Before the United States House of Representatives
Committee on Energy and Commerce
Subcommittee on Environment and Climate Change

"Building America's Clean Future: Pathways to Decarbonize the Economy"

Testimony of Armond Cohen, Executive Director, Clean Air Task Force

July 24, 2019

SUMMARY OF TESTIMONY

Earth's atmosphere has more carbon dioxide than at any time in human experience, most of it added in the last half century. To preserve a natural world anything like we have known, we need to build a 100% carbon-free energy economy by 2050, and then progressively withdraw some of the carbon we have put into the skies already.

Building a 100% carbon-free energy economy by 2050 is tough but achievable. It will require assembling a complete set of solutions across all sectors, including clean, carbon-free electricity, zero-carbon fuels, and decarbonized industrial processes. States like New York, California, Colorado and New Jersey have taken legislative or planning actions toward a completely carbon-free economy and more are considering it. Eight states have firmly committed to carbon free electricity by mid-century, as have many major utilities such as Xcel Energy, MidAmerican, and Idaho Power.

Zero-carbon electricity is critical, and its importance will grow as electricity use expands in transportation, heating, and industry. But it is insufficient. Some emissions sources, including high-temperature industrial process heat and long-distance transportation, will be very difficult if not impossible to electrify. Zero-carbon fuels (such as ammonia, hydrogen and synthetic hydrocarbons) are needed to decarbonize these activities. Emissions from direct industrial processes such as steel and cement are big too; to address them, we will need carbon capture and sequestration or new inherently carbon-free processes. It is best to think of a zero-carbon energy economy as a system with interlocking and mutually supporting options. Federal and state government policy can help accelerate innovation to create that system.

We have a good head start on electricity: the U.S. grid is already a third carbon-free with wind, solar, hydroelectric and nuclear power. Wind and solar have dropped in price and grown to 8% of our total supply electricity, and battery storage is getting cheaper too. That is great news and these sources have a long way to grow – to many times their current level. But the best way to build a 100% clean, carbon-free electricity system is to harness a complete portfolio of resources, including wind, solar, storage, and firm low-carbon resources. Having multiple firm resources to complement power from the wind and sun is not only the most affordable but also the lowest-risk way to achieve our goal. Such a system will also help us decarbonize transportation and industry through electrification. Congress should build on momentum from the states and enact policies to transition to 100% carbon-free electricity nationwide harnessing all available carbon-free sources, and enact innovation policies and incentives to support the full suite of carbon-free options.

Natural gas with carbon capture is one option for a zero carbon grid. Hydrogen could also be an important way to decarbonize electricity and fuels for industry and transportation; it can be made by renewable and nuclear energy but, at present, by far the cheapest route to hydrogen is from natural gas with carbon capture and storage. However, to play a major role in climate mitigation via either power or fuels, natural gas will need to virtually eliminate its collateral emissions of the super pollutant methane, which packs more warming punch than carbon.

In short, we have many of the tools in view for a carbon free-energy economy by mid-century, and good momentum to build on. We need to commit to binding emissions targets or other economy-wide carbon pricing policies calibrated to reach zero emissions by mid-century, while expanding the technology toolkit by supporting technology incentive policies that will deliver additional affordable zero-carbon energy options in time. Clean Air Task Force commends the leadership of this committee for taking the first step in its announcement that it will produce by the end of 2019 comprehensive climate legislation to create a zero-carbon economy by midcentury.

Chairman Tonko, Ranking member Shimkus, and distinguished members of the Subcommittee:

My name is Armond Cohen and I am Executive Director of Clean Air Task Force, an environmental organization dedicated to the protection of Earth's atmosphere, focusing especially on strategies to commercialize carbon-free energy. I appreciate the opportunity to testify today.

1. *We need a carbon-free energy system by mid-century, not just carbon free electricity*

Earth's atmosphere has more carbon dioxide than at any time in human experience, most of it added in the last half century. To preserve a natural world anything like we have known, need to build a 100% carbon-free energy economy by 2050, and then progressively withdraw some of the carbon we have put into the skies already. And, achieving climate stabilization targets, as Figure 1 below shows, will require essentially zeroing out energy-related greenhouse emissions from all sectors of the economy around 2050. That means not just the electric sector, but also transportation, industry, buildings and agriculture. And we must accomplish this as global demand for energy could as much as double in the coming decades, as developing economies get richer. (See Figure 2 below). So, U.S. comprehensive climate legislation with the goal of zero-carbon emissions by midcentury must cover all of these sectors.

