# Long-Duration Energy Storage: the key to making the most of zero-carbon electricity

When the energy produced by renewable technologies such as solar photovoltaic panels or wind turbines exceeds demand, which often happens during Spring and Summer months when there is abundant sunshine, that output is reduced, or *curtailed*. In short, these resources are taken offline.

The production of renewable energy below capacity levels is a missed opportunity in terms of avoided carbon emissions. If that energy could have been stored until demand increased, the full carbon reduction potential of those renewable technologies could be harnessed. The ability to store large amounts of clean energy to be discharged over longer periods of time when needed is one of the greatest challenges of our transition to a low-carbon grid.

While there are multiple definitions of Long-Duration Energy Storage (LDES), the LDES Council defines it as "any technology that can be deployed competitively to store energy for prolonged periods and that can be scaled up economically to sustain electricity provision for multiple hours, days, or even weeks, and has the potential to significantly contribute to the decarbonization of the economy." Storage bridges the gap between intermittent renewables generation and energy demand, enabling clean energy to power the grid more reliably. As such, it is a critical piece of a clean energy future, and the pathway to ensuring the reliability of renewable energy sources, given that there is often a mismatch between peak demand and potential renewable generation.

## How much energy is actually lost to curtailment?

Obtaining precise information on curtailment levels and practices is challenging, as data availability varies and conditions change each year. Generally, the curtailment of renewable generation depends on the market construct, energy mix, renewable resource penetration, transmission constraints, available storage, and climate conditions of the region. In California, the nation's top producer of electricity from solar, solar accounted for 17% of the state's utility-scale net generation in 2021, while wind accounted for 8%. The California Independent System Operator (CAISO) curtailed approximately 1,400 GWh of utility-scale solar and nearly 80 GWh of wind in 2021, for a total of just over 1,500 GWh – enough to power nearly 220,000 Californian homes for a year. In just the first half of 2022, the state curtailed nearly 2,000 GWh of solar and nearly 90 GWh of wind.

