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https://doi.org/10.1016/j.joule.2021.09.014

Commentary

Cross-sector storage and modeling needed for deep decarbonization

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As many researchers work to achieve a decarbonized grid, there is a general appreciation that we need to model the total energy system, but that doing so is difficult, if not impractical. Studies may focus on one piece of the grid and reach a conclusion whether a particular approach will or won't work. Including cross-sector storage in modeling provides opportunities to enable solutions that are otherwise impossible to identify and that may become the key to reaching a lowest-cost, lowest-carbon energy system.

The dramatic decline in cost of wind and solar electricity generating technologies illustrates this point, with wind and solar well-positioned to replace high-carbon energy sources. Due to their variability, wind and solar require enabling technologies to maximize their potential as part of a decarbonized energy system. Enabling technologies that could help achieve rapid decarbonization and integration across sectors include—but aren't limited to—long-duration energy storage, electric vehicles, distributed energy resources (DERs), heat pumps, thermal storage, net-zero hydrogen production, and negative emission technologies. These technologies differ in terms of their role and function in the electricity grid and reach across sectors. A focus on a single technology could lead to narrow solutions. This commentary provides a structure to articulate the role of different enabling technologies and cross-sector options to achieve energy system decarbonization and background to help readers assess whether a modeling study is likely to have missed opportunities that could limit the applicability of the conclusions. Today, energy storage is rapidly increasing in performance and decreasing in cost.[1]

The integration of energy storage and renewables into the grid demands new models that focus on novel approaches to explore and manage their optimal operation and least-cost solutions. These types of systems models are already evident in analyses considering electrification of transportation, space heating, and cooking. Typically, in the electric sector, there has been a focus on short-duration, electric energy storage to assist with the variability of wind and solar–think lithium-ion batteries for a Powerwall or utility-scale installations such as the Tesla Megapack in South Australia. Lithium-ion batteries are dominant for electric vehicles and in new grid-scale storage models. In the transportation sector, emerging research considering vehicle-to-grid applications of lithium-ion batteries is at the state-of-the-art. A cross-sector approach could be even more informative. With renewed interest in green hydrogen, produced by excess electricity from solar and wind, there could be a scaling effect in the demand for hydrogen affecting transportation electricity trajectories and power sector load profiles. A shift toward hydrogen has multiple implications that we need to understand more clearly, not just in the electricity sector, but also for transportation, agricultural, and industrial applications.

Whereas decarbonization efforts have focused on identifying sector-specific interventions—such as the reduction of CO_2 intensity in a coal-fired power plant or the adoption of energy efficient appliances—new classes of tools are needed to consider cross-sector, cross-day aspects of energy choices. Transforming variable solar and wind electricity into reliable generation sources places a greater emphasis on forecasting the timing of energy supply and demand. For instance, will increased reliance on solar and wind demand a strategic hydrogen reserve similar to current stocks of natural gas production? If we move to a decarbonized future that heavily emphasizes electrification, how much more supply will we need to produce? To some extent, cross-sector models have been implemented and are interrogated by different groups–these include NEMS, GCAM, and TIMES/MARKAL.[2–4] Yet some of these models have not yet fully integrated the temporal and operational implications of solar and wind-dominated transition—from short-term supply fluctuations to seasonal changes in resource availability. For instance, recent work highlights how important duration and temporal resolution becomes when thinking about deep decarbonization of electricity.[5] A cross-sector solution would identify complementary technologies across multiple durations and locations in the energy system. The electric sector demand from transportation, heating, cooling, and power-to-gas may completely shift because of a decarbonized energy system and change our needs during different months and hours. Therefore, cross-sector storage may be quite important in solving both diurnal challenges and seasonal fluctuations. Simply lumping all energy storage into single categories such as short-term, seasonal, and cross-day durations may fall short of our needs though as there are technologies that fulfill multiple purposes and can adapt based on geography-specific energy system requirements.

Some studies have explored, from a decarbonization standpoint, the role of solar thermal, electric, and gas water/space heating in integrating renewable energy to the grid.[6,7] Other studies begin to analyze the implications of a cross-sector shift in heating demand from gas-based fuels to electricity.[8] Yet more work of this nature is needed to understand the size, scale, and scope of technology interventions that cross sectors and the resulting implications for total energy system decarbonization.