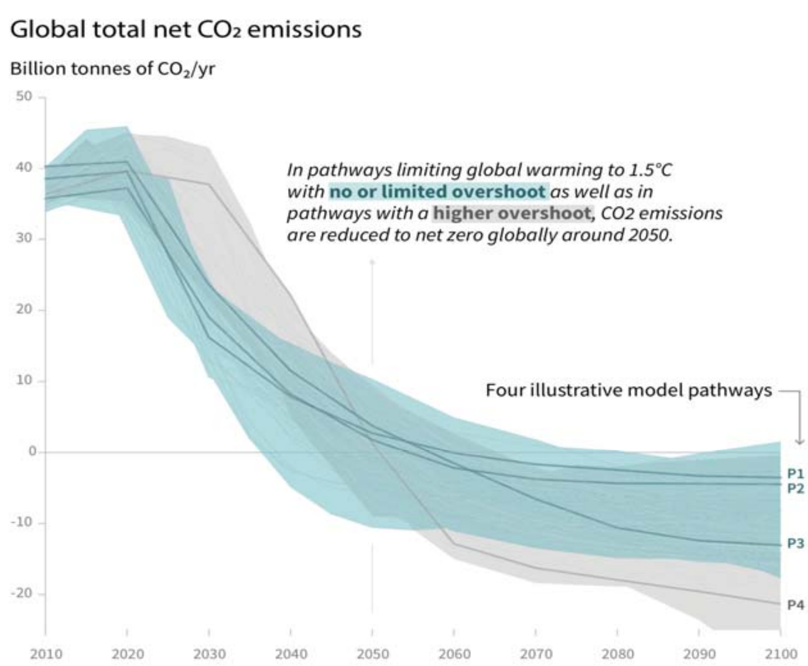

Figure 1: Pathways to limit global temperature to the Paris Agreement target of no more than 1.5 degree warming (Source: IPCC, Special Report: Global warming of 1.5^{0} C, 2018)

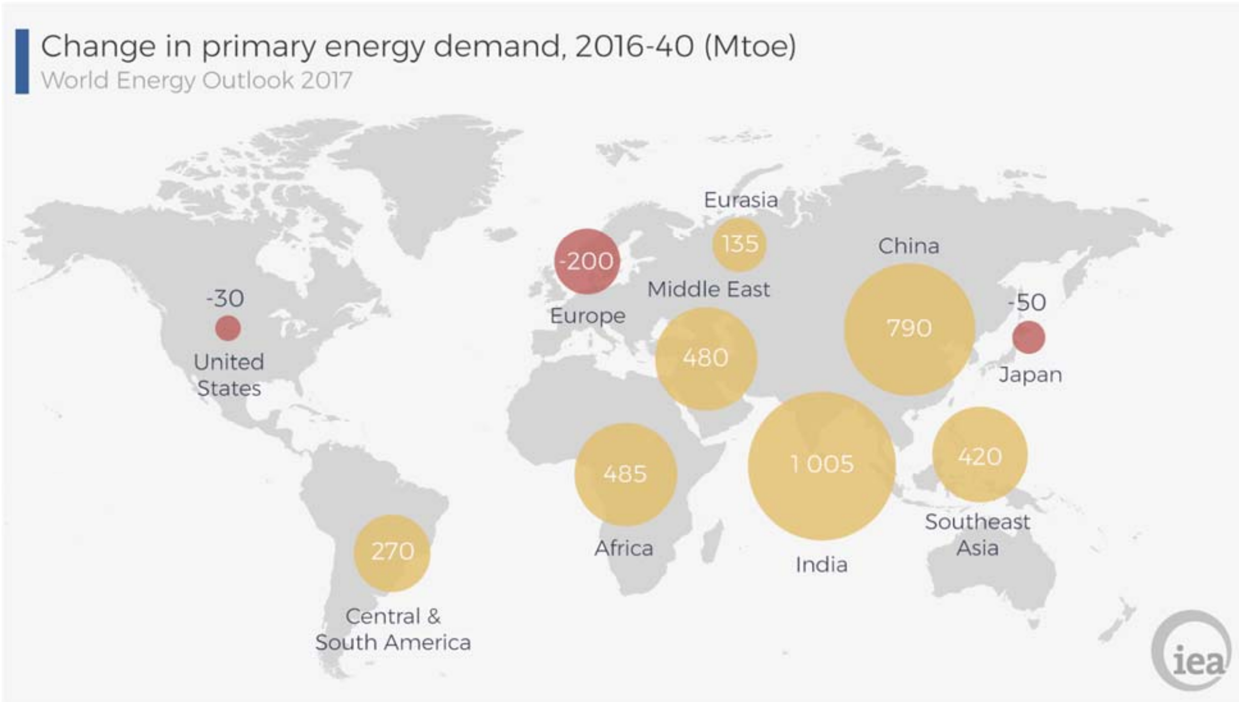

Figure 2: Projected energy demand increases in the coming decades. Source: International Energy Agency, World Energy Outlook 2017.

Although there are significant challenges, the pathway to a carbon-free economy is in concept straightforward: replacing existing greenhouse gas-emitting energy sources with zero-emitting resources and building additional zero-emitting resources to meet future growth. Eventually, we will also likely need to progressively withdraw some of the carbon we have put into the skies already. [1]

The conclusion: Building a 100% carbon-free energy economy requires assembling a complete set of solutions across all sectors, including clean, carbon-free electricity, zero-carbon fuels, and carbon-free industrial processes.

We have a good head start on electricity: the U.S. grid is already a third carbon-free with wind, solar, hydroelectric and nuclear power. Wind and solar have dropped in price and grown to 8% of our total supply electricity, and battery storage is getting cheaper too. Carbon-free electricity is critical, and its importance will grow as electricity use expands in transportation, heating, and industry. But it is insufficient.

Today electricity and associated by-product heating are responsible for less than half of all energy-related carbon emissions; transport, building, industry and other sources represent the dominant share. (See Figure 3 below).

[1] This testimony addresses creating a carbon-free energy supply. It does not address energy efficiency improvements, carbon in agriculture, which represents roughly 25% of the greenhouse gas emissions problem, or carbon dioxide removal. We assume those topics will be covered in future hearings of the subcommittee.