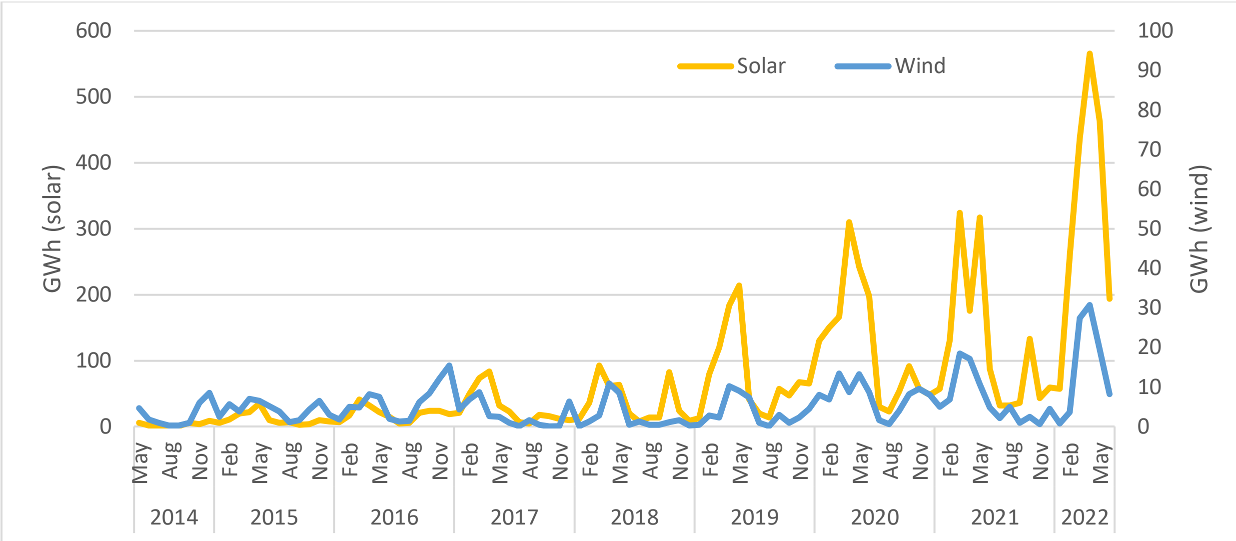


**Figure 1**: **CAISO yearly renewable energy curtailment, 2014-2022.**
**Source of data:** CAISO.

New York obtains 4% of its renewable energy from wind and 2.5% from solar, and NYISO reported wind curtailment of nearly 84 GWh for 2021.[1] If this power were stored and then available on-demand, it would be enough to power 11,500 homes in New York for a year. In the Southwest Power Pool (SPP), where 29.6% of generating capacity is wind, just over 6,300 GWh of wind energy was curtailed in 2021 – enough to power nearly 600,000 American homes for a year.

A recent study found that in 2021, the average wind curtailment rate across ISO and RTO areas was 4.8%, ranging from 0.4% in CAISO to 5.2% in ERCOT and 6.4% in SPP (**Figure 2**).[2] Solar curtailment in CAISO and ERCOT averaged 3.6% in 2020, with 3.3% for CAISO and 6.4% for ERCOT (**Figure 3**).[3] Given renewable generation levels in CAISO and ERCOT for 2021, solar curtailment in those two regions alone would have amounted to just over 2,400 GWh, and wind just over 5,300 GWh, for a total of nearly 7,800 GWh.[4] This would be enough to power nearly 730,000 American homes for a year. Gas-fired plants would have required 1.6 billion cubic meters of natural gas to produce that amount of electricity. While some energy would certainly be lost in conversion and the operation of LDES systems, there are various benefits to being able to use this energy.

[1] Solar curtailment data is not available for NYISO, but would presumably be significantly smaller given the lower share of solar generation in New York.
[2] Weighted average (by wind penetration rate) of 2021 curtailment rates for CAISO, PJM, ISO-NE, NYISO, MISO, ERCOT, and SPP.
[3] Weighted average (by solar penetration rate) of 2021 curtailment rates for CAISO and ERCOT.
[4] This estimate is calculated based on curtailment rates in ERCOT for 2021 (wind) and 2020 (solar), as well as wind and solar generation levels for ERCOT in 2021 (see "Fuel mix" section, https://www.ercot.com/). It also assumes that solar curtailment rates in ERCOT for 2021 were similar to the previous year's. CAISO wind and solar curtailment levels are taken directly from CAISO reports, which are updated to 2021 (http://www.caiso.com/informed/Pages/ManagingOversupply.aspx).