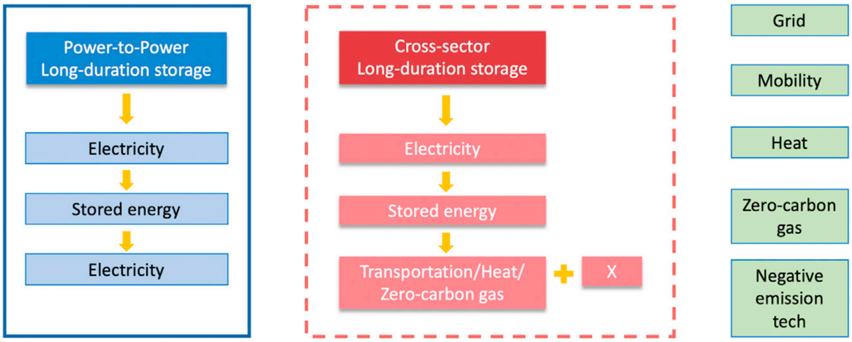

Figure 1. An example of self-contained Power-to-Power storage (blue), cross-sector storage (red), and different categories of input and end-use sectors (green) that could benefit from different energy forms such as electricity, heat, and hydrogen

Negative emission technologies are also becoming a topic of important research and debate convergent with energy storage. How much energy should we divert toward implementing negative emission technologies, such as carbon capture and storage, direct air capture of CO_2, and innovative processes such as the CO_2-to-liquid fuels for use across different energy sectors? Direct air capture, such as systems developed by Climeworks, to directly convert ambient CO_2 in the air using heat and electricity into stored or re-usable CO_2 that feeds agricultural greenhouses and useful products is emerging as a potential consumer of heat and electricity as a flexible load. Existing plants capture up to 4,000 tons of CO_2/year, but as costs decline to below \$750/ton, these facilities could increase to hundreds of millions of tons of CO_2 removed from the air.[9,10] They could offer flexibility in the timing of operation – yet this scale-up would also require increasing amounts of electricity and (ideally waste) heat.

With all these technologies emerging as potential storage options, it could help to map out different applications and use-cases of energy storage. For instance, biogas, which is typically viewed as a generation technology, could be used as a way to balance the grid regardless of its categorization as generation or storage. One way to represent opportunities across sectors is to consider the time-scale or duration of storage and second, the input and end-use form of energy.

Input and end-use storage categories

Storage can occur within and across sectors. For example, hydrogen can be used as storage within the power sector or can be used to couple the power sector with different sectors such as transportation, industrial, or agriculture. Distinguishing between power-to-power storage and cross-sector storage is crucial for better modeling approaches and policy decisions. Rather than treating storage as one monolith with similar properties – including some categorizing features of input and output energy forms would be helpful to develop more integrated pathways toward deep decarbonization.

A long-established challenge of integrating higher shares of variable solar and wind electricity on the grid is modeling storage. Inevitably, there are periods where a system may generate a surplus of electricity and not enough during times of high demand such as at night when the sun does not shine or when the wind is not available either. Having flexibility on what to do with that electricity becomes increasingly important.

We could store electricity into different energy carriers or vectors and then transform them into electricity, gas, heat, hydrogen, or use it to capture CO_2. Each of these options carries its own pros and cons and depends geographically on needs. Figure 1 displays a few configurations of input and end-use storage options. The blue displays a self-contained, power-to-power form of storage. In the middle, in red, we see there are other potential forms of cross-sector storage that can be used with electricity. Alternately, there is a list of services on the right side in green that can take different forms of energy–electricity, heat, hydrogen gas, or other energy that are important areas for decarbonization research.

The form of energy flowing in and out of an energy reservoir such as electricity, heat, and hydrogen and the form of the final energy demand served from storage could be represented as one way to classify different types of decarbonization strategies. This has been referred to as Power-to-X but can be expanded when electric power is not the input category. For instance, waste heat from thermal generation could be stored as thermal storage and then converted into electricity for use when the sun is not shining. If that was not an ideal or efficient use of the thermal energy, it could be used to contribute to other heat applications, gasification, or use in a negative emission technology such as direct air capture.