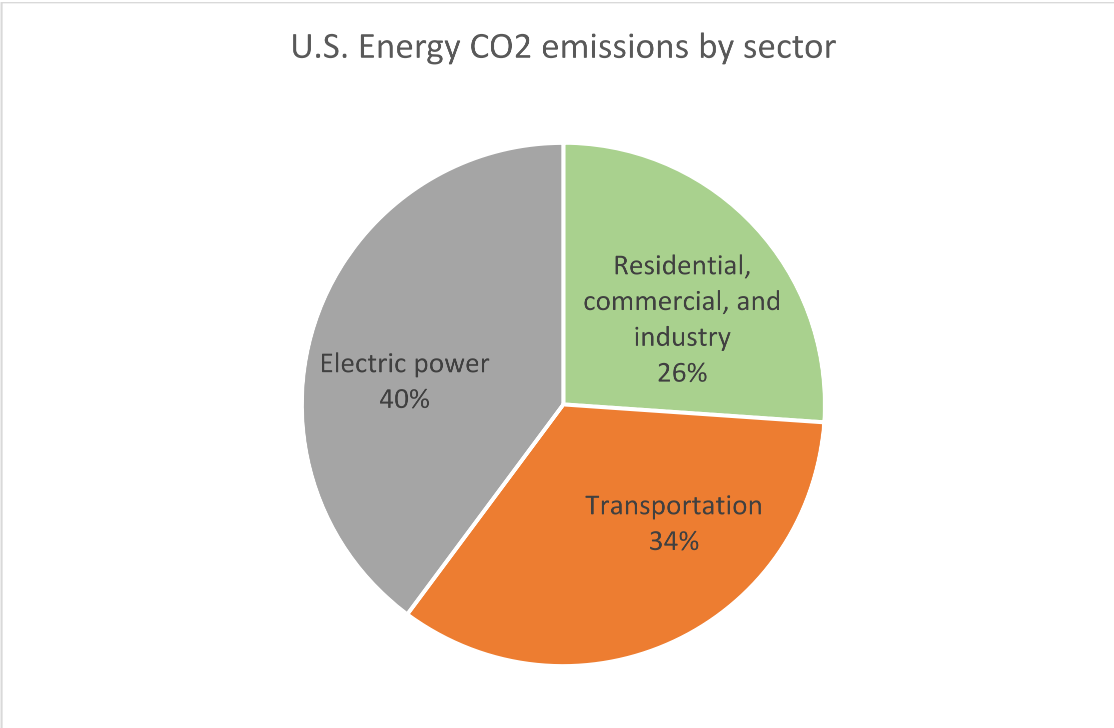

Figure 3: US CO2 emissions by sector. Source: US Energy Information Administration (2011).

While it is important to decarbonize our power grids, and electrify as much as we can of industry, transport and building heat, there are steep challenges to electrification that are likely to leave a large residual emissions footprint.

For starters, as Figure 4 illustrates, about half of CO_2 emissions from three large emitting industries come from chemical processes (e.g. iron reduction, chemical reactions in cement), not from energy use:

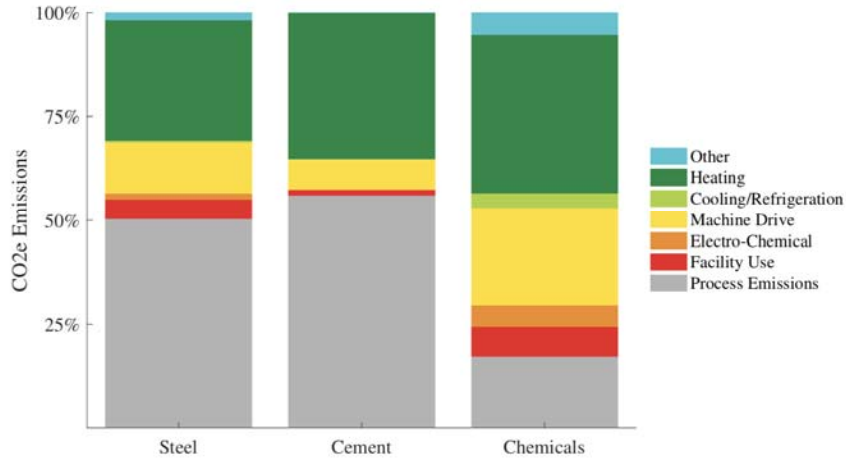

Figure 4: Carbon emissions from US heavy industries, by source. Source: US EPA (2018)

Additionally, a substantial portion of the heat-related portion of heavy industry emissions comes from ***high temperature heat***, typically greater than 400 degrees C, which is not readily economically supplied by electricity. (See Figure 5 below).

