THE OPPORTUNITIES AND LIMITATIONS OF SEASONAL ENERGY STORAGE

November 2020

Oscar Serpell

Kleinman Center
for Energy Policy

CONTENTS

EXECUTIVE SUMMARY

Wind and solar power will form the bedrock of a future clean energy system. They are cheap, easy to maintain, widely deployable, and long-lasting. They do, however, have one significant and ultimately unavoidable fault: intermittency.

Over the course of hours and days, this intermittency can be somewhat compensated for using demand response, variable-rate electricity pricing, and short duration storage. Lithium-ion batteries, though still fairly expensive, have become an increasingly economical solution to load balancing challenges. However, wind and solar capacity factors also vary over the course of seasons and years.

Meanwhile, seasonal energy demands such as home heating will need to be decarbonized—likely via electrification. Lithium-ion batteries become significantly less viable solutions for load balancing over these longer timescales because of their inherent technological limitations and because of insufficient market compensation for "stand-by" services.

Balancing a decarbonized grid over seasonal and annual timescales will require several changes in policy and investment priorities including revisions to storage markets, increased transmission investment, and development of alternative storage solutions.

INTRODUCTION

This digest introduces readers to the many challenges inherent in a renewable energy system and discusses some of the ways technology and policy can help address these challenges. Setting aside their enormous contribution to global carbon emissions, fossil fuels (oil, natural gas, and coal) are phenomenal energy resources. They are plentiful, cheap to produce, extremely energy dense, and relatively easy to transport and store. These properties have been the bedrock on which our modern global economy has been built and transitioning away from these resources will be neither cheap, nor straightforward.

Nevertheless, the inevitable disruption and expense of transitioning the existing energy system to one powered by carbon-neutral and renewable energy resources pales in comparison to the system-wide disruption and economic costs of maintaining the status quo (Hausfather 2019). Weaning ourselves off of hydrocarbons is a far easier task than relocating hundreds of millions of people away from coastlines, combatting intolerable heatwaves in our largest cities, and preserving enough fresh water to meet demand in the face of severe drought (Podesta 2019).

In this sense, decarbonizing our energy system in time to prevent the worst effects of climate change is as much of a necessity over the coming decades as is sufficient generation capacity and load-balancing. To achieve the United Nation's climate and energy goals, we have less than 30 years in which to design, implement, and sustain an energy system that offers zero-carbon energy, meets all of our essential energy needs, and provides affordable and reliable access to everyone (IPCC 2018, UN General Assembly 2015).

Solar and wind power coupled with battery storage provide the pivot to this transition, as costs for all three technologies have decreased and efficiencies have increased dramatically in recent years, allowing them to compete favorably with fossil fuel generation in many cases (IRENA 2020).

However, these technologies are inherently limited: Wind power is highly variable by day, region, and season and is difficult to predict (Wan 2012). Solar power is only generated at its highest capacity factor for several hours in the middle of the day and disappears overnight. Battery storage, meanwhile, continues to be costly, and can only be used over relatively short time periods. Leaving a lithium-ion battery empty for weeks or longer can allow copper dendrites to form and degrade the internal infrastructure, thereby permanently reducing the cell's capacity and causing the cell to become unstable (Battery University 2018).

Over the course of a single day, or even a week, these limitations are not necessarily serious constraints to designing and implementing a renewably powered electricity system. By deploying a good diversity of solar and wind power across different regions, and by building enough additional storage capacity to account for a cloudy day here or a particularly windless day there, an electricity system entirely powered by renewables ought to be feasible. However, the relative feasibility of complete decarbonization changes depending on both the temporal and physical scale of the system being modeled.

Consider a single homeowner who has decided to sever all ties to the local electricity company. That homeowner puts a number of solar panels on the roof, a large wind turbine in the backyard, and an impressive battery storage system in the basement, complete with automated charging and discharging that responds instantaneously to supply and demand to and from the system.

One sunny fall day, the homeowner tests the system, which successfully powers the home without help from the grid for an entire day and night. The homeowner then decides to permanently disconnect from the electricity grid, and while they're at it, they decide to electrify the home's heating system as well.

The next week, the skies get cloudy and the temperature plummets. Every few hours the homeowner goes to the basement to check the batteries and watches the charge slowly deplete. After a few days of this weather, the homeowner is huddled in the dark, wrapped in every blanket they own, wondering what went wrong.

Obviously, the electricity system as a whole is not the same as a single home; the electricity system has access to a more diverse portfolio of generation assets and can use transmission to move energy to where it is needed most. Still, many of the principles that caused the homeowner's system to fail also apply to the larger grid network. These challenges will make a fully renewable energy system a monumental achievement.

