emitting intermittent generation capacity in the future, which could reduce CO_2 emissions. These impacts are known as the dispatch and investment effects, respectively. They found that the investment effect dominated the energy dispatch effect under a range of sensitivity scenarios tested. BES was more likely to reduce emissions in locations where wind and solar are more economically competitive relative to natural-gas-fired generation. Issues raised in studies discussed in the previous section were addressed in this study: Bistline et al. assumed a round-trip efficiency of 91% and market participation for arbitrage, capacity, spinning reserve services, and inter-regional transmission deferral. This analysis shows that the short-term emissions increases found by previous analyses may be justified by emissions decreases in the long-term, in regions where wind and solar generation were economically competitive with natural-gas-fired generation.

Storage value stacking, or the use of an energy storage system to provide multiple local or grid services simultaneously may effectively increase battery use and economic benefits and potentially reduce emissions (Fitzgerald, 2015). To date, regulatory barriers have hindered use of

[6] WattTime uses artificial intelligence to combine EPA data on power plant emissions, information on wholesale market prices, fuel costs, wind and weather data and other inputs to produce day-ahead forecasts of carbon intensity of the grid.

[7] The U.S. Regional Economy, Greenhouse gas, and ENergy (REGEN) model is a capacity planning and dispatch model that projects electric sector pathways given assumptions about policies, technologies, and markets, minimizing total system costs subject to the applied technical and economic constraints.

storage value stacking. This is discussed further in the Policy Review section below. However, several forward-looking studies investigated how value stacking could impact emissions and other environmental impacts in the future. Craig et al. evaluated energy storage systems participating in energy only, reserve only and energy and reserve markets in the ERCOT system from 2015 through 2045 for CO_2 emissions reduction targets of 50% and 70% below 2015 levels by 2050. The study concluded that, in the long term, storage systems reduced emissions the most when participating on both energy and reserve markets by facilitating a stronger shift from coal generation to more efficient natural gas and renewable generation and a greater reduction of renewable curtailment - 25-50% for wind and 0-100% for solar (Craig, 2018). More recently, Kern et al. showed that value stacking led to significant reductions in battery energy losses and capacity required to perform multiple services, with consequent reduction in environmental impacts (Kern, 2019).

Figure 2. Ongoing research and real-world experience will help determine which energy storage scenarios can minimize emissions.

Life Cycle Assessment Studies Confirm Use Phase Emissions are Important

Environmental Life Cycle Assessments (LCAs) facilitate the identification of particular BES technologies, system designs or operational changes that can reduce overall emissions while optimizing other metrics, such as minimizing costs. LCAs calculate total emissions and other environmental impacts across a range of technology life cycle phases, such as materials extraction, manufacturing, use, and end-of-life management, rather than just during use phase as dispatch and capacity models do. The suite of available LCA studies of stationary BES systems that considered emissions includes both front-of-the-meter grid and residential or commercial behind-the-meter applications. Lithium ion chemistries, as well as NaS, vanadium redox flow batteries, hydrogen fuel cells and other technologies, have been assessed.

LCA studies that included both manufacturing and use-phase impacts for stationary BES consistently find that use-phase impacts are a, if not the, major contributor to environmental endpoints such as emissions (Baumann, 2017) (Ryan, 2018) (Vandepaer, 2018). Hiremath et al. considered several battery technologies providing six different grid services in the German electricity mix and recommended the deployment of batteries with higher round-trip efficiency, such as lithium ion batteries, to reduce overall GHG impacts (Hiremath, 2015). Ryan et al. stressed the importance of considering both round-trip efficiency and type of energy mix used for charging (Ryan, 2018). Another study found that use must be maximized to reduce emission impacts with respect to the manufacturing phase (Le Varlet, 2020). Similarly, Baumann et al. and Peters et al. recommended maximizing the life cycle of the batteries to reduce environmental impacts (Baumann, 2017)(Peters, 2017). An exception is Arbazadeh et al., who found higher impacts from the manufacturing phase when batteries were operated for power reliability, because this storage application requires a limited number of charge/discharge cycles (Arbabzadeh, 2017).