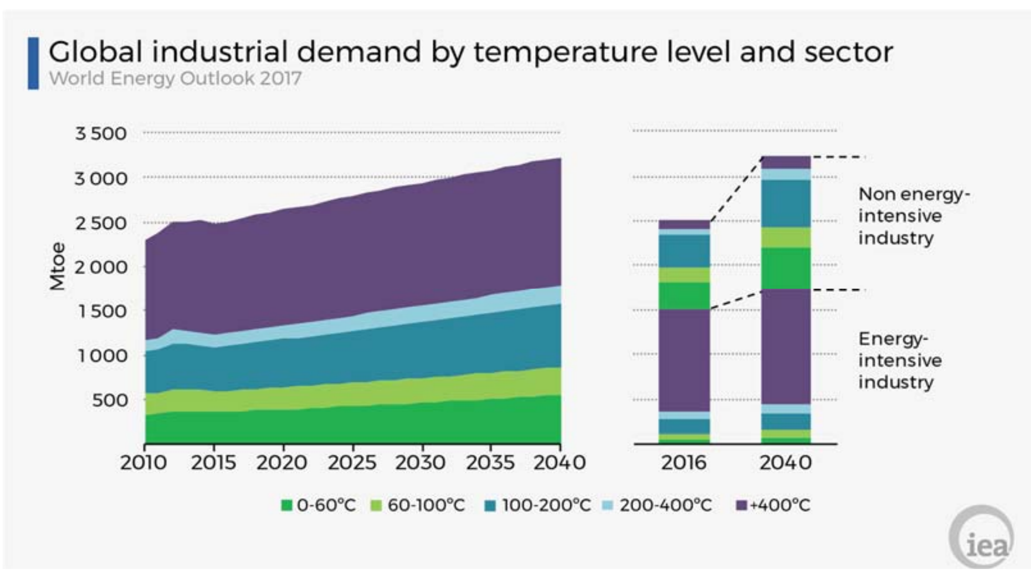

Figure 5: Heavy industry heat requirements. Source: International Energy Agency, World Energy Outlook (2017)

Electrification is an important option for transportation but there are several challenges here as well. The most obvious place to start is light duty cars and trucks, and some nations and states have shown increasing penetration of electric vehicles in new car sales. But all-electric vehicles in 2018 represented just over 2% of new US car sales; concerns over range and charging times persist. And even assuming all light duty vehicles were electrified, 40% of transport fuel use and

GHG emissions come from sources other than light duty vehicles, such as heavy freight, aviation, and shipping. (See Figure 6 below).

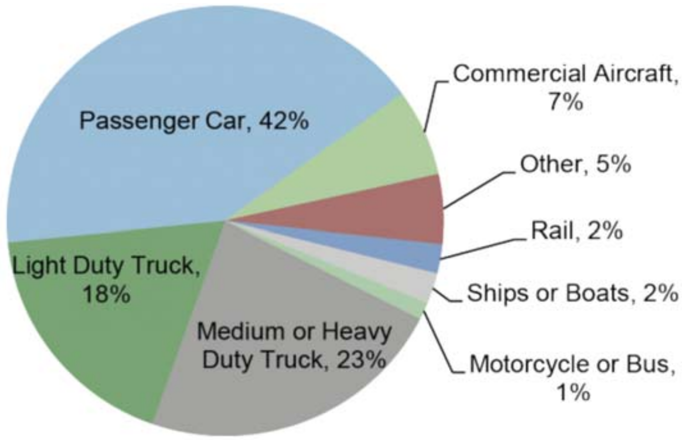

Figure 6: Greenhouse gas emissions by transportation sub-sector. Source: University of Michigan (2018)

Although prototypes of fully electrified medium and heavy-duty trucks have emerged, battery size and weight remain a substantial challenge.

Where we cannot replace emitting energy sources with carbon-free electricity, four additional and overlapping energy pathways could be critical and should be addressed in comprehensive climate legislation or enacted as complementary policies:

- Zero-carbon liquid or gaseous fuels that can be used for transport, high temperature industrial heat, and building heat (and to create firm, non-weather-dependent electricity)
- Direct sources of zero-carbon high temperature heat such as supercritical geothermal energy and high temperature nuclear energy
- Industrial processes that do not inherently produce carbon emissions
- Direct carbon capture for otherwise unavoidable industrial carbon emissions

Note that there are a variety of interconnections and complementarities between these pathways and pathways for carbon-free power sector. For example, zero-carbon liquid or gaseous fuels can be made (a) via electrolysis of water which requires zero-carbon electricity, but also by (b) stripping carbon from responsibly-sourced natural gas through steam reforming and carbon capture and (c) direct chemical conversions using nuclear energy.[2] Likewise, carbon capture is not only useful for directly capturing power and industrial emissions, but also for decarbonizing industrial heat or producing carbon-free hydrogen from natural gas. And zero-carbon fuels, as well as nuclear and carbon capture, as discussed below, can be important enablers of a zero-carbon electric grid in complement to wind, solar and energy storage.

[2] See Clean Air Task Force, "Fuel Without Carbon" (2018), https://www.catf.us/wp-content/uploads/2018/12/Fuels_Without_Carbon.pdf

I was honored last year to be part of a group of authors who published an article in *Science* entitled “Net-zero emissions energy systems.” [3] The key insight of that article is that it is best to think of a net-zero greenhouse gas emissions energy economy as a ***system*** of complementary and overlapping parts. These parts include zero-carbon electricity, fuels, storage, low-carbon industrial processes, and carbon capture and sequestration from fossil fuel use. A greatly simplified schematic picture of such a system can be seen in Figure 7 below.

[3] Davis, Steven J., et al. "Net-zero emissions energy systems." *Science* 360.6396 (2018): eaas9793.