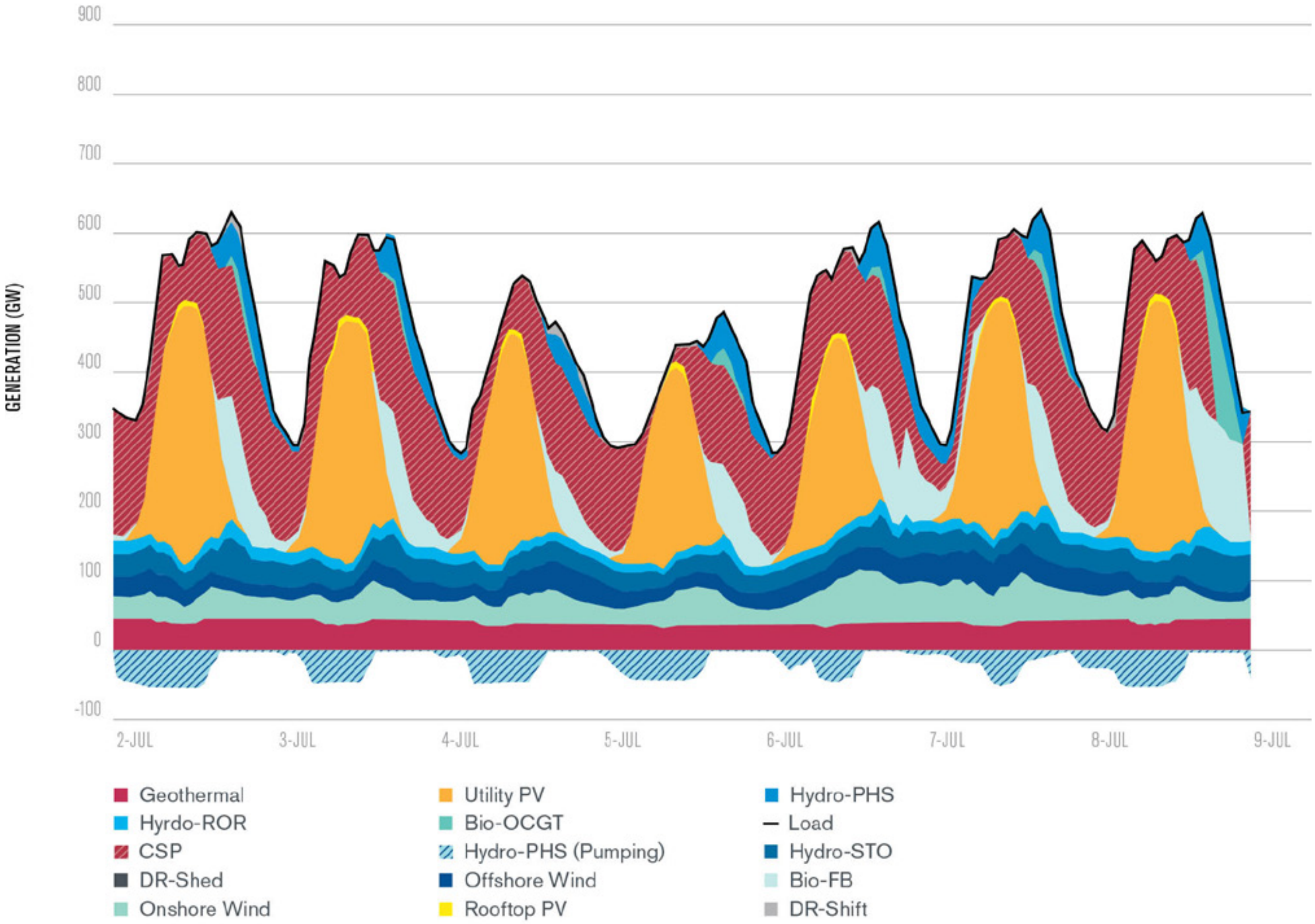
The intention of this digest is not to offer a predictive model of the U.S. power system in 2050, nor is it to conclude the feasibility or infeasibility of a carbon-neutral grid. There are several existing studies, such as the NREL Electrification Futures Study that have tried to offer these predictive insights by modeling scenarios of technology deployment.

The Kleinman Center itself recently published a report on seasonal storage that models the theoretical deployment of different storage technologies (Serpell et al. 2020). The objective of this digest is instead to introduce readers to the many challenges inherent in a renewable energy system and discuss some of the ways technology and policy can help address these challenges.

SEASONAL SUPPLY AND DEMAND

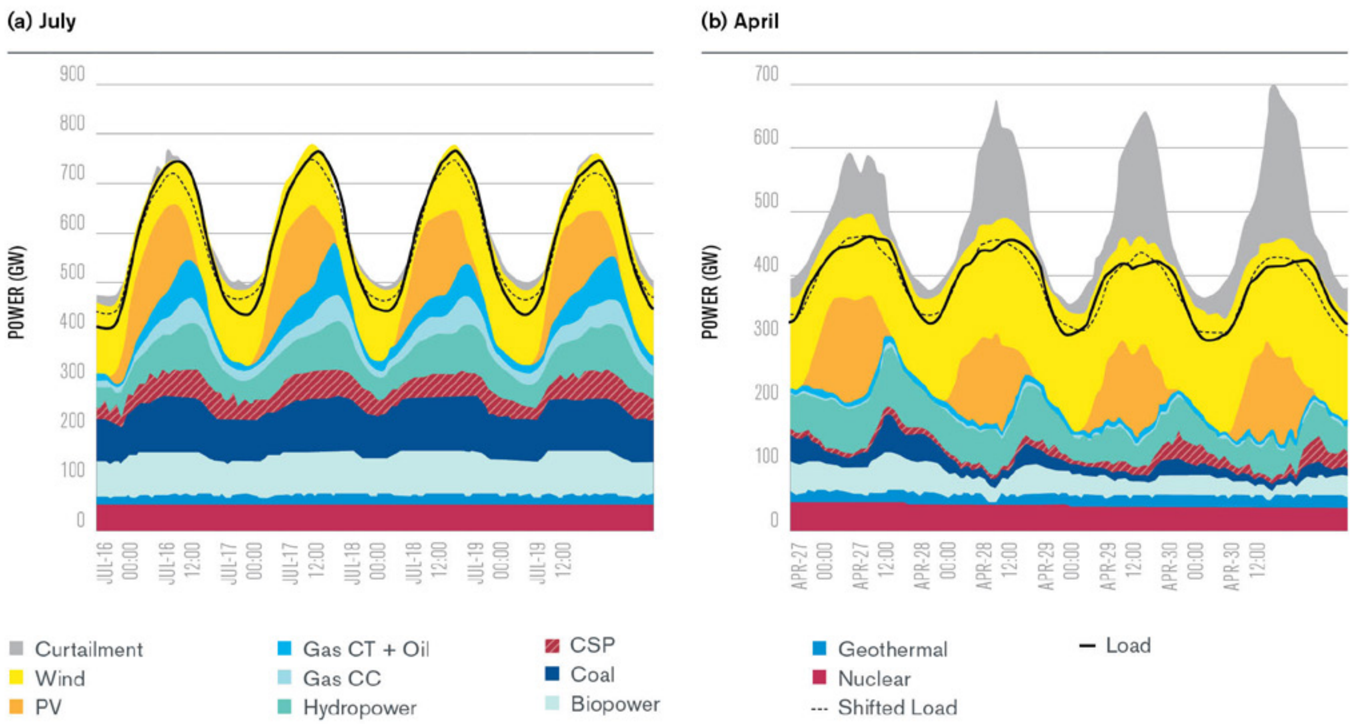
Many of us are familiar with graphics like the one shown in Figure 1. These charts visualize the daily or, in this case, weekly balance between power supply and demand for a future power system, according to the specific criteria, assumptions, and constraints of the model that is being used. Different energy technologies are deployed at varying levels (each represented by a unique color), and the hourly generation of these technologies are stacked on top of each other to show the total supply of electricity to the system at a given time.

FIGURE 1: HOURLY DISPATCH FOR A TYPICAL SUMMER WEEK IN THE EU, BASED ON 2010 WEATHER DATA



Source: Zappa et al. 2019.

FIGURE 2: 80% RENEWABLE ENERGY SCENARIO, SEASONAL COMPARISON



Although fossil fuel demand is very minimal in the month of April, it makes up a very considerable share of generation in July.

Source: Baldwin 2013.

Any production in excess of demand is shown below the x-axis and represents available energy for storage. In Figure 1, the daily load profiles are relatively consistent, as are the daily patterns of generation mix. Each day, from late morning to mid-afternoon, there is excess generation which, in this case, is stored in pumped hydrological storage systems (striped) and is then discharged from these systems to meet a shortfall in the early evening (dark teal). The next day, this storage asset is used in the same way.