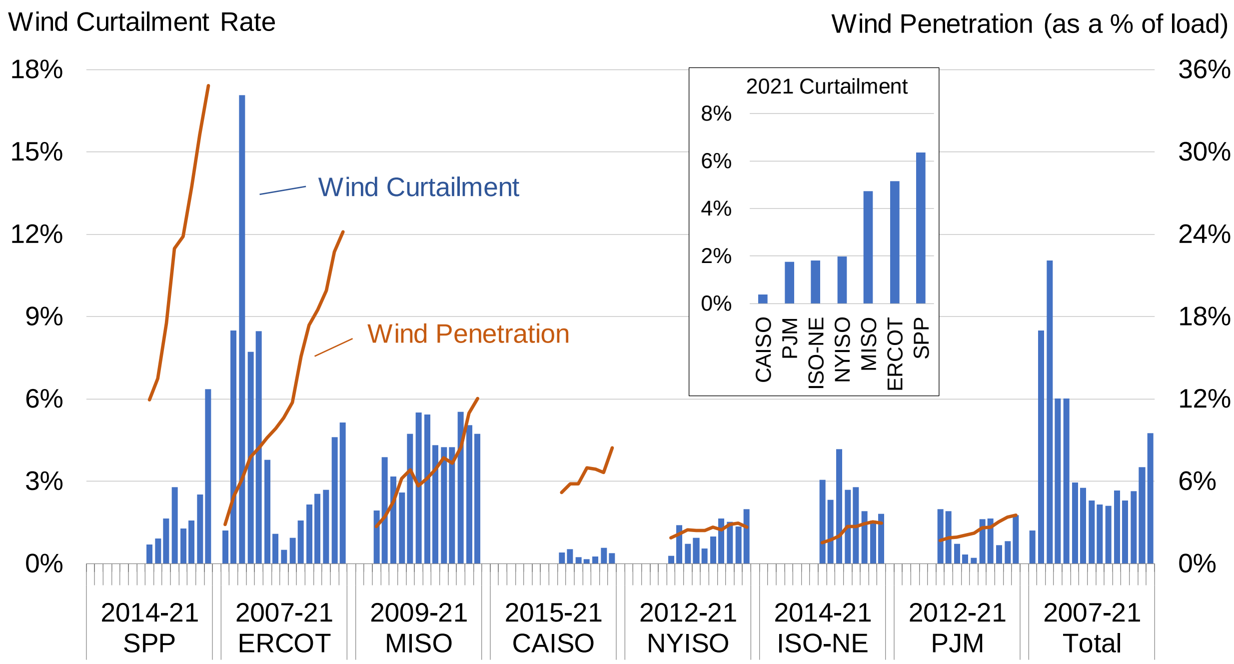


**Figure 2. Wind curtailment and penetration rates by ISO.**
**Source**: Ryan H Wiser, Mark Bolinger, Ben Hoen, Dev Millstein, Joseph Rand, Galen L Barbose, Naïm R Darghouth, Will Gorman, Seongeun Jeong, and Bentham Paulos, *Land-Based Wind Market Report: 2022 Edition*, Lawrence Berkeley National Laboratory for the Wind Energy Technologies Office of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, https://eta-publications.lbl.gov/sites/default/files/2022_land_based_wind_market_report.pdf.