Policy Review

The technical assessments described above suggest BES value stacking provides an opportunity to recoup investments while maximizing battery use and minimizing environmental impacts. In the current regulatory environment investors may not be able to collect compensation from multiple sources when providing services that fit into two or more of the traditionally defined utility functions of generation, transmission and distribution. These traditional functions allow for compensation of investments through the regulatory framework (e.g., charges across utility customer bills) or the free market. Responding to this issue, the Federal Energy Regulatory Commission (FERC) issued ordinances that culminated with Order 841 (FERC, 2019) which adjusted the previously-inflexible rules designed with traditional generators in mind. Likewise, California and New York (ESA, 2018) implemented rules to facilitate the utilization of energy storage for value stacking. The federal appeals court has recently upheld Order 841 and rejected a suit to challenge the authority of its implementation (GTM, July 10, 2020). Thus, the potential for additional emissions reductions through value stacking will result.

Federal tax incentives also exist to support development of energy storage systems owned by a private (i.e., tax-paying) entity, but not if owned directly by a public entity (NREL, 2018). The Investment Tax Credit (ITC) has provisions that specify storage installed along with solar can count towards the ITC in many cases. Battery systems that are charged with renewable generation more than 75% of the time are credit-eligible. The exact value depends on the amount of renewable charging and the year of operation. The last extension of the ITC program phases out the residential ITC by 2022, although commercial sites will still be eligible for a 10% federal credit. It is possible the program will be renewed in a modified form in future years. Battery systems that are not installed with a renewable energy system may also be eligible for a Modified Accelerated Cost Recovery System (MACRS) depreciation deduction.

Several states have also developed policies to encourage energy storage development, generally to support their low carbon/climate change goals. According to the Pacific Northwest National Laboratory energy storage database (PNNL, 2020), 24 states adopted energy storage policies by 2020 that involve procurement targets, regulatory adaptation, demonstration programs, financial incentives and/or consumer protections (Twitchell, 2019). Some states, such as Hawaii (Hawaii.gov, 2014) or Oregon (gov.oregonlive, 2019), attached at least a portion of their energy storage procurements or targets to renewable generation + storage systems. Yet, only a few are adopting or exploring strategies to ensure that use of energy storage effectively reduces carbon emissions.

California's SGIP has already been discussed. Massachusetts approved in 2018, and is still developing, the Clean Peak Energy Portfolio Standard (Mass.gov, 2020) to ensure that (1) a portion of the peak-hour electricity comes from clean energy sources[8], and (2) energy storage used under the program will be charged primarily with renewable energy (Mass.gov, 2020). For that purpose, electricity providers must obtain "clean peak certificates" to demonstrate the renewable sources[9]. New York is working towards a carbon pricing policy that would indirectly penalize BES charging with fossil fuel energy (NYISO, 2018) (Tierney, 2019), but the program is still being evaluated. And, Oregon loosely attached the requirement that energy storage procurements must include consideration for GHG emissions reductions (gov.oregonlive, 2015).

Energy storage provides a variety of crucial services that are needed for grid modernization, even if system inefficiencies lead to short-term emissions increases. Robust research, demonstration projects and real-world experience will all have an important role in continuing to investigate and optimize the impact of policies, technologies, operations and strategies to facilitate a smooth transition with minimal environmental impact to a low carbon economy.

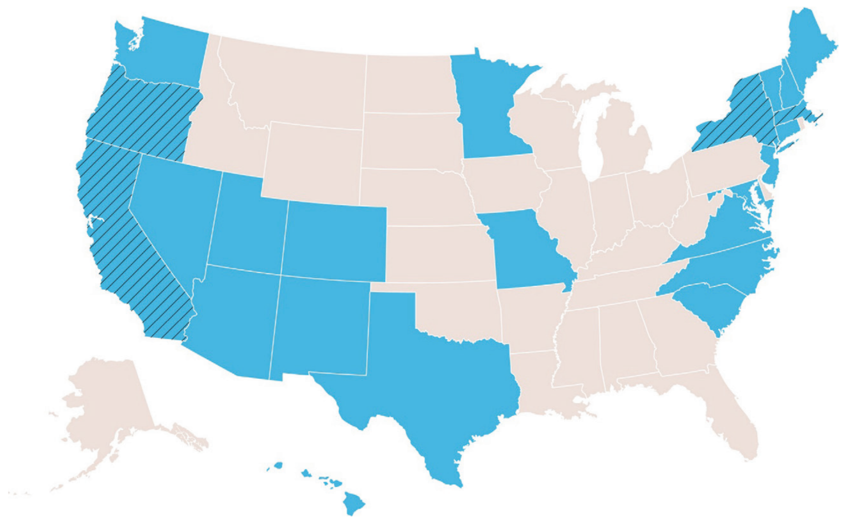

Figure 3. 23 states and the District of Columbia have policies to support the development of energy storage systems. Four of these (hashed) are exploring various storage implementation strategies to reduce carbon emissions.