However, what this chart does not show is that over longer periods of time (months, seasons, or years) these daily patterns of supply and demand vary. Over these longer periods of time, the ease with which excess supply can be stored and saved for periods of supply shortfalls rapidly decreases. This occurs because the daily surpluses or shortfalls accumulate over time, requiring more storage capacity for longer periods of time. If there is one day with 1000 GWh of generation in a system and then a subsequent day with only 900 GWh of generation, you only need 50 GWh of storage to ensure that supply is equal to 950 GWh both days.

However, if you have a week where 1000 GWh are generated each day and a subsequent week where 900 GWh are generated each day, the system will require approximately seven times as much storage to balance daily load at 950 GWh for all 14 days and requires a storage technology that can discharge over the course of at least seven days. This effect is magnified when looking at load shifting between seasons or even years.

To solve this problem of seasonal variation, the simplest solution is to use fast-ramping generation such as natural gas power plants. These, coupled with a willingness to curtail surplus generation (e.g. disconnecting otherwise productive wind turbines or solar panels), removes the need for long-term, large-scale storage.

This solution is visible in the 80% renewable energy scenario depicted in Figure 2. Here, gas peaking (blue and light blue) is used during the summer (top) when afternoon demand outlasts the available supply of photovoltaic power but is effectively unused during a period of lower demand in the fall (bottom). Also visible in Figure 2 is the considerable level of curtailment required during low-demand periods.

Unfortunately, reliance on gas-powered peaking plants also reintroduces a considerable seasonal dependence on fossil fuels into an otherwise renewable power sector. In order for a power system using this fast-ramping emergency generation to remain carbon neutral, either the substitution of a carbon-neutral fuel (such as biofuels or synthetic methane), or a method of carbon capture at the point of combustion, would be required (Serpell et al. 2019).

The alternative to fast-ramping carbon-neutral generation is chemical or mechanical energy storage—such as batteries, pumped hydroelectric systems, or reversible hydrogen fuel cells (Serpell et al. 2020). Instead of generating additional energy when it's needed and curtailing excess energy when it's not, storage systems allow you to "move" surplus energy to better match demand.

Both of these carbon-neutral solutions for balancing long-term generation and consumption—carbon neutral peaking power or storage—suffer from the same economic challenge: the less frequently load balancing is required, the larger the balancing systems have to be, and the fewer times those systems can be used over the course of a year.

For example, the cost per discharge of a storage system that is charged and discharged every day will be 365 times less than the same technology if it were only charged and discharged once a year (to carry over excess supply in the fall to an energy shortfall in the winter, for example).

A similar rule holds for fast-ramping natural gas capacity. A power plant and associated carbon capture system that only operates for 20% of the year will have an ROI that is significantly longer (or prices that are significantly higher) than an identical power plant that runs as base-load capacity 100% of the time.

Fuel cost considerations complicate this calculation somewhat compared to the low operational costs of storage technologies, but it stands that the less frequently a balancing asset is used, the more expensive that balancing asset is to use. The total yearly utilization might be the same, but the capital costs (levelized over the same ROI period) will be significantly higher for the larger and less frequently used systems, as well as those with fixed costs that are larger fractions of total cost.

Therefore, the greater the seasonal variation of supply or demand on the power system, the more costly and difficult it will be to deploy carbon-neutral solutions. The economic viability of carbon capture and sequestration technology is already deeply uncertain and would be made even less viable if only used during times of generation shortfalls (Kheshgi et al. 2012).

ELECTRIFICATION

Currently in the United States, electricity only accounts for 16.8% of end-use energy consumption (see Figure 3 on page 10). The overwhelming majority relies upon direct consumption of petroleum products and natural gas. Decarbonizing our entire economy (not just our existing electricity demand) requires us to either electrify the remaining ~80% of the economy that still relies on distributed burning of fossil fuels, or find a way to capture the carbon emissions being produced by these sectors of the economy. The latter could be achieved by deploying carbon capture and sequestration (CCS) technology at each point of consumption, or by replacing fossil fuels with a carbon neutral alternative fuel.

All of these strategies are expensive, but it is generally agreed that with existing technological constraints and pricing, it makes more sense, from the point of view of the consumer, to electrify all but a few specialized industrial processes and air travel (Roberts 2017). A recent report by the Kleinman Center on the future of Philadelphia Gas Works (PGW) further supports this conclusion (Serpell et al. 2019).

This suggests that as part of the energy transition, the majority (at least 70–75%[1]) of energy consumption will eventually be electrified—at least tripling, if not quadrupling, the size of the existing electricity system. This ballpark approximation does not consider any future increase in system-wide energy demand, nor does it consider the many possible efficiency improvements that could be pursued alongside this transition.