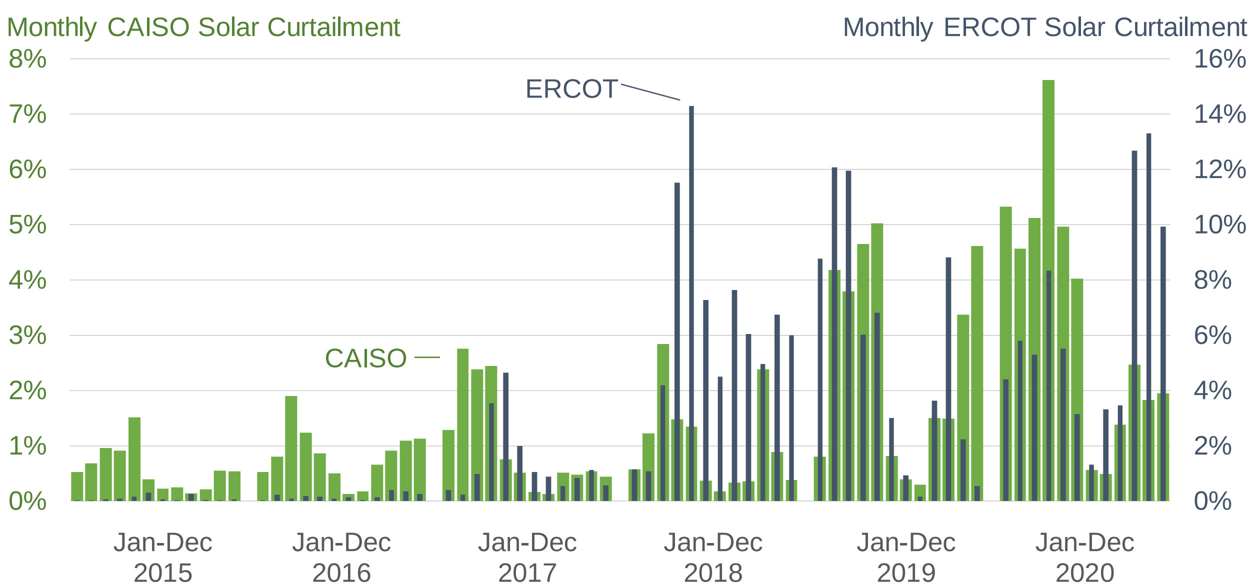


**Figure 3. Monthly solar curtailment in CAISO and ERCOT, 2015-2020.**
**Source**: Mark Bolinger, Joachim Seel, Cody Warner, Dana Robson, *Utility-Scale Solar, 2021 Edition: Empirical Trends in Deployment, Technology, Cost, Performance, PPA Pricing, and Value in the United States*, Lawrence Berkeley National Laboratory for the Wind Energy Technologies Office of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, https://emp.lbl.gov/publications/utility-scale-solar-2021-edition.

# Implications for emissions reductions and consumer wallets

On an average afternoon in August 2022, CAISO energy production generated around 233 mTCO2/GWh. At that rate, if all 1,500 GWh of curtailed solar and wind energy in 2021 had been stored for later use, over 350,000 metric tons (mTCO2) of carbon emissions would have been avoided. That is equivalent to the yearly CO2 emissions of over 76,000 passenger vehicles.

Considering power sector emissions and net electricity generation for 2020 in both Texas and California, the power sector emissions rate for those states in 2020 was 225 mT CO2/GWh for California, and 427.5 mT CO2/GWh for Texas. At those rates, if all of the curtailed energy in CAISO (over 1,500 GWh) and ERCOT (over 6,200 GWh) for 2021 had been stored and used, this could have avoided a total of just over 3 MMT CO2 (up to 0.3 MMT CO2 for California and 2.7 MMT CO2 for Texas), equivalent to the yearly CO2 emissions of over 658,000 passenger vehicles. Globally, a recent estimate indicates that by 2040, LDES deployment could avoid between 1.5 and 2.3 GT CO2e per year – up to 6% of global energy-related CO2 emissions.

The magnitude of curtailed energy and lost opportunities for avoided emissions will continue to grow as more renewable generation is brought online, if recent trends are any indication. Cumulative solar PV capacity in California, for example, more than doubled between 2015 and 2020 with curtailment increasing nearly sixfold over the same period. In ERCOT, solar capacity in 2020 was 16 times what it was in 2015, and curtailment increased sixty-three-fold during those years (**Table 1**).

| | CAISO | | | ERCOT | | |
|---|---|---|---|---|---|---|
| | **Cumulative capacity, utility PV ($MW_{AC}$)** | **Penetration** | **Curtailment** | **Cumulative capacity, utility PV ($MW_{AC}$)** | **Penetration** | **Curtailment** |
| **2015** | 5,513 | 9.5% | 0.6% | 295 | 0.2% | 0.1% |
| **2016** | 8,610 | 12.4% | 0.8% | 559 | 0.3% | 0.2% |
| **2017** | 9,139 | 15.3% | 0.9% | 1,220 | 0.7% | 1.5% |
| **2018** | 9,975 | 17.4% | 1.0% | 1,866 | 1.1% | 6.7% |
| **2019** | 10,954 | 19.0% | 2.4% | 2,363 | 1.4% | 5.0% |
| **2020** | 12,709 | 21.2% | 3.3% | 4,859 | 2.8% | 6.3% |

**Table 1. Solar curtailment and penetration rates, and cumulative capacity in CAISO and ERCOT, 2015-2020.**
**Source**: Mark Bolinger, Joachim Seel, Cody Warner, Dana Robson, *Utility-Scale Solar, 2021 Edition: Empirical Trends in Deployment, Technology, Cost, Performance, PPA Pricing, and Value in the United States*, Lawrence Berkeley National Laboratory for the Wind Energy Technologies Office of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, https://emp.lbl.gov/publications/utility-scale-solar-2021-edition.