Many storage technologies can address different sectors or different storage applications across durations. In models that focus on deep decarbonization, with an end goal of zero or near-zero emissions across sectors, the desired goals should focus on the function of the storage to meet the major objective rather than compartmentalizing each storage technology into a reduced-function form–where batteries either provide ancillary services or longer-duration resilience needs. Under a changing climate, resilience needs may arise as extra redundancies in storage may allow us to adapt and cope with extreme wildfires, heat events, and flooding that are increasingly experienced.

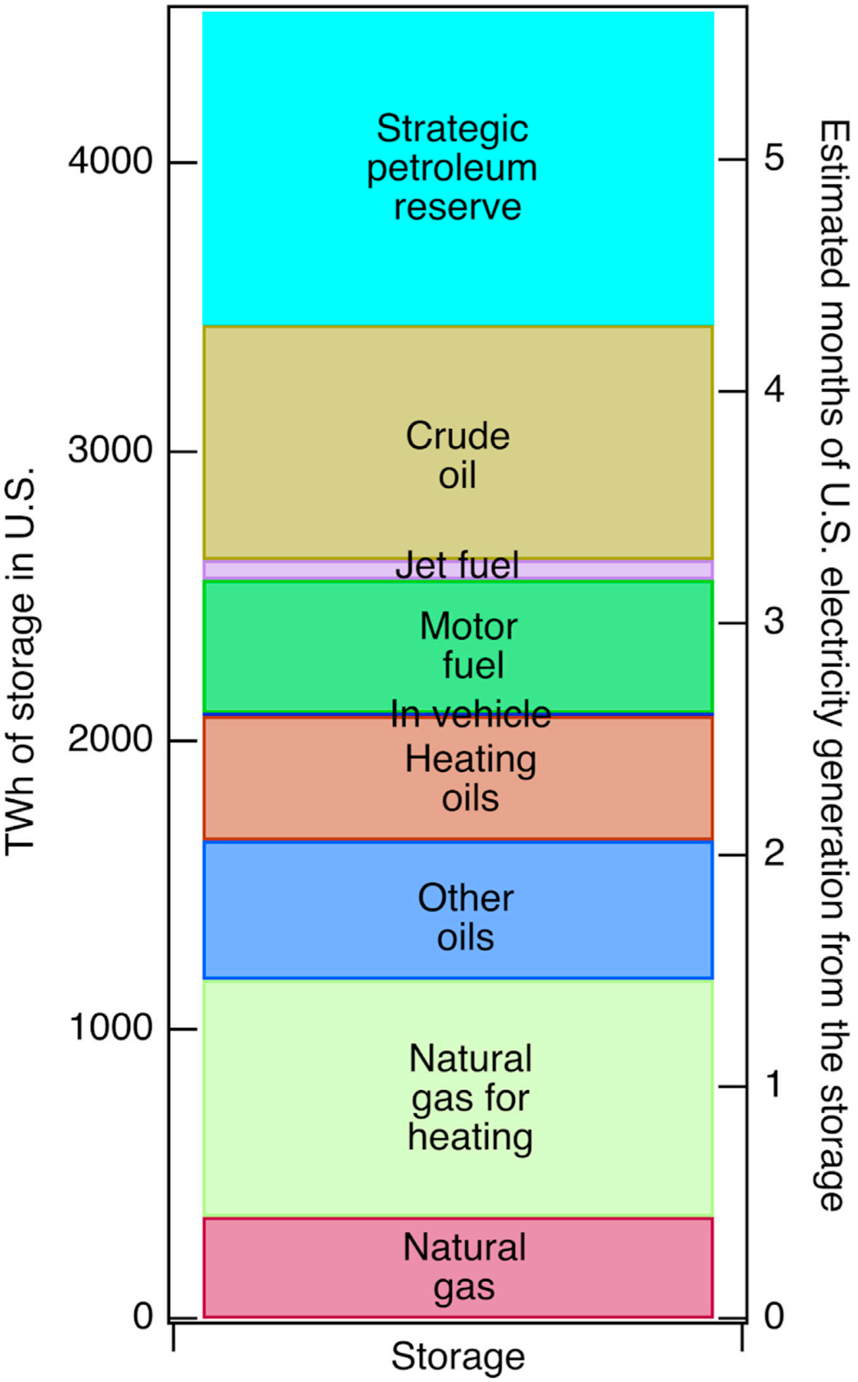

Figure 2. Approximate chemical energy storage used to supply the transportation, heating, power, and chemical sectors today

