As Operation Warp Speed demonstrated, demand commitment mechanisms can be transformative when applied to a clear, well-scoped, commercializable goal. Similarly, demand commitments in the form of renewable portfolio standards have been instrumental in accelerating the deployment of wind and solar energy. Today, the same demand commitments can jumpstart a robust market for long-term energy storage, which is essential to a clean energy transition.

61% of US electricity is currently generated by burning fossil fuels (EIA 2022a). Decarbonizing the electricity grid will require a significant shift in the electricity generation mix towards carbon-free electricity sources such as wind, solar, and nuclear, particularly if other sources of fossil fuel consumption such as vehicles and home appliances are electrified (Griffith 2021).

Other than wind and solar, the most widely deployed, carbon-free electricity sources are hydroelectric and nuclear. Nuclear is currently 18% of US electricity generation (EIA 2022a), but new construction faces permitting difficulties and cost and schedule overruns (Potter 2022). There is currently only one planned nuclear power plant scheduled for construction in the US (EIA 2022b). Hydroelectric is 6.1% of generation (EIA 2022a), and has become less popular as the best sites have become occupied and its negative environmental impacts have become better understood. (Moran 2018) New hydropower projects make up just 0.23% of planned US electricity projects. Other low-carbon energy technologies, such as blue/green hydrogen or geothermal, make up a small fraction of current capacity and are still in the early stages of development.

Wind and solar, however, are being deployed in increasingly large volumes. Of the 150 MW of planned new electricity generation projects, 67% are wind or solar. (EIA 2022b). If electricity consumption stays constant, and wind and solar continue their current growth rates (roughly 30% and 11% annually, respectively (DOE 2022, SEIA 2022), solar will be roughly 25% of US electricity generation by 2030, and wind will be roughly 20%.

Unlike current sources of electricity generation, which can output power constantly and store large quantities of fuel for generation (Albertus 2020), solar and wind are inherently variable sources of electricity, and their output fluctuates over timescales “ranging from seconds to years” (Albertus 2020). While this variation can be damped to some extent as geographic dispersion increases (Tong 2021), demand for wind and solar will require increased energy storage. Transmission is often slow to construct, while energy storage is more tractable and may damp variation more quickly (Repeat 2022). Energy storage requirements will vary depending on the sources of electricity used in the future and their relative costs (Trancik 2019, Albertus 2020, Sepulveda

2021), but are projected to be high in almost all scenarios. And the larger the share of intermittent renewables (particularly solar), the greater the needs for energy storage (Albertus 2020). A study of the requirements for a fully decarbonized electrical grid estimated a need for energy storage capacity equal to 33%-50% of current generation capacity (McKinsey 2021). Current energy storage is only 2.6% of generation capacity, (EIA 2022b), with another 6% in the planning stages (FERC 2023, EIA 2022).

Most current and planned energy storage capacity is either pumped hydro (PHS) or batteries, mainly lithium-ion. PHS makes up 70-75% of current and planned power capacity, and over 90% of current energy capacity, with the balance mostly batteries (EIA 2022, FERC 2023). Both PHS and lithium-ion tend to be used for short-term energy storage, and generally provide power for 10-12 hours or less (Albertus 2020, MIT 2021). But a high amount of wind and solar generation requires a significant amount of long-duration storage (LDES) capable of operating for 50-100 hours or more (Trancik 2019, Sepulveda 2021, Albertus 2020).

To be competitive with gas turbines for accommodating variation in generation, LDES will need to be very cheap, on the order of $1 to $7 per kWh (Albertus 2020, Sepulveda 2021). By comparison, current capital costs per kWh for PHS range from $75-$150 (Lazard 2016, NREL 2022). Costs of lithium-ion battery storage are even higher, over $300 per kWh (NREL 2022). PHS facilities are large construction projects whose costs are unlikely to fall significantly (IRENA 2017). And though the costs of lithium-ion batteries have fallen substantially (Our World in Data 2021), they are approaching the costs of their material inputs, and aren't projected to get cheap enough to be effective as LDES (MIT 2022). Lithium-ion batteries have low costs per watt, but high costs per watt-hour (NREL 2022), making them more appropriate for short-term storage requirements. The more the cost of LDES falls, the easier it will be to decarbonize the grid without incurring increased electricity costs (Sepulveda 2021).

LDES technologies generally fall into four categories. **Thermal systems** store energy by heating up a storage medium, and then using it to power a generator (or using it directly). **Electrochemical systems** are batteries of different chemistries. **Mechanical systems** store energy by physically moving mass, such as with raised weights or spinning flywheels. **Chemical systems** create and break chemical bonds, such as by using power to create combustible gasses that can then be burned for power. Though there are many potential low-cost LDES technologies, the technology is still nascent. It's unclear which of them will be viable, and which can best scale to the large amounts of storage needed. Some could be extremely inexpensive per watt-hour. The chemical costs of some metal air batteries, for instance, are up to 100 times less than the costs of lithium-ion batteries (MIT 2022), and could plausibly reach extremely low costs when produced at scale.

While there are a variety of companies developing LDES technology, this industry currently faces significant technical and market risk, hindering its development. On the technical side, energy storage technologies often require significant efforts to develop into commercial-grade products. Lithium-ion batteries were first experimented with in the 1960s, but weren't successfully commercialized until the late 1980s and early 1990s, despite attempts by Exxon in the 1970s (Li 2018). Compressed air energy storage was first developed in the 1970s but has yet to be deployed widely (Schaper 2021, Barbour 2021). Development work on new storage technology frequently fails to pan out, even after large amounts of funding (Bullis 2015, Jon Y 2022, Wesoff 2016, Choi 2017).