Nationwide, capacity additions planned for 2023 amount to 24 GW for solar (in addition to 20 GW for 2022), and 4 GW for wind. The Energy Information Administration (EIA) expects solar energy to account for 20% of U.S. generation by 2050, up from 3% today. Just in California, solar generation is expected to increase over 24 GW in the next 5 years.

The rapid expansion of renewable generation will require increased storage capabilities to ensure the creation of a stable, 24/7 low-carbon grid. It will also require additional transmission and distribution system upgrades and expansion, and adding LDES to the grid can reduce these costs by acting as a buffer for intermittent renewable resources. In the US alone, adoption of LDES technologies could reduce the total cost of decarbonizing the power sector by $35 billion a year.

In certain market structures, an extreme mismatch between supply and demand can lead to widely varying wholesale electricity prices across regions, or blackouts. For example, a recent study found that the Energy Not Served (ENS) during the 2021 power outage in Texas was 955 GWh, with prices soaring to the ERCOT price cap ceiling of $9,000 per MWh.[5] Price surges are also not exclusive to exceptional extreme weather events – in May of 2022, prices in the Houston area soared to over $5,000 per MWh, an increase attributed to congested transmission lines. When power can't reach an area of high demand due to transmission line congestion, prices can dramatically increase. Conversely, congestion can cause negative pricing in areas with ample generation but minimal demand, as the power has nowhere to go and floods the market – as happened south of Houston in May. As more renewables are brought online, these price variations have become more frequent. In the case of the Texas outage, the 955 GWh of ENS is surpassed by the magnitude of curtailed renewable energy in 2021 in Texas (estimated at 6,200 GWh) and California (1,500 GWh), pointing to the significant costs that could be avoided by storing cheap, renewable energy for use during such events. While the installation of energy storage systems certainly carries its own cost, they could be used for multiple events for years to come.

## Technological options for long-duration energy storage

There is a range of technological options for expanding long-duration storage capabilities. To date, most grid-scale storage resides in pumped hydropower, which currently accounts for 95% of utility-scale storage in the US. Lithium-ion batteries have historically dominated new storage capabilities, but they currently cannot provide more than four hours of storage duration economically. They face the additional challenge of depending upon a supply chain dominated by foreign countries, some of which are geopolitical rivals or nations with questionable human rights records. The Democratic Republic of the Congo (DRC) is responsible for 71% of global production of cobalt, for example, and China controls at least two thirds of the world's lithium refining capacity. China also accounted for 80% of US lithium-ion battery imports in the last quarter of 2021. Recent legislation has taken steps to build secure battery supply chains both domestically and with geopolitical allies, but this evolution will likely take years. In the meantime, support for next generation energy storage technologies will be crucial in harnessing the full potential of renewable generation.

Some novel technologies offer significant promise for expanding storage duration. Power-to-gas technologies such as hydrogen, where electricity powers electrolyzers that produce hydrogen that is then used in a hydrogen turbine or fuel cell, can store energy for weeks, or even months. Various LDES alternatives that do not require expensive minerals not readily available in the US have the added benefit of enhancing energy security. Iron flow batteries, for example, which replace solid electrodes with energy-dense electrolytic compounds, have a discharge duration of up to 12 hours, and do not use minerals such as lithium and cobalt. Compressed air storage, whereby air is pumped underground and is heated to turn turbines when electricity is needed (and which has actually been used since the late 19th century), can also provide up to 12 hours of storage. Ultimately, the type of LDES most adequate for each region will depend on factors such as the share of renewable resources in the local energy mix, or the electricity load served.

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[5] This price cap was subsequently reduced to $5,000 per MWh.