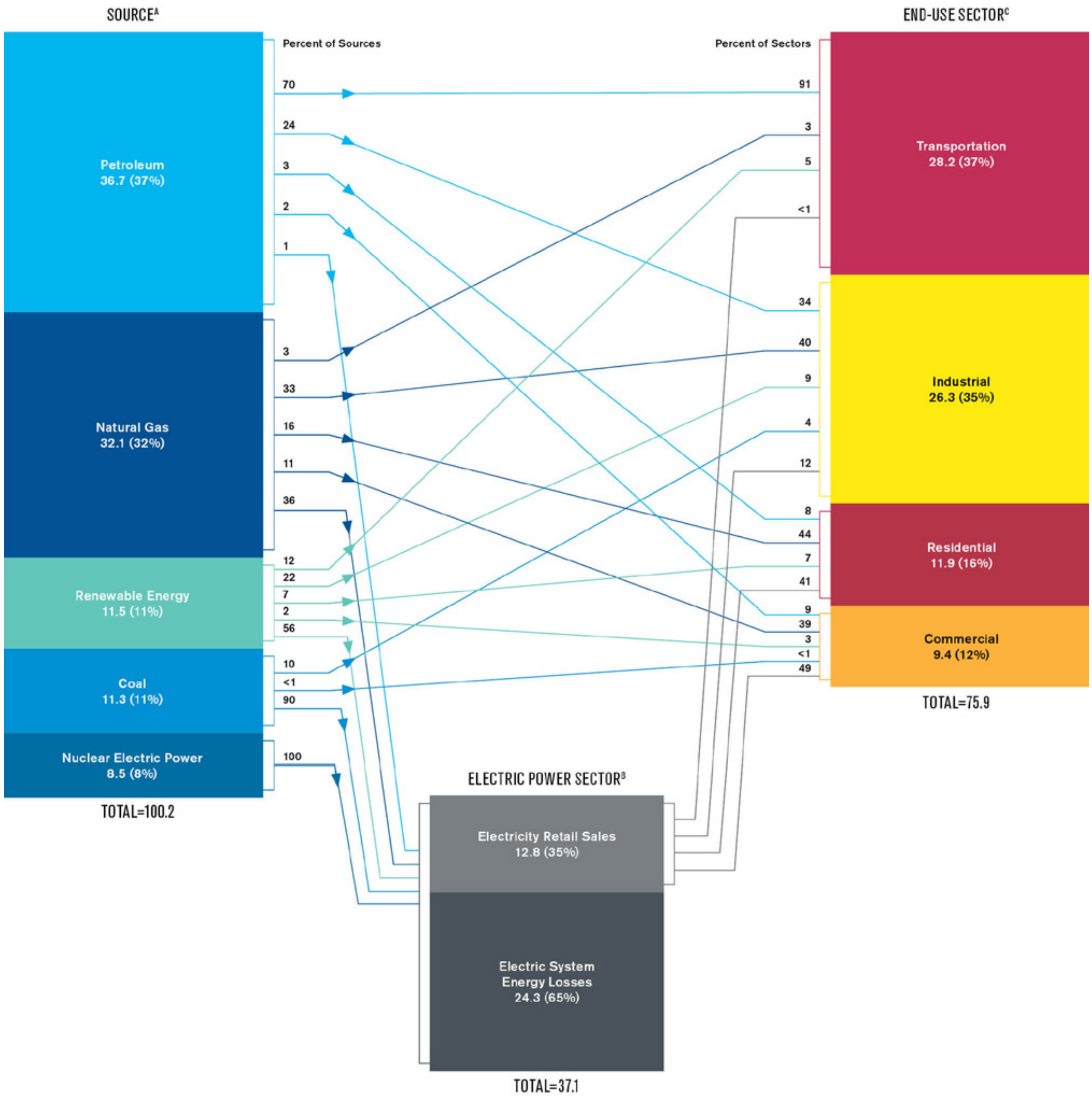
For example, the black box in the bottom–center of Figure 3 demonstrates that there is considerable energy saving potential in the power sector, where 65% of the input energy is lost in the process of generation and distribution. Furthermore, many electric technologies such as battery-powered vehicles and air-source heat pumps can be more efficient than the fossil fuel powered appliances they are replacing.

The potential of system-wide efficiency gains will be discussed in a later section. Even with these uncertain variables taken into account, the overall size of the nation's power system is likely to dramatically increase over the coming decades. In addition to the obvious need to build additional generation capacity to meet this demand, there will also be a number of other, less obvious costs and benefits of a larger grid.

In the Kleinman Center's recent report on seasonal storage within the PJM footprint, we looked specifically at the implications of electrifying building heating, a sector that, for obvious reasons, has a much higher energy demand in winter months. The findings from this analysis (see Figure 4) showed that electrifying this specific end-use shifted peak demand from the summer to the winter and noticeably increased seasonal variation in demand from ~16% to 50% (Serpell et al. 2020. Consequently, demand for costly load-balancing storage assets also increased.

1 All non-industrial energy demand.

FIGURE 3: U.S. ENERGY CONSUMPTION BY SOURCE AND SECTOR, 2019 (QUADRILLION BTU)



[A] Primary energy consumption. Each energy source is measured in different physical units and converted to common British thermal units (Btu). See U.S. Energy Information Administration (EIA), *Monthly Energy Review*, Appendix A. Noncombustible renewable energy sources are converted to Btu using the "Fossil Fuel Equivalency Approach," see EIA's *Monthly Energy Review*, Appendix E

[B] The electric power sector includes electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public. Energy consumed by these plants reflects the approximate heat rates for electricity in EIA's *Monthly Energy Review*, Appendix A. The total includes the heat content of electricity net imports, not shown separately. Electrical system energy losses are calculated as the primary energy consumed by the electric power sector minus the heat content of the electricity retail sales. See Note 1, "Electrical System Energy Losses," at the end of EIA's *Monthly Energy Review*, Section 2.

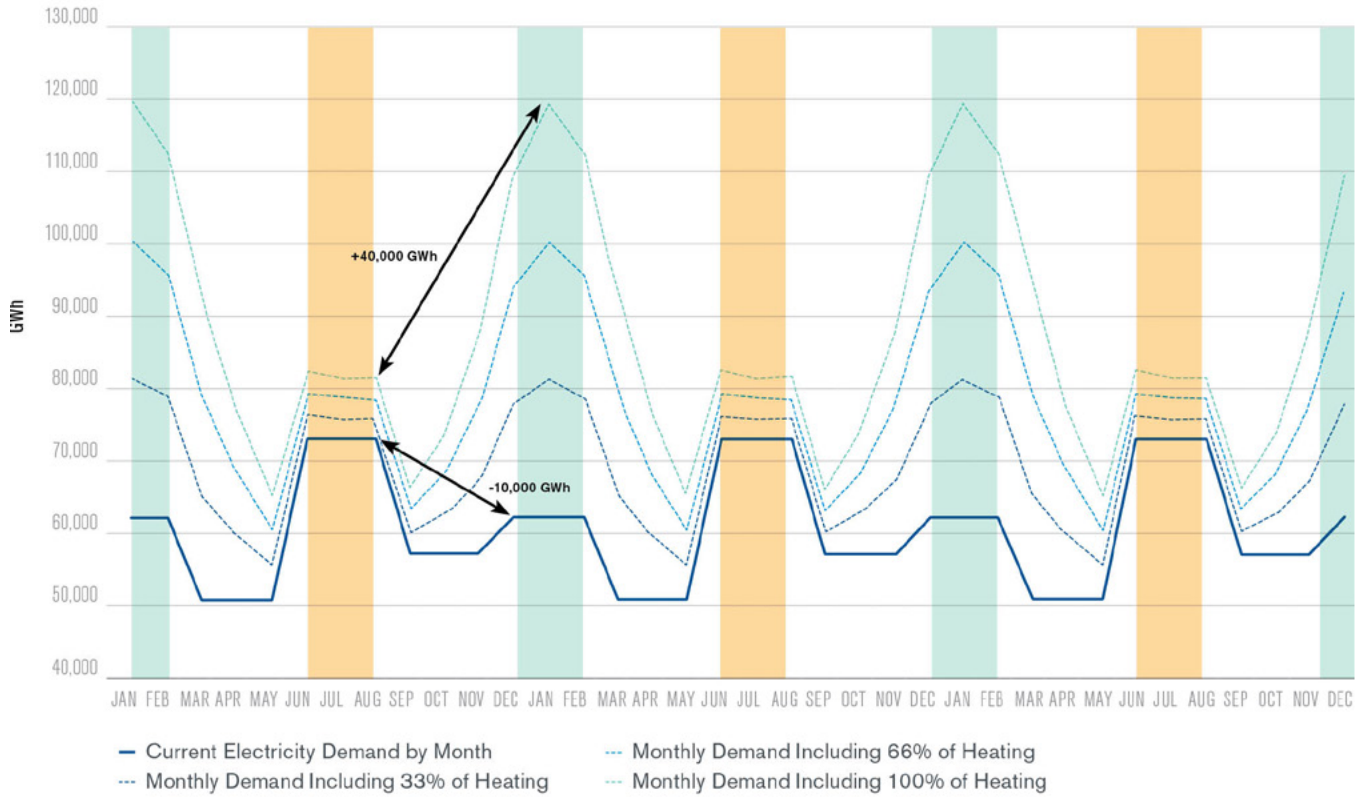
[C] End-use sector consumption of primary energy and electricity retail sales, excluding electrical system energy losses from electricity retail sales. Industrial and commercial sectors consumption includes primary energy consumption by combined-heat-and-power (CHP) and electricity-only plants contained within the sector.