Conclusions

Battery energy storage technologies are becoming more cost-effective and efficient, and policies and markets continue to adjust in order to support increased future deployment. The question remains as to how to most-effectively design and operate BES systems to maximize future environmental benefits. A key environmental metric is emissions of GHG and air pollutants from the electricity system, which are directly and indirectly affected by BES deployment, and often a driving factor for BES deployment. The major drivers of emissions changes from BES are 1) the battery round-trip efficiency, 2) the marginal electricity generation mix used to charge the battery vs. what is displaced during discharge (i.e., the dispatch effect), and 3) changes in capacity investment into zero-emitting intermittent generation (i.e., the investment effect). While the first factor rests on battery internal inefficiencies and balance-of-plant components and operations and is straightforward to determine and optimize to the intended use, the last two factors exhibit a higher degree of complexity. Grid topology, share of renewable energy and wholesale electricity market configuration and pricing structure, as well as battery operational profile and type of service(s) provided, are all contributing factors. Thus, studies that focus on specific regional markets or test systems may not be easy to extrapolate to other regions and/or set of conditions.

References

Albright, G., Edie, J. and Al-Hallaj, S., 2012. *A comparison of lead acid to lithium-ion in stationary storage applications.* Available at http://www.batterypoweronline.com/wp-content/uploads/2012/07/Lead-acid-white-paper.pdf.

Arbabzadeh, M., Johnson, J.X. and Keoleian, G.A., 2017. Parameters driving environmental performance of energy storage systems across grid applications. *Journal of Energy Storage* 12, pp. 11-28.

Arbabzadeh, M., Sioshansi, R., Johnson, J.X. and Keoleian, G.A., 2019. The role of energy storage in deep decarbonization of electricity production. *Nature communications* 10(1), pp. 1-11.

Arciniegas, L.M. and Hittinger, E., 2018. Tradeoffs between revenue and emissions in energy storage operation. *Energy* 143, pp. 1-11.

Babacan, O., Abdulla, A., Hanna, R., Kleissl, J. and Victor, D.G., 2018. Unintended effects of residential energy storage on emissions from the electric power system. *Environmental science & technology* 52(22), pp. 13600-13608.

Baumann, M., Peters, J.F., Weil, M. and Grunwald, A., 2017. CO2 footprint and life-cycle costs of electrochemical energy storage for stationary grid applications. *Energy Technology* 5(7), pp. 1075-1083.

Bistline, J.E. and Young, D.T., 2020. Emissions impacts of future battery storage deployment on regional power systems. *Applied Energy* 264, p. 114678.

[8] 1.5% of electricity sales in 2020 to be increased by a minimum of 0.25 percent of kW-h sales annually, aiming to reach 16.5% by 2030

[9] The storage device may qualify if co-located with a renewable energy resource, has some kind of operational or contractual pairing with a renewable resource or is charging from the grid during hours when renewables are at their highest percentage of the generation mix (ESA, 2019)

Campbell, R. J. 2019. Available at https://www.everycrsreport.com/reports/R45980.html.

California Public Utility Comission (CPUC), 2010. Decision Modifying the Self-Generation Incentive Program and Implementing Senate Bill 412. September 16. Available at: https://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/143459.PDF.

California Public Utility Comission (CPUC), December 11, 2015. Decision Revising The Greenhouse Gas Emission Factor to Determine Eligibility to Participate in the Self-Generation Incentive Program Pursuant to Public Utilities Code Section 379.6(B)(2) As Amended by Senate Bill 861. Avaliable at: https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M156/K044/156044151.PDF.

California Public Utility Comission (CPUC), March 29, 2001. Interim Opinion: Implementation of Public Utilities Code Section 399.15(B), Paragraphs 4-7; Load Control and Distributed Generation Initiatives. Available at: https://docs.cpuc.ca.gov/PublishedDocs/WORD_PDF/FINAL_DECISION/6083.PDF.

California Public Utility Comission (CPUC), January 16, 2020. Self-Generation Incentive Program Revisions Pursuant to Senate Bill 700 and Other Program Changes. Available at: https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M325/K979/325979689.PDF.

Craig, M.T., Jaramillo, P. and Hodge, B.M, 2018. Carbon dioxide emissions effects of grid-scale electricity storage in a decarbonizing power system. *Environmental Research Letters* 13(1), p. 014004.