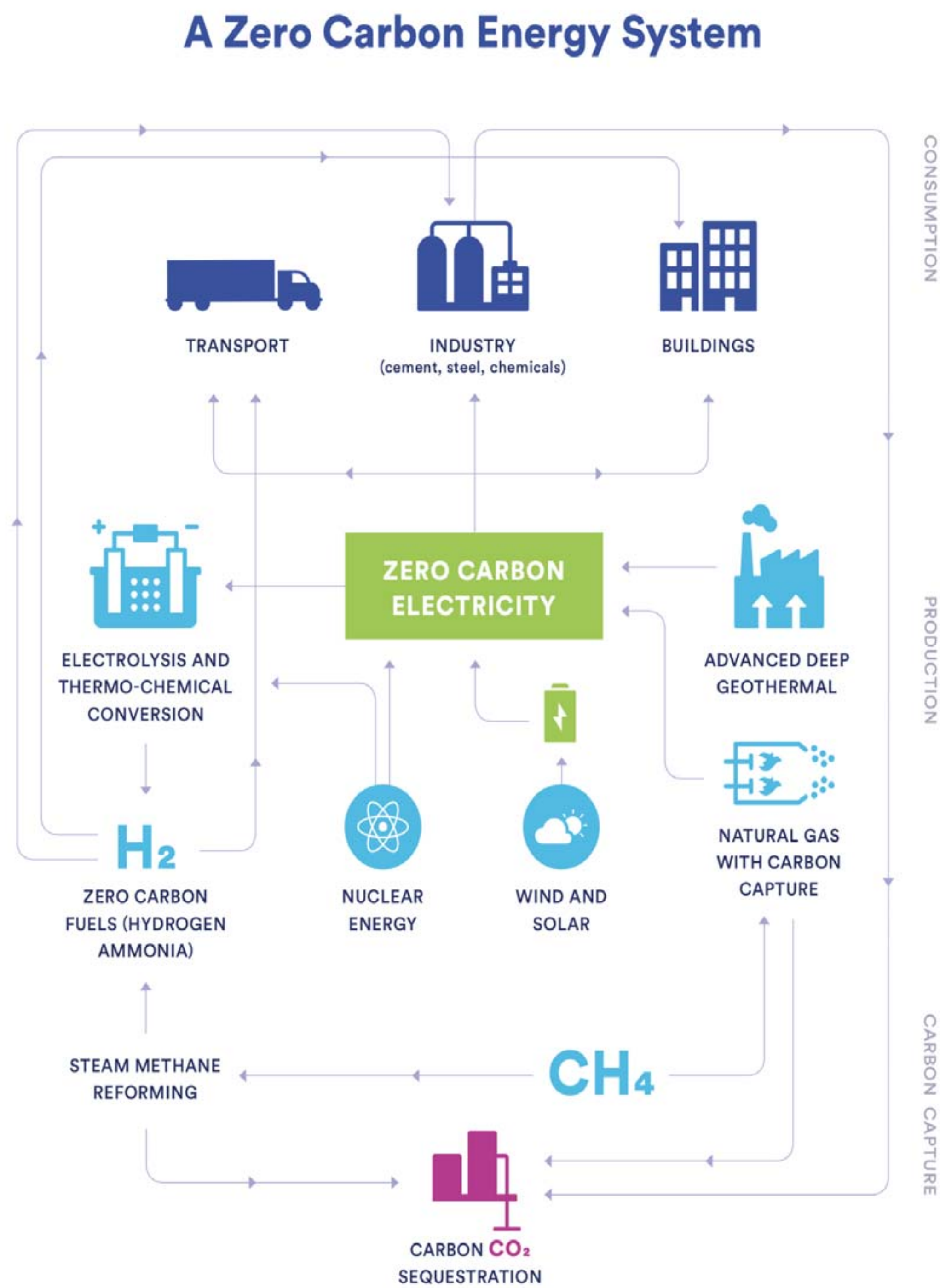

Figure 7: Schematic of a zero-carbon energy system (Source: Clean Air Task Force, 2019)

It is just such a system that we must assemble globally in the next several decades. This will require innovation across a broad range of technologies, and innovation policies to drive that innovation, which I am sure will be the subject of future hearings held by this subcommittee.

2. ***The best way to build a 100% clean, carbon-free electricity system is to harness a complete portfolio of resources, including wind, solar, storage, and firm low-carbon resources. Congress should particularly emphasize innovation and policy support for firm resources to complete the clean electricity portfolio.***

We have an abundance of potential technology options available now and likely to be available in the future to meet the goal of zero-carbon emissions on the US power grid. As noted, solar and wind energy costs have come down substantially in recent years, and supply a little over 8% of today's electricity; there is plenty of headroom to grow them. Energy storage which can balance variability of solar and wind has also dropped in price. Parts of the US are also blessed with hydroelectric resources within the state (and from our neighbor Canada), providing 7% of our electricity. Nuclear energy provides another 19%. As a result, the U.S. grid is already a third decarbonized.

Moreover, emerging technologies are in place today, and more are coming forward, which can make use of responsibly-sourced natural gas for power generation with minimal carbon dioxide emissions to the atmosphere, utilizing carbon capture and sequestration.[4] In addition, multiple companies are working to bring to market new nuclear plants that may be less expensive and even safer than today's technology.[5] There may be the opportunity for advanced geothermal power using injection of water into deep hot rock formations, which could provide on-demand steam to generate electricity.[6] And there will be some role for climate-beneficial bioenergy as well.[7]

If we keep all of our options and enact supporting policies to make them even more viable, we stand a good chance of meeting a mid-century target of 100% carbon-free electricity. Nations and regions such as Sweden, France, Ontario, and Brazil have already achieved extremely low electricity carbon emission rates through use of some of these technologies, chiefly hydroelectric, wind and nuclear energy.