Note: Sum of components may not equal total due to independent rounding. All source and end-use sector consumption data include other energy losses from energy use, transformation, and distribution not separately identified.

Electricity consumption makes up a relatively small share of current end-use consumption. This means the road to carbon-free energy is much more complicated than installing solar and wind power to meet existing demand.

Sources: EIA, *Monthly Energy Review* (April 2020), Table 1.3 and 2.1–2.6.

FIGURE 4: THE IMPACT OF ELECTRIFIED HEATING ON PJM GRID DEMAND



Electrifying heating demand in the PJM Interconnection could lead to a considerable shift in peak demand from the summer to the winter.

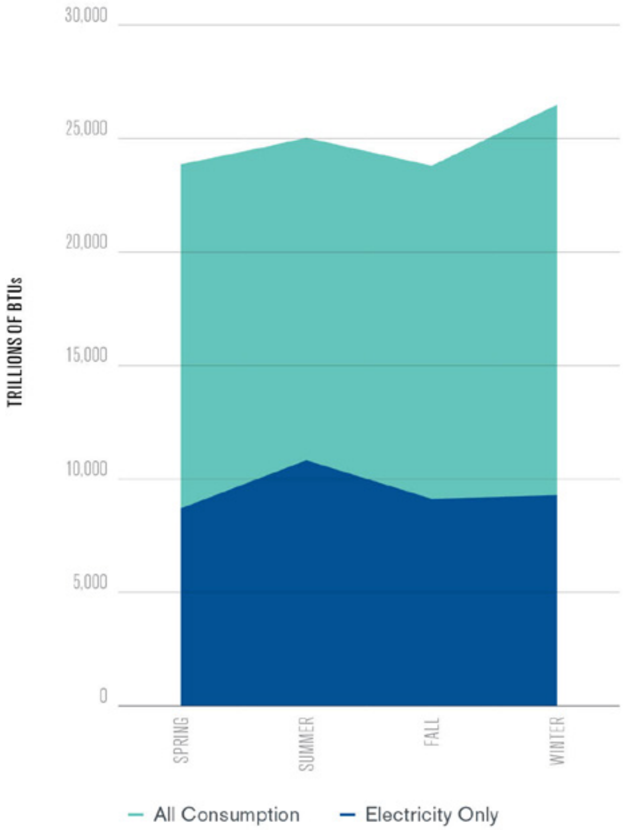
This analysis only considered the electrification of one part of a much larger overall energy system. It is possible that by electrifying a diversity of end uses, the seasonal variability of those end-uses could work to balance each other out, reducing the relative amplitude of load variation.

For example, road transportation is a sector that is ahead of most in its readiness to electrify. Electric vehicles are becoming increasingly affordable, and concerns about range and recharging times are continuously being addressed with new technology innovations. Even once all road vehicles are electrified, this increased demand will not weigh on the system evenly across time.

There will be daily peaks as people get home from work and plug their vehicle in to recharge, and daily slumps during rush hour when few vehicles are plugged-in. Based on vehicle miles traveled in the United States, it appears that there is a seasonal difference in vehicle usage as well. People drive approximately 20% less in the winter than they do in the summer, indicating that the seasonality of transportation and building heating would, to some extent, balance each other out (Zimmermann 2014).

One way to estimate the overall impact of system-wide electrification is to look at the overall energy demand of the economy by month. The most recent four years of EIA data reveal that the relative seasonal variability of all primary energy consumption (~10%) is somewhat less than the relative variability experienced by the existing electricity system (~20%), despite absolute variation increasing (2,500 vs 2,100 trillion BTUs) (EIA 2018). There is, however, a shift in the peak demand season from summer (electricity only) to winter (all energy consumption).

FIGURE 5: SEASONAL VARIATION IN U.S. ENERGY DEMAND (2018 & 2019)



Relative seasonal demand variation for all energy consumption decreases relative to existing variation within the electric power sector.