Additionally, under the current structure of the electrical grid, the value of LDES is low, making it difficult to compete in the market. As one vice president of an energy storage company noted, "5 hours [of energy storage] has maybe 5% more value than 4 hours. 10 hours has ~1% more value than 8. 100 hours [is] a rounding error vs 24 hours" (Hill 2021). LDES is more valuable the higher the fraction of electricity that is delivered by intermittent renewables, but today that fraction is low. Most storage needs are short term, better suited for technologies such as lithium-ion batteries that have low costs per watt and can deliver a high amount of power cheaply over a short period of time. Because the current market only requires short-term storage requirements, it's hard for technologies better suited for LDES to compete.

As the renewable fraction of generated electricity rises, and as gas turbines face increasing regulatory costs, the value of long-duration storage will increase (Roberts 2021). However, if appropriate and cost-effective long-term energy storage isn't ready to be deployed when needed, it may hinder future deployment of wind and solar capacity, resulting in a chicken and egg problem.

Having both market risk and technical risk makes LDES difficult to fund privately (Blank 2009). Between 2001 and 2021, only $1.8 billion was privately invested in LDES startups (Bloomberg 2022a). By comparison, more than $33 billion was invested in blockchain and crypto startups in 2021 alone (Melinek 2022). Public funding efforts such as ARPA-E's DAYS program for LDES (ARPA 2018) and the DOE's $350 million program for funding LDES technologies (DOE 2022a), are substantial, but due to the scale of deployment required — 600 gigawatts of LDES (50% of current grid capacity) could plausibly cost $500 billion to $1 trillion (Form 2021) — additional private investment will need to be encouraged. Existing funding efforts also fund a comparatively small number of projects, and run the risk of the government trying and failing to “pick a winner” (Ho 2021). There is currently “little to no policy support in place to overcome these [market] barriers and drive industrialization of the sector” (LDES Council 2022).

Demand commitment mechanisms that provided a guaranteed market for LDES technologies could help overcome current market barriers. What would demand commitment mechanisms look like? A demand commitment for long-term storage could be scoped concretely in the form of a specific price per kilowatt-hour of delivered electricity storage. In the short term the DOE could offer subsidies to utilities for the purchase of energy storage at a certain price per kWH, up to some cap. This funding certainty for early stage technologies would de-risk private sector investment, but would still incentivize utilities to source the lowest-cost methods of storage, ensuring market competition. In the longer term, this could transition to state level demand-side support, which could take the form of modified renewable portfolio standards.

To accelerate this transition, DOE could offer incentives to states that adopt renewable portfolio standards (similar to how the Department of Education used “Race to the Top” to encourage states to adopt more rigorous standards and assessments). These could either require the purchase of storage directly as a "storage portfolio standard" complementing the renewable portfolio standard, or modify existing portfolio standards to require increasing amounts of clean energy on an hour-by-hour basis (known as 24/7 clean energy). This would prevent the filling in of supply troughs with natural gas peaker plants, and incentivize the deployment of clean energy sources like LDES that can backfill demand over extended periods. As the most cost-effective technologies get developed and scaled out, their costs will fall.

A guaranteed market for LDES technologies would de-risk private investment (LDES 2022) by shortening the “valley of death” period between when a company starts developing a technology and when it generates revenue. Committing funding to this technology would jump-start the market. As production scaled up and costs fall, concurrent with long-duration storage becoming more valuable (Tuttman 2020), traditional markets could take over and make LDES a feasible purchase for utilities and grid suppliers.

The US wind industry benefited from a remarkably similar approach. Wind-generated electricity is over a century old, but until the 1980s was deployed on an extremely limited commercial basis due to its high costs. A combination of state and federal tax subsidies in the early 1980s enabled large commercial investments in wind farms and turbine technology, and costs fell steeply. The subsidies were removed at the end of the

1980s after a roughly $1.4 billion spend in tax credits ($3.7 billion in 2023 dollars), but were replaced by additional tax credits in 1992 (administered by the DOE) as well as state-level renewable portfolio standards (Owens 2018). These subsidies were instrumental in jumpstarting the wind energy market, and would have cost even less had they been better targeted (Owens 2018). The cost of wind-generated electricity (as well as solar photovoltaics, also aided by demand-side renewable portfolio standards), continued to fall until it became one of the cheapest available sources on an LCOE basis.

While there are many potential LDES technologies being developed, new battery chemistries are a particularly good target for demand commitments. Large-scale deployment of long-duration battery technology would involve the manufacturing of thousands or millions of nearly identical battery cells, and would likely see significant reductions in cost due to learning curve effects. Demand commitment mechanisms could kick off this learning process. At an experience rate of 20% (the learning rate seen on similar mass produced energy technology such as lithium-ion batteries, solar PVs, and LEDs), ten doublings (roughly equivalent to going from prototypes to mass production) would result in installed costs falling by roughly 90% (Form 2021). Long-duration batteries are also likely to be large and bulky due to the size of the cells required, potentially making them more resistant to outsourcing, as large bulky products tend to be produced close to their point of use.

Large amounts of LDES will be critical to decarbonizing electricity generation. Current technologies are not cheap enough to be widely deployed, and new technologies, such as novel battery chemistries that use low cost materials, face both technical and market risk that makes private funding of them difficult and risky. Demand pull mechanisms such as advanced market commitments would de-risk investment significantly, which would allow the space of LDES technology to be explored, the most promising systems to be found, and commercial production to ramp up. This would result in falling costs from learning curve effects, enabling LDES to compete with fossil fueled-sources of demand smoothing and reduce the costs of grid decarbonization.

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