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[4] See R. Service, "Goodbye smokestacks: startup invents zero emissions fossil power," *Science,* May 24, 2017, https://www.sciencemag.org/news/2017/05/goodbye-smokestacks-startup-invents-zero-emission-fossil-fuel-power

[5] See Clean Air Task Force, "Advanced Nuclear Energy: Need, Characteristics, Projected Costs, and Opportunities" (April 2018), https://www.catf.us/resource/ane-need-characteristics-project-costs/

[6] See presentation from a recent Clean Air Task Force-sponsored symposium, https://www.catf.us/resource/catf-eon-geothermal-workshop/

[7].See Appendix 1 for a discussion of opportunities and limits to bioenergy as part of deep decarbonization.

Policy is moving in this technology-inclusive direction. States like New York, California, Colorado and New Jersey have taken legislative or planning actions toward a completely carbon-free economy and more are considering it. Six states in the last year – California, New Mexico, Nevada, Colorado, Washington State, and New York – enacted so-called "Clean Energy Standard" legislation to require their grids, or portions thereof, to be supplied ***zero-carbon*** emitting generation, not entirely by renewable generation – representing 15% of US power sales.[8] Similar technology-inclusive targets are being debated in Illinois and Wisconsin. (See Figure 8 below). In addition, electric utilities such as Xcel Energy, MidAmerican, and Idaho Power have also committed to technology-inclusive, 100% carbon-free power supply by midcentury.

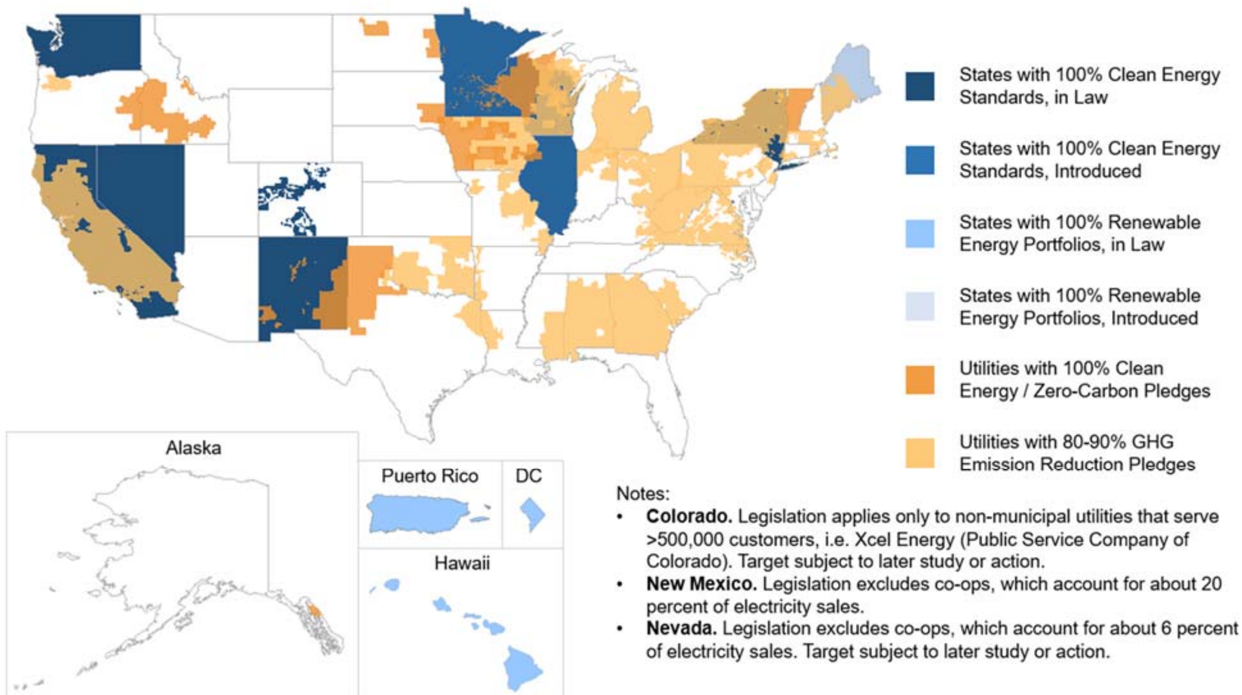

Figure 8: Map of State laws enacted and proposed, and power company carbon pledges (compiled by Clean Air Task Force, June 2019, https://www.catf.us/resource/state-utility-climate-change-targets/)

Moreover, in addition to supporting renewable energy and storage, Congress has in the past year demonstrated bipartisan support for firm, zero-carbon power in enacting policies to help bring advanced nuclear, carbon capture and storage, and other advanced energy technologies to market including the 45Q tax credit for carbon storage[9], the Nuclear Energy Innovation and Modernization Act (NEIMA)[10], and the Nuclear Energy Innovation Capabilities Act (NEICA)[11] in

[8] Hawaii Maine, Washington DC, Puerto Rico have opted for 100% renewable electricity targets.
[9] 26 U.S.C §45Q.
[10] Public Law No. 115-439
[11] Public Law No: 115-248.

the 115th Congress and the current Congress appears poised to move other important clean energy legislation this year.[12]

Here I want to focus specifically on the importance of policies such as Clean Electricity Standards that keep the door open for "firm" zero-carbon energy sources in a 100% zero-carbon grid. Firm sources are those that are available on demand, any time of year, for as long as needed. Firm sources are thus not dependent on weather and are a critical complement to wind and solar power. Firm low-carbon resources include, today, fossil fuels with carbon capture and storage, nuclear energy, and hydroelectric power and bio-energy.[13] In the future, as noted, they could include advanced geothermal and perhaps advanced cellulosic biofuels or combustion of zero-carbon fuels such as hydrogen or ammonia derived from electrolysis from zero-carbon energy, steam reforming of natural gas combined with carbon capture, or nuclear energy.[14]

a. *Technology diversity reduces the cost of a carbon-free electric system*

Why is firm zero carbon energy important? First is the issue of cost. A recent review of 40 studies concluded that the most affordable path to 100% clean, carbon-free electricity is to combine wind and sun with firm carbon-free electricity sources.[15] A typical recent detailed analysis of the role of firm energy in a Northeast and Southern electric system found a dramatic cost difference between 100% clean electric systems that harness wind, solar, and firm resources and those that rely solely on wind and sun.[16] (See Figure 9 below).