The TWh of chemical energy on the left axis is translated into estimated months of electricity generation assuming 40% efficiency and U.S. use of 3800 TWh of electricity in 2020. The natural gas stored for heating applications was estimated from the depletion of the stored natural gas during the heating season. The 350 TWh "Natural gas" may be used for power generation, heating, or other uses. The "In vehicle" estimate assumed 300 million vehicles with 30 kWh of storage in each. Data from EIA.[11–13]

Large-scale, long-duration energy storage

In this vein of resilience and providing a backup for power balancing, energy storage may also strategically provide security for a household, company, or country seeking to ensure their likelihood of having energy services available during a time of crisis. For instance, the United States currently maintains a strategic petroleum reserve to use—as a result of the 1973 Oil Crisis—and continues to pursue large storage reserves. These stocks are maintained as a way to hedge against extreme crisis–such as during the COVID-19 pandemic, wildfire season, or natural disaster disruptions that can affect the ability to produce energy resources.

Figure 2 shows how the United States maintains its Strategic Petroleum Reserve as well as chemical energy storage for transportation, heating, electricity, and other sectors. This concept demonstrates there is a cross-sector opportunity to provide energy security for a grid that has high penetrations of wind and solar electricity yet may remain vulnerable to outside threats.

In a deeply decarbonized US, there are many ways that a Strategic Energy Reserve could take shape. Having a cross-sector approach would build resilience, yet much of the chemical energy stores could shift across different energy sectors. For instance, for those who view electrification of end-use sectors as a critical pathway toward meeting aggressive climate reduction targets, having a Strategic Electricity Reserve could come in handy–particularly during natural disasters such as the California wildfires, Texas winter cold spells, or extreme heat waves that are likely to occur over the next half-century as global warming continues. This Strategic Energy Reserve for Electricity could take multiple forms serving as an example of a cross-sector opportunity. The reserve would allow for a resilient response to threats such as climate change, cybersecurity breaches, or resource scarcity. It could be a multipronged strategy that contains long-duration energy storage, zero-carbon generation sources, and distributed infrastructure that can operate independent of the larger electric grid.

With increased attention toward electrifying transportation, a cross-sector approach may suggest that vehicles need strategically located DC-fast chargers to provide short bursts of power rather than long duration energy storage devices that serve multiple days. Yet, for more remote areas that are heavily reliant on one or two primary high voltage transmission lines, there may be significant value in siting more flexible technologies such as flow batteries, gravity storage, or liquid-air type energy storage plants that could provide such a Strategic Electricity Reserve.

Currently, balancing authorities are responsible for matching electricity supply and demand within a specific region. In the United States, there are 74 different balancing authorities. These interconnections govern the transmission of power and are responsible for power grid reliability in real time. Multiple months of distributed and centralized electricity reserves could be coordinated across balancing authorities with an accounting of both transmission and utility-scale storage resources to improve interconnectivity and resilience in case of emergency. This would also benefit utilities during a cybersecurity threat or attack even if the physical amount of chemical storage is decreased, going beyond the capabilities of capacity markets.

The volume of the Strategic Petroleum Reserve in energy will likely decrease in an electrified future. However, as estimated on the right-hand side of Figure 2, it's likely that a Strategic Energy Reserve for Electricity would be useful that lasts up to six months, if not more. For instance, this storage volume could be simultaneously considered across energy sectors, for electricity, transportation, industry, and chemicals. When coupled with renewable energy such as solar and wind plants, the reserve would consist of the necessary enabling technologies to recharge the grid and maximize the availability of the solar and wind that could reconnect in an emergency. This energy reserve could focus on the availability of longer-duration storage, expanded transmission, or zero-carbon generation options in the event of a significant catastrophe, where one would need to not only utilize solar and wind for real-time loads, but also recharge storage devices to ensure against a cloudy or windless day. The reserve does not need to consist of all chemical storage, a diverse range of sectors would build resilience and opportunities to recover from outages or security threats and ensure the availability of energy for conversion to electricity.