# Policy recommendations and market practices: Supportive mechanisms for nascent LDES technologies

As of 2023, investments in standalone energy storage facilities will be eligible for an Investment Tax Credit (ITC) of 30% for the first time. For solar-plus-storage facilities, the ITC has been extended to 2030. Regions expected to witness a significant growth of standalone storage projects will likely include urban areas with high energy demand and likely higher revenues, yet are not suitable for renewable energy projects.[6] Regions with transmission constraints; isolated areas or island grids; and regions with opportunities for arbitrage can also be expected to attract new standalone storage projects.[7]

While the ITC expansion is expected to provide a significant boost to energy storage projects generally, not all LDES technologies are at an equal stage of development. The US has taken steps to accelerate commercialization with initiatives such as the Energy Department's Long Duration Storage shot. However, many nascent technologies, and even some that are market-ready, still face high initial project costs; high risk-perception by investors; uncertainty on future project revenue; and infrastructure constraints.

Additional policy measures and voluntary practices in the marketplace that would help reduce uncertainty for investors and project developers include:

- **Clear and precise regulatory definition of LDES as an asset class** distinct from traditional short-duration storage technologies. This will help provide certainty to investors and project developers, as it will clarify what regulatory structures and incentive programs apply to LDES technologies.
- **Measures to drive investment in LDES technologies and reduce clean energy costs for consumers.** Bolstering financial support for new technologies will aid the deployment of LDES systems and exploit their full potential to facilitate emissions reductions in the energy sector. Some examples include:
    - **Adding a timestamp to Renewable Energy Certificates (RECs)[8]** is one possible mechanism to increase investment in LDES projects, as traded volumes of RECs have grown steadily in recent years. Time-matched RECs would ensure that buyers are able to more accurately match hours of energy they use with low-carbon electricity generated in the same time period. As companies move to commit to run on carbon-free energy 24/7, this type of robust accounting would be beneficial to LDES systems by valuing their ability to store and deploy clean energy when needed as well as increase the precision of carbon accounting systems generally.
    - **Long-term compensation schemes for ancillary services.** Contracts or agreements spanning several years for the ancillary services provided by LDES (congestion management, providing reserves) could also increase predictability of future revenue for developers.

[6] Jackson Cutsor, George Hilton, Tiffany Wang, Alex Kaplan, and Eric Wright, "Inflation Reduction Act: Landmark climate and energy security bill
supercharges solar and energy storage industry in the United States," *Solar PV Insight*, IHS Markit.
[7] Ibid.
[8] Also referred to as "Time-based Energy Attribute Certificates (T-EAC)."

# Conclusion

It is difficult to obtain nationwide estimates on the amount of renewable energy that is curtailed each year, but estimates point to the importance of harnessing it. If curtailed energy could be stored and made available on-demand, it could increase the utilization of existing renewable energy generation capacity and improve the utilization of new capacity as it is added. In California, for example, which leads the US in solar energy production, the 1,500 GWh of solar and wind energy that was curtailed in 2021 would have been enough to power nearly 220,000 Californian homes for a year, avoiding up to 350,000 metric tons (mTCO2) of carbon emissions. The adoption of LDES technologies will also provide considerable financial opportunity: by storing energy when abundant (and therefore low cost) and discharging when demand is high but supply is low, operators of grid-connected storage projects have the opportunity to realize economic benefits while reducing carbon emissions.

New LDES technologies beyond hydropower that can provide storage for up to 12 hours – such as flow batteries or compressed air storage – or even weeks – such as hydrogen – would allow the US to make great strides in harnessing the full potential of intermittent low-carbon energy during periods of high demand. Given that most LDES technologies do not require critical minerals with supply chains tied to geopolitical adversaries, they are also a key pathway to bolstering American energy security.

Storage technologies have recently received significant support with an ITC expansion yet many still face high initial project costs, high risk-perception by investors, and infrastructure constraints. Measures such as increased precision in defining LDES as an asset class and increased investment will further aid the deployment of LDES systems and exploit their full potential to facilitate the decarbonization of the energy system.