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[12] See e.g., Senate Energy and Natural Resources Committee https://www.energy.senate.gov/public/index.cfm/hearings-and-business-meetings?ID=1F661065-9C39-4A6B-B044-12FA17DD6FDD; House Energy and Commerce Committee https://energycommerce.house.gov/committee-activity/markups/markup-of-26-bills-full-committee-july-17-2019

[13] Hydroelectric power output can vary with climate conditions, and dispatch can be constrained in some cases by environmental considerations that affect reservoir management. It should be noted that there are unsettled issues around greenhouse gas emissions from large hydroelectric reservoirs, even in northern latitudes. See, e,g, Scherer, Laura, and Stephan Pfister. "Hydropower's biogenic carbon footprint." *PloS one* 11.9 (2016): e0161947. See Appendix 1 for a discussion of opportunities and limits to bioenergy as part of deep decarbonization

[14] See Clean Air Task Force, "Fuels Without Carbon: Prospects and the Pathway Forward for Zero-Carbon Hydrogen and Ammonia Fuels" (December 2018) https://www.catf.us/resource/fuels-without-carbon/

[15] Jenkins, Jesse D., Max Luke, and Samuel Thernstrom. "Getting to Zero-carbon Emissions in the Electric Power Sector." *Joule* 2.12 (2018): 2498-2510. (Link here)

[16] Sepulveda, Nestor A., et al. "The role of firm low-carbon electricity resources in deep decarbonization of power generation." *Joule* 2.11 (2018): 2403-2420. ("Across all cases, the least-cost strategy to decarbonize electricity includes one or more firm low-carbon resources. Without these resources, electricity costs rise rapidly as CO_2 limits approach zero. Batteries and demand flexibility do not substitute for firm resources. Improving the capabilities and spurring adoption of firm low-carbon technologies are key research and policy goals.") (Link here).