A deeply electrified and decarbonized energy system dramatically changes the timing and intermittency of generation. Domestic renewable energy fluctuates, yet potentially builds resilience by having many more generators—both centralized and distributed—than a system that historically is reliant on large-scale (> 300 MW) thermal generators and nuclear power stations for electricity. The geographic distribution of variability offers some benefits that could reduce need for a Strategic Energy Reserve. Short-duration forms of power support for reliability in a low-inertia power system would be critical–areas where batteries, flywheels, and supercapacitors shine. For vehicular and building resources, more dense and distributed charging stations for batteries and other gas supplies such as hydrogen vendors would also reduce the need for conventional chemical storage. Depending on the energy input type and the energy output type, the security afforded by large stocks of petroleum and oil resources could be replaced. In a new system, security could be defined by the ability to produce electricity, heat, or hydrogen gas at a moment's notice, with the accompanying generation source. It could be a literal store of these energy types. In a system focused on electricity that could include greater electricity storage such as long-duration gravity or hydro-based systems. With opportunities to store energy as hydrogen gas or liquid hydrogen, this low carbon fuel could provide stable seasonal storage to balance demands and offer flexibility across electricity, transportation, agricultural, and industrial sectors, as needed.

The role of gaseous fuels in an electrified world

The role of gas in a deeply decarbonized electrified world remains uncertain. Some proponents suggest carbon capture and storage technology will decrease in cost to become more competitive than alternative and expensive storage. Other potential gas alternatives such as hydrogen could provide low-carbon substitutes into existing pipeline and infrastructure networks. Gas is typically considered an available, on-demand resource that can meet electricity, transportation, and other versatile needs. That's why either liquid hydrogen or hydrogen gas attracts enough attention for a $1/kg Energy Earthshot, as low-cost renewable hydrogen could replace existing natural gas systems with a decarbonized alternative. For existing natural gas and biogas systems, there are potential synergies that utilize the Allam cycle to generate heat and capture CO_2 and water. Carbon capture and storage coupled with power generation makes sense for some places that have legally mandated net-zero emission energy systems. Yet, there may be challenges ahead—one is the impact on air quality from upstream extraction—particulate matter emissions and nitrous oxides may still be present in such systems that can concern public health.[14]

On the other hand, hydrogen presents an interesting opportunity to utilize cross-sector storage in a way that could be mutually beneficial and more efficient to achieve deep decarbonization. Zero-carbon hydrogen gas can be used in a variety of industrial applications where electricity is expensive or inefficient. Zero-carbon hydrogen could facilitate further electrification of end-use sectors and allow for reconversion to electricity through fuel cells as back-up to individual buildings or communities. There could also be the inclusion of hydrogen in steel-making and industrial process heat. If electric heat pumps, vehicles, and induction cooking stoves become more pervasive, there will be less need for natural gas.

Cross-sector approaches can enable commercialization of seasonal storage

A forward-looking modeling and policy approach would analyze cross-sector decarbonization from a systems perspective. Though it is tempting to investigate individual sectors and their responses—better, more holistic, and realistic solutions will likely emerge. Additionally, while technological synergies can be captured that are often neglected, such as the example if hydrogen demand surges, there could be unintended effects of diverted solar and wind electricity to the hydrogen sector when electricity is scarce and expensive. Vehicle-to-grid based electric vehicle interactions could allow for substantial benefits for both the electricity sector and the transportation sector by offering different value streams and making electric vehicles more affordable for large fleets of vehicles, which today consume diesel and natural gas.

By identifying the input and end-use energy types for classifying storage technologies and other generation, one can move beyond labels and confusion arising from short-duration and long-duration classifications of storage. The functional purpose of energy systems can be used in a cross-sector way to solve broader system challenges of decarbonization. Cross-sector thinking can improve overall energy security. Then, modelers and policymakers can identify better technologies suitable toward overall societal goals such as deep decarbonization and rapidly make the changes needed to achieve our ambitions.

ACKNOWLEDGMENTS

The authors would like to thank the California Energy Commission for funding this work under contract number EPC-19-060. The authors also thank M. Aziz, J. Burwen, R. Hanna, M. Yuan, and R. Go for useful input.

DECLARATION OF INTERESTS

The authors declare no competing interests. This document was prepared as a result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees, or the State of California. The Energy Commission, the State of California, its employees, contractors, and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this document; nor does any party represent that the use of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the Energy Commission nor has the Energy Commission passed upon the accuracy of the information in this report.

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https://doi.org/10.1016/j.joule.2021.09.003