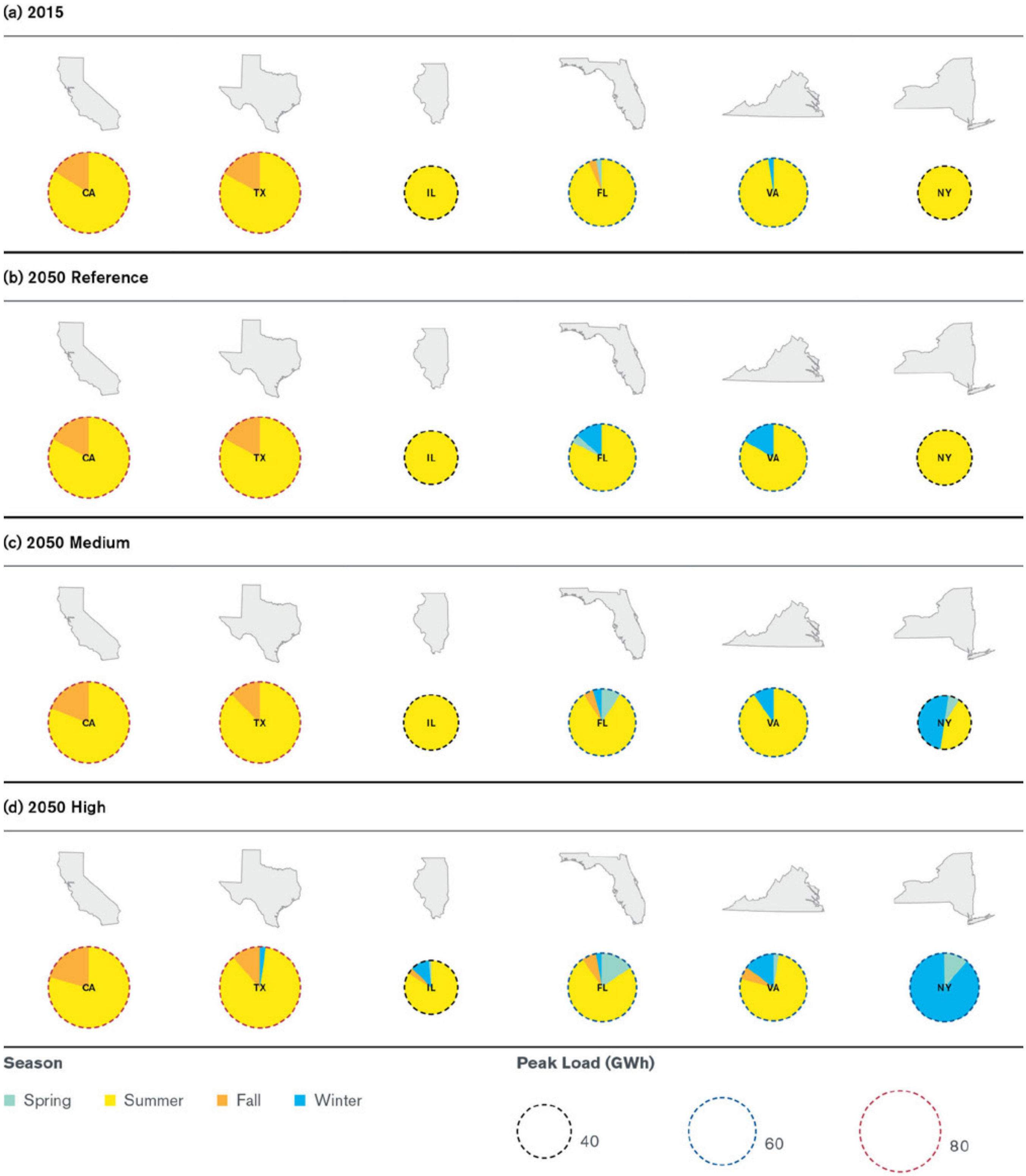
Source: EIA 2020.

This preliminary analysis does not consider the efficiency benefits or costs of electrification, nor the changing energy demand of the U.S. economy; however, it does suggest that widespread electrification of the economy will reduce the relative seasonal variation in demand, perhaps making it easier to implement affordable storage or carbon-neutral peaking generation over longer periods of load-balancing. Although total variation increases, so does overall generation. This would offer a more balanced and predictable supply and would allow the costs of storage to be distributed more widely.

It is important to note that these rough estimations are only representative of a nation-wide total. Variation within different regions or grid interconnections could be substantially larger. This rough national estimate may obscure regional variation because, for example, the low wintertime cooling demand in Texas may counter balance a considerable increase in demand in the Northeast. The same could be true for regional vehicle usage patterns. Nationally, driving—as measured by vehicle miles traveled—increases in the summer; but this demand could vary across regions.

These regional differences in seasonal peaking can easily be seen in Figure 6 from NREL's Electrification Futures Study. This graphic shows a state-by-state seasonal breakdown of the 100 highest demand hours over the course of a year under four varying intensities of grid electrification. At the highest level of grid electrification (bottom–right) many states in the Northeast and Northwest begin to experience a considerable shift in peak demand to the winter and spring, whereas many southwestern and mid-western states maintain summertime peak demands.

FIGURE 6: STATE-SPECIFIC PIE CHARTS SHOW THE SEASONAL DISTRIBUTION OF THE 100 MOST ENERGY-DEMANDING HOURS OF THE YEAR



The size of each pie chart corresponds to total gigawatts demanded by each state during its highest demand hour. With the electrification of heating in the bottom two maps, peak demand shifts to winter for many northeastern states.

Source: Mai et al. 2018.

TRANSMISSION

We have already seen that on a national scale, relative variation in seasonal demand of a heavily electrified energy system is likely somewhat less than the relative variation within the existing electricity system. It is only on a region to region basis where the electrification of new sectors of the energy system can have a highly significant effect on seasonal variation and timing of annual peak demand—for example, wintertime heating in the Northeast shifting peak demand from summer months to winter months.

One solution to this challenge would be to improve the efficiency and connectivity of national transmission infrastructure in such a way as to help balance—or distribute—these regional peaks or shocks in demand. In the context of increasing deployment of intermittent generation sources like wind and solar, transmission investment in the United States has typically focused on connecting resource-rich regions with demand centers like cities and creating east–west connections to allow for daily load balancing (St. John 2020). This way, surplus solar energy generated in the southwestern desert afternoon can be swiftly diverted to the Northeast to meet the evening demand spike.

In order to achieve longer seasonal load balancing, it may be necessary to also consider north–south transmission that would connect demand centers to *other* demand centers. In the winter months, cooling demand in southern states like Florida, Texas, and California will be at an annual low, while northern states like New York, Illinois, and Washington are dealing with their most extreme cold weather.

Similarly, in the summer when northern regions of the country have less need for heating, southern states will be blasting their A/C. New transmission alone will not address all of the intricacies of daily, weekly, or seasonal demand, and it is an extremely costly option when compared to demand response, load aggregation, and perhaps even surplus regional deployment of clean generation sources (Brown & Sedano 2004).

Furthermore, similar to gas and oil pipelines, efforts to build new transmission infrastructure is often hobbled by NIMBYism (Helman 2015). However, in order to improve system efficiencies and allow regional variation to more closely resemble projected national variation in a heavily electrified future, transmission, particularly increased north–south transmission, will be necessary.

STORAGE MARKETS AND TECHNOLOGY

With limited regional transmission, there will also need to be local and regional load balancing technologies implemented. The challenges of energy storage, especially over longer time periods, is both a technology and a market challenge. The technology challenge, as discussed above, relates to the translatability of short-duration energy storage solutions to more long-duration solutions.

Lithium-ion batteries, for example, have demonstrated themselves to be one of the most reliable, versatile, and affordable methods of short-duration storage. They have a reasonably long lifespan (~10 years) and are energy dense, allowing for their deployment in electric vehicles and other wireless appliances (NREL, EESI 2019).

However, they can suffer badly from disuse. When left uncharged, the total capacity of the battery begins to decline, permanently reducing the utility of that cell. For long-duration storage, there may be weeks or even months when demand for storage is insufficient and a lithium-ion storage system would be left without change. Lithium-Ion batteries also suffer, to some extent, from charge loss—a fully changed battery after a few weeks or months may only have 90% or less of its original charge (Battery University 2018).