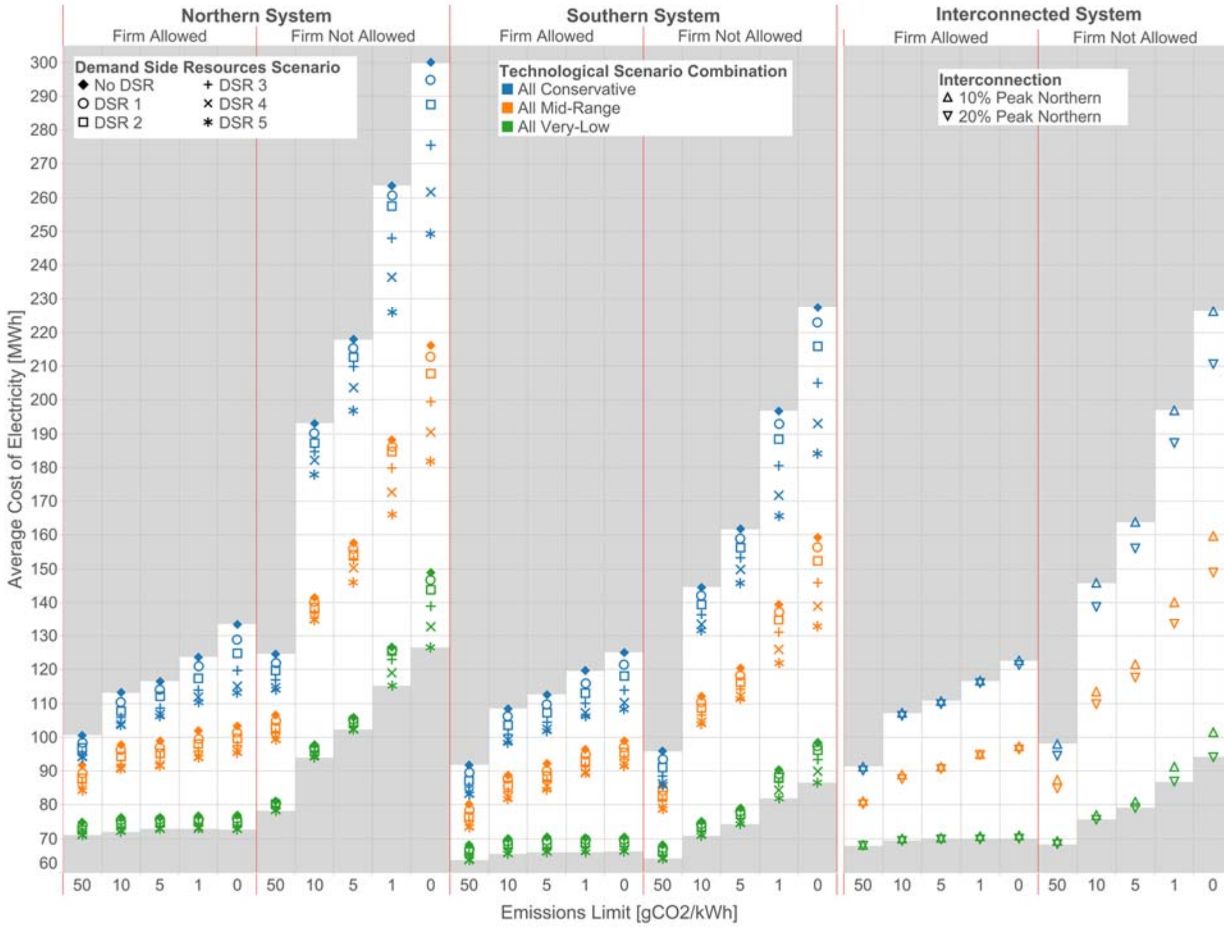

Figure 9: Costs of achieving zero-carbon grids are much higher where form resources are not allowed and only wind, solar and storage are permitted. Used by permission from Sepulveda, Nestor A., et al. "The role of firm low-carbon electricity resources in deep decarbonization of power generation." *Joule* 2.11 (2018): 2403-2420

To further illustrate the cost advantages of a full portfolio of wind, solar, and firm resources, I will consider data for California. I have chosen California because it is a state rich in wind and solar resources, a state committed to eliminating carbon emission from its power grid by 2045, but also a state that adopted technology-inclusive portfolio approach: its new law, SB 100,[17] requires 60% of the state's electricity to come from renewable sources but allows for other technology families to comprise the balance.

The fundamental dynamic driving the need for firm energy is ***seasonal variability***. It is commonplace to say that "the wind doesn't always blow and the sun doesn't always shine." But this statement does not capture the real challenge of a wind- and sun-dominated electric system. Wind and sun do not just vary on ***daily*** cycles; they vary substantially over ***weekly*** and ***monthly*** periods.

[17] https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB100

This seasonal effect can be seen in California for wind in Figures 10-11 below, illustrating smoothed, daily-average production[18] for onshore wind and solar photovoltaics:

Smoothed Daily Average Wind Production in CAISO, 2018 (MW)

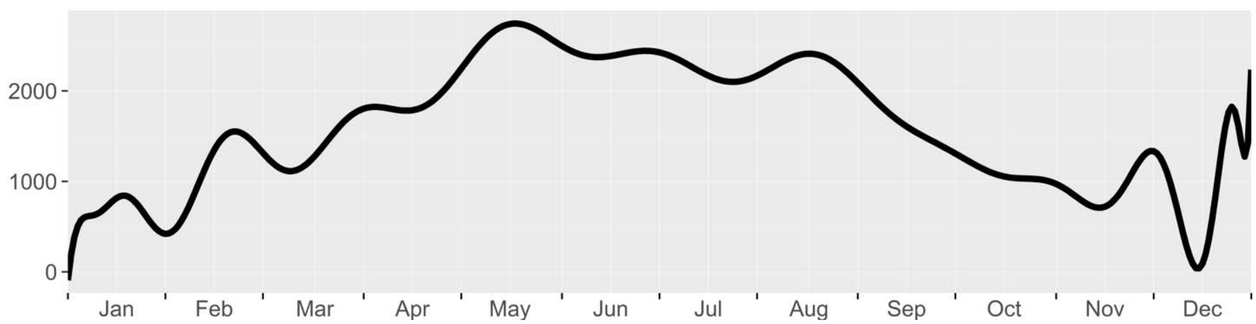

Figure 10

Smoothed Daily Average Solar Production in CAISO, 2018 (MW)

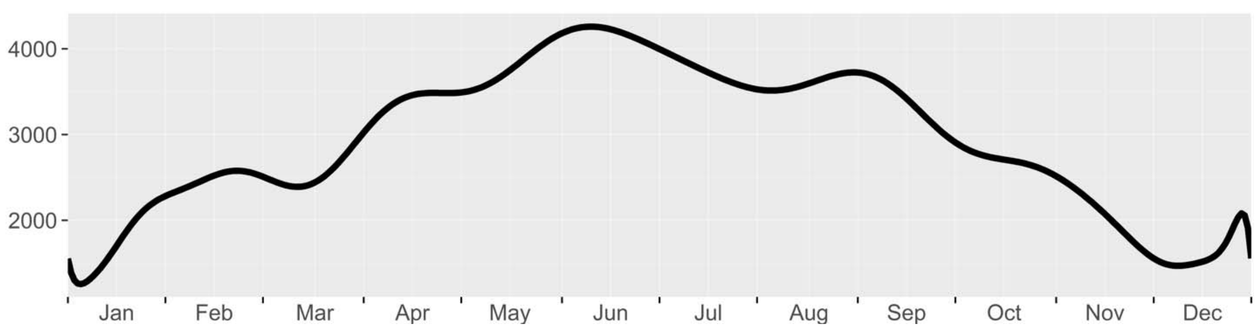

Figure 11

We see a variation in output plus of 300% or more between seasons.

What happens when we combine wind and solar output to equal 100% of California electric demand on an annual basis, and contrast it to actual demand in each day, week and month? Assuming that we have a 50% wind/50% sun system, we get a pattern like Figure 12 below:

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[18] This daily average smoothing conceals more significant variability *within* the day.

Smoothed Daily Load & Renewable Energy Generation, Mixed Renewable Scenario (MW)

Scenario definition: 2018 wind and solar generation scale to each meet 50% of total 2018 CAISO load