Environmental and Energy Study Institute (EESI), February 22, 2019. Fact Sheet: Energy Storage. Avaliable at: https://www.eesi.org/papers/view/energy-storage-2019.

Energy Information Administration (EIA), January 29, 2020. Annual Energy Outlook 2020. Available at: https://www.eia.gov/outlooks/aeo/pdf/aeo2020.pdf.

Energy Information Administration (EIA), June 2020. Energy Storage Tracking Report 2020. Available at: https://www.iea.org/reports/energy-storage.

Energy Information Administration (EIA), May 21, 2018. U.S. Battery Storage Market Trends. Available at: https://www.eia.gov/analysis/studies/electricity/batterystorage/.

Energy Storage Association (ESA), 2018. *States in the Spotlight.* https://energystorage.org/policies-issues/states/states-in-the-spotlight/.

Energy Storage Association (ESA), October 2019. *The Clean Peak Standard in Massachusetts.* Available at: https://energystorage.org/wp/wp-content/uploads/2019/10/Clean-Peak-Standard-Summary_FINAL.pdf.

Federal Energy Regulatory Comission (FERC), May 23, 2019. *Docket Nos. RM16-23-001; AD16-20-001; Order No. 841-A: Electric Storage Participation in Markets Operated by Regional Transmission.* Available at: https://www.govinfo.gov/content/pkg/FR-2019-05-23/pdf/2019-10742.pdf Fisher, M.J. and Apt, J. 2017. Emissions and economics of behind-the-meter electricity storage. *Environmental science & technology* 51(3), pp. 1094-1101.

Fitzgerald, G., Mandel, J., Morris, J., Touati, H., 2015. *The Economics of Battery Energy Storage: How Multi-use, Customer-sited Batteries Deliver the Most Services and Value to Customers and the Grid.* Rocky Mountain Institute.

Forrester, S.P., Zaman, A., Mathieu, J.L. and Johnson, J.X., 2017. Policy and market barriers to energy storage providing multiple services. *The Electricity Journal* 30(9), pp. 50-56.

Fosterling, T., 2020. *Energy Tool Database: A Definitive Guide to the Updated SGIP Incentive Program (2020 Edition).* Available at: https://www.energytoolbase.com/newsroom/blog/a-definitive-guide-to-the-updated-sgip-incentive-program-2020-edition.

Globesnewswire, May 26, 2020. Global Battery Energy Storage Market & COVID-19 Impact Assessment 2020-2021. Available at: https://www.globenewswire.com/news-release/2020/05/26/2038378/0/en/Global-Battery-Energy-Storage-Market-COVID-19-Impact-Assessment-2020-2021.html.

gov.oregonlive, 2015. *HB 2193 - Relating to Energy Storage - Section 3 (d).* Available at: https://olis.leg.state.or.us/liz/2015R1/Downloads/MeasureDocument/HB2193.

gov.oregonlive, 2019. *House Bill 2618 - Relating to Solar Incentives - Section 2 (b).* Available at: https://olis.leg.state.or.us/liz/2019R1/Downloads/MeasureDocument/HB2618.

GreenTech Media, July 10, 2020. 'Enormous Step' for Energy Storage as Court Upholds FERC Order 841, Opening Wholesale Markets. Available at: https://www.greentechmedia.com/articles/read/court-upholds-ferc-order-841-opening-wholesale-markets-to-energy-storage.

Hawaii.gov, 2014. *Hawaii Senate Bill 2932 - Energy Portfolio Standards; Public Utility Comission.* Available at: https://www.capitol.hawaii.gov/session2014/bills/SB2932_.htm.

Hiremath, M., Derendorf, K. and Vogt, T., 2015. Comparative life cycle assessment of battery storage systems for stationary applications. *Environmental science & technology,* 49(8), pp. 4825-4833.

Hittinger, E. and Azevedo, I.M., 2017. Estimating the quantity of wind and solar required to displace storage-induced emissions. *Environmental Science & Technology* 5(21), pp. 12988-12997.

Hittinger, E.S. and Azevedo, I.M., 2015. Bulk energy storage increases United States electricity system emissions. *Environmental science & technology* 49(5), pp. 3203-3210.

ISO 14040, 2006. Environmental Management – Life Cycle Assessment – Principles and Framework; International Organization for Standardization. Geneva, Switzerland.

Kern, A., Johnson, J. and Mathieu, J., 2019. Environmental impacts of using energy storage aggregations to provide multiple services. Proceedings of the 52nd Hawaii International Conference on System Sciences.