Pumped hydrological storage systems have a similar challenge with evaporation during hot, dry weather (MWH 2009). If left for a considerable length of time for the purposes of long-duration storage, these pumped-hydro systems could also be limited by "self-discharge."

In order for infrequent, long-duration storage to become widely viable, affordable storage technologies that can tolerate being left fully charged or fully discharged for weeks or months at a time will need to be developed.

Reversible fuel cell technology, compressed hydrogen, gravity-based systems, or compressed air storage are all possible solutions to this storage challenge, though all suffer from cost and scalability challenges.

Technology alone will not solve all of the challenges of infrequent, long-duration storage. Even with an ideal energy storage system that would provide lossless storage for months and could safely be left "empty" during times of high demand, there still needs to be a business case for providing this storage service. Building this business case is contingent on two factors: market structure, and rate of charge/discharge demanded by the system.

In today's market, grid-level storage providers offer daily load and power frequency adjustments and generally have deals with regional electricity utilities based on how much storage is provided by the system over a given time period. This means that the operator of a 100KW grid storage system can, in today's market, reliably charge and discharge their system every few hours and receive payment from the utility in addition to any profit made by selling at daily high prices and buying at daily lows.

However, if that same operator was providing long-duration storage services, this would mean that for most days of the year, the system would sit either fully charged or fully discharged until it was needed. In order for this to be a viable business model, a regional utility would have to pay the storage operator a "stand-by" fee, regardless of the actual utilization rate and sufficient to give the operator a reasonable ROI (Sankar 2019). This is a significant departure from the market structure used for most grid-level storage providers and would require a revaluing of load-balancing and load flexibility. This transition is analogous to the difference between energy-only markets and capacity markets for energy generation (Bade 2017).

Another cost consideration for infrequent, long-duration, storage providers is the rate at which power would be demanded from, and directed to, the storage system. This ultimately comes down to a consideration of energy versus power. Energy is a measurement of the capacity to perform work. The measurement of energy does not consider or care about the time it takes to perform that work.

Power, on the other hand, is a measurement of the amount of energy a system can deliver over a given period of time. A kilowatt is a unit of power, a kilowatt-hour is a unit of energy. Crucially, two systems (e.g. battery systems) can have exactly the same *energy* capacity but entirely different *power* outputs. If battery A can deliver 1 KW of energy every hour for 10 hours and battery B can deliver 5 KW of energy every hour for 2 hours, both systems have the same *energy* capacity, but battery B has a much higher *power* output and battery A has a longer *duration*.

This distinction becomes increasingly important as the demand for storage duration increase. Today, most grid-level storage systems are used as a method of balancing load over periods of minutes or hours. For this type of use-case, knowing that a storage system is capable of providing a very high power output relative to its overall energy capacity is important.

However, as will be demonstrated, the cost of providing a higher power output can be considerable. As the demand on storage systems extends to include intermittent longer-duration storage, total energy capacity may become far more important than power output, allowing for larger and more affordable storage systems. Furthermore, provided this capacity is sufficiently distributed to allow for coordinated power delivery, it will also be capable of balancing daily variations.

In a recent digest by the Kleinman Center, the importance of this consideration became very apparent in our cost estimation of reversible fuel cell storage systems (Serpell et al. 2020). In the process of scaling up existing estimations by Susan Schoenung at Sandia National Laboratory, we decided to scale both the reversible fuel cell system and the hydrogen storage capacity evenly, maintaining a similar power-to-energy ratio.

However, because the fuel cell system was far more expensive than the hydrogen storage tanks, we could have increased the overall storage capacity while maintaining a lower power output and, in doing so, dramatically reduced the system costs for the reversible fuel cell storage solution explored in that digest. By maintaining the power-to-energy ratio of the smaller systems, we maintained a far greater level of system flexibility, allowing the system to discharge rapidly or more slowly, but that flexibility came at great additional cost.

CONCLUSIONS AND POLICY RECOMMENDATIONS

The need to transform our energy system to utilize only carbon-neutral and environmentally sustainable resources grows with each passing day. While the aggressive deployment of wind and solar power is an essential piece of this puzzle, the existing electricity system is going to have to transform in much more considerable and fundamental ways if we are going to build a carbon-neutral energy system.

Market and technological limitations on the deployment of storage technology, inherent resource intermittency, and the changing patterns of demand from a heavily electrified system mean that creative solutions will be required to develop an electricity system that is capable of balancing load variations over hours, days, months, and even years. Finding these solutions requires us to think critically about the inherent limitations of electricity and the carbon-neutral resources we must use to generate it.

Firstly, it is essential that we recognize that storage technology remains a significant barrier to deep decarbonization. Lithium-ion batteries have become increasingly affordable and are fabulously well suited for applications such as electric vehicles where they replace an already costly engine. For larger grid-scale applications, they remain limited by cost and fragility.

Electrolysis and hydrogen fuel cell technology is relatively inefficient and expensive and presents severe safety concerns if using hydrogen stored in large volume or at high pressure. In order to speed the development of a cheaper, more efficient, and more stable storage solution, public and private investment must be directed to pilot projects, prototyping, and technology scaling.

Policymakers, planners, and renewable energy advocates should also recognize that future projections of load can only reasonably be designed around the existing constraints imposed by limited transmission. This digest briefly suggested why a nation-wide analysis of demand electrification may not reveal accurate storage and load-balancing demand estimates, but a much more in-depth analysis performed at a regional scale is needed to clearly show the potential demand for storage or carbon-neutral peaking generation.

Lastly, deploying sufficient storage capacity to balance seasonal and yearly variation, should be seen as much a market challenge as a technology challenge. Investors expect a reasonable ROI on infrastructure investments and the less frequently a storage asset can be deployed each year, the more expensive that electricity will have to be in order to meet capital commitments. A financing structure for compensating the storage provider based on the total capacity for storage, rather than the actual energy that provider redistributes, could be used to solve this challenge.

BIBLIOGRAPHY

Bade, Gavin. 2017. "The Great Capacity Market Debate: Which Model Can Best Handle the Energy Transition?" *Utility Dive*. Accessed 08/10/20: *https://www.utilitydive.com/news/the-great-capacity-market-debate-which-model-can-best-handle-the-energy-tr/440657/*

Baldwin, Sam. 2013. "High-Penetration Levels of Renewable Electricity: Challenges and Opportunities." *U.S. Department of Energy*. Accessed 08/07/20: *https://sites.nationalacademies.org/cs/groups/internationalsite/documents/webpage/international_083752.pdf*

Battery University. 2018. "What Does Elevated Self Discharge Do?" Accessed 08/07/20: *https://batteryuniversity.com/index.php/learn/article/elevating_self_discharge*

Brown, Matthew and Richard Sedano. 2004. "Electricity Transmission: A Primer" National Council on Electric Policy. Accessed 08/10/20: *https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/primer.pdf*

EESI. 2019. "Fact Sheet: Energy Storage (2019)" *Environmental and Energy Study Institute*. Accessed 08/10/20: *https://www.eesi.org/papers/view/energy-storage-2019*

EIA. 2018. "Monthly Energy Review, December 2018" U.S. *Energy Information Administration*. Accessed 08/07/20: *https://www.eia.gov/totalenergy/data/monthly/archive/00351812.pdf*

EIA. 2020. "Monthly Energy Review, September 2020—Table 2.1" *U.S. Energy Information Administration*. Accessed 08/07/20: *https://www.eia.gov/totalenergy/data/monthly/pdf/sec2_3.pdf*

EIA. 2020. "U.S. Energy Facts Explained" *U.S. Energy Information Administration*. Accessed 08/07/20: *https://www.eia.gov/energyexplained/us-energy-facts/*

Hausfather, Zeke. 2019. "Explainer: The High-Emissions 'RCP8.5' Global Warming Scenario" *CarbonBrief*. Accessed 08/07/20: *https://kleinmanenergy.upenn.edu/sites/default/files/proceedingsreports/KCEP-Comprehensive-Efficiency-Plan-Singles.pdf*

Helman, Christopher. 2015. "Nimby Nation: The High Cost to America of Saying no to Everything" *Forbes*. Accessed 08/10/20: *https://www.forbes.com/sites/christopherhelman/2015/07/30/nimby-nation-the-high-cost-to-america-of-saying-no-to-everything/#70f25d9c4f8e*

IPCC, 2018: *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. In Press. Accessed 08/07/20: *https://www.ipcc.ch/sr15/*

IRENA. 2020. "Renewable Power Generation Costs in 2019" *International Renewable Energy Agency*. Accessed 08/07/20: *https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019*

Kheshgi, H., H. de Coninck. & J. Kessels. 2012. "Carbon Dioxide Capture and Storage: Seven Years After the IPCC Special Report" *Mitigation and Adaption Strategies for Global Change* 17, 563–567. Accessed 08/07/20: *https://link.springer.com/article/10.1007/s11027-012-9391-5#citeas*

Mai, Trieu, Paige Jadun, Jeffrey Logan, Colin McMillan, Matteo Muratori, Daniel Steinberg, Laura Vimmerstedt, Ryan Jones, Benjamin Haley, and Brent Nelson. 2018. "Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States." *National Renewable Energy Laboratory*. Accessed 08/10/20: *https://www.nrel.gov/docs/fy18osti/71500.pdf*

MWH. 2009. "Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest: Final Report" MWH, prepared for U.S. Army Corps of Engineers. Accessed 08/10/20: *https://www.hydro.org/wp-content/uploads/2017/08/PS-Wind-Integration-Final-Report-without-Exhibits-MWH-3.pdf*

NREL. 2017. "Electrification Futures Study" *National Renewable Energy Laboratory*. Accessed 08/07/20: *https://www.nrel.gov/analysis/electrification-futures.html*

NREL. "Battery Lifespan" *National Renewable Energy Laboratory*. Accessed 08/10/20: *https://www.nrel.gov/transportation/battery-lifespan.html*

Podesta, John. 2019. "The Climate Crisis, Migration, and Refugees" Brookings. Accessed 08/07/20: *https://www.brookings.edu/research/the-climate-crisis-migration-and-refugees/*

Roberts, David. 2017. "The Key to Tackling Climate Change: Electrify Everything" *Vox*. Accessed 08/08/20: *https://www.vox.com/2016/9/19/12938086/electrify-everything*

Sankar, Giridhar. 2019. "Building More Energy Storage Means Building the Right Incentives" *The Kleinman Center for Energy Policy*. Accessed 08/10/20: *https://kleinmanenergy.upenn.edu/blog/2019/12/17/building-more-energy-storage-means-building-right-incentives*

Schoenung, Susan. 2011. "Economic Analysis of Large-Scale Hydrogen Storage for Renewable Utility Applications" *Sandia National Laboratories*. Accessed 08/10/20: *https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2011/114845.pdf*

Serpell, O., A. Chu, B. Paren, G. Sankar. 2019. "Preparing PGW for a Low-Carbon Future" *The Kleinman Center for Energy Policy*. Accessed 08/07/20: *https://kleinmanenergy.upenn.edu/paper/preparing-pgw-low-carbon-future*

Serpell, O., A. Chu, B. Paren, G. Sankar. 2020. "Feasibility of Seasonal Storage for a Fully Electrified Economy" *The Kleinman Center for Energy Policy*. Accessed 08/07/20: *https://kleinmanenergy.upenn.edu/policy-digests/feasibility-seasonal-storage-fully-electrified-economy*

St. John, Jeff. 2020. "7 Transmission Projects That Could Unlock a Renewable Energy Bounty" *Green Tech Media*. Accessed 08/10/20: *https://www.greentechmedia.com/articles/read/9-transmission-projects-laying-the-paths-for-cross-country-clean-energy*

UN General Assembly. 2015. *Transforming Our World: the 2030 Agenda for Sustainable Development*. Accessed 08/07/20: *https://www.refworld.org/docid/57b6e3e44.html*

Wan, Y.H. 2012. "Long-Term Wind Power Variability" *National Renewable Energy Laboratory*. Accessed 08/07/20: *https://www.nrel.gov/docs/fy12osti/53637.pdf*

Zappa, W., M. Junginger, M. van den Broek. 2019. "Is a 100% Renewable European Power System Feasible by 2050?" Applied Energy, Vol. 233–234, p.1027–1050. Accessed 08/07/20: *https://www.sciencedirect.com/science/article/pii/S0306261918312790*

Zimmermann, Christian. 2014. "How Much Do Americans Drive?" *The FRED Blog*. Accessed 08/08/20: *https://fredblog.stlouisfed.org/2014/06/how-much-do-americans-drive/?utm_source=series_page&utm_medium=related_content&utm_term=related_resources&utm_campaign=fredblog*

ABOUT THE AUTHOR

Oscar Serpell is a research associate at the Kleinman Center for Energy Policy.

Cover Photo: iStock.com/jgroup

STAY UP TO DATE WITH ALL OF OUR RESEARCH:

kleinmanenergy.upenn.edu

Kleinman Center for Energy Policy

University of Pennsylvania
Stuart Weitzman School of Design
Fisher Fine Arts Building, Suite 401
220 S. 34th St.
Philadelphia, PA 19104

P 215.898.8502
F 215.573.1650

kleinmanenergy@upenn.edu