Le Varlet, T., Schmidt, O., Gambhir, A., Few, S. and Staffell, I., 2020. Comparative life cycle assessment of lithium-ion battery chemistries for residential storage. *Journal of Energy Storage* 28, p. 101230.

Mass.gov, 2020. *Clean Peak Energy Standard Guidelines.* Available at: https://www.mass.gov/info-details/clean-peak-energy-standard-guidelines#determination-of-sales-.

Mass.gov, 2020. *Massachusetts Clean Peak Standard Notices and Updates.* Available at: https://www.mass.gov/service-details/clean-peak-energy-standard-notices-and-updates.

McManus, M.C., 2012. Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. *Applied Energy* 93, pp. 228-295.

National Renewable Energy Laboratory (NREL), 2018. Federal Incentives for Energy Storage Systems. Available at: https://www.nrel.gov/docs/fy18osti/70384.pdf.

NYISO, December 7, 2018. Integrating Public Policy Task Force (IPPTF) Carbon Pricing Proposal. Available at: https://www.nyiso.com/documents/20142/2244202/IPPTF-Carbon-Pricing-Proposal.pdf/60889852-2eaf-6157-796f-0b73333847e8?t=1547044924178.

Oliveira, L., Messagie, M., Mertens, J., Laget, H., Coosemans, T. and Van Mierlo, J., 2015. Environmental performance of electricity storage systems for grid applications, a life cycle approach. *Energy conversion and management* 101, pp. 326-335.

Olivetti, E.A., Ceder, G., Gaustad, G.G. and Fu, X., 2017. Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. *Joule* 1(2), pp. 229-243.

Olivieri, Z.T. and McConky, K., 2020. Optimization of residential battery energy storage system scheduling for cost and emissions reductions. *Energy and Buildings* 210, p. 109787.

Pellow, M.A., Ambrose, H., Mulvaney, D., Betita, R. and Shaw, S., 2020. Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues. Sustainable Materials and Technologies, 23, p.e00120.

Peters, J.F., Baumann, M., Zimmermann, B., Braun, J. and Weil, M., 2017. The environmental impact of Li-Ion batteries and the role of key parameters–A review. *Renewable and Sustainable Energy Reviews* 67, pp. 491-506.

Pacific Northwest National Laboratory (PNNL), 2020. *Energy Storage Policy Database.* Available at: https://energystorage.pnnl.gov/regulatoryactivities.asp.

Ryan, N.A., Lin, Y., Mitchell-Ward, N., Mathieu, J.L. and Johnson, J.X., 2018. Use-phase drives lithium-ion battery life cycle environmental impacts when used for frequency regulation. *Environmental science & technology* 52(17), pp. 10163-10174.

Sullivan, J.L. and Gaines, L., 2012. Status of life cycle inventories for batteries. Energy conversion and Management, 58, pp. 134-148.

Tierney, S. F., Hibbard, P. J., October 2019. Clean Energy in New York State: The Role and Economic Impacts of a Carbon Price in NYISO Wholesale's Electricity Markets. Available at: https://www.nyiso.com/documents/20142/2244202/Analysis-Group-NYISO-Carbon-Pricing-Final-Summary-for-Policymakers.pdf/75a766a8-623f-c105-ddcf-43dd78cb4bca?t=1570098881971.

Twitchell, J., 2019. A Review of State-Level Policies on Electrical Energy Storage. *Current Sustainable/Renewable Energy Reports* 6(2), pp. 35-41.

Vandepaer, J.C., Bauer, J., Amor, B., 2018. Integrating Batteries in the Future Swiss Electricity Supply System: A Consequential Environmental Assessment. *Journal of Industrial Ecology, Vol 23, Issue 3, pp. 709-725.*

Wood MacKenzie(1), 2020. Global Energy Storage Monitor Outlook H2 2020. Available at: https://www.woodmac.com/reports/power-markets-global-energy-storage-outlook-h2-2020-440628.

Wood MacKenzie(2), 2020. U.S. Energy Storage Monitor Q2 2020. Available at: https://www.woodmac.com/reports/power-markets-us-energy-storage-monitor-q2-2020-413101/.

Zhou, H.Y., 2017. Is electricity storage green? A study on commercial buildings. *Singapore Management University. Research Collection Lee Kong Chian School of Business.*

Contact Information

For more information contact the EPRI Customer Assistance Center at 800.313.3774 (askepri@epri.com).

3002020074 November 2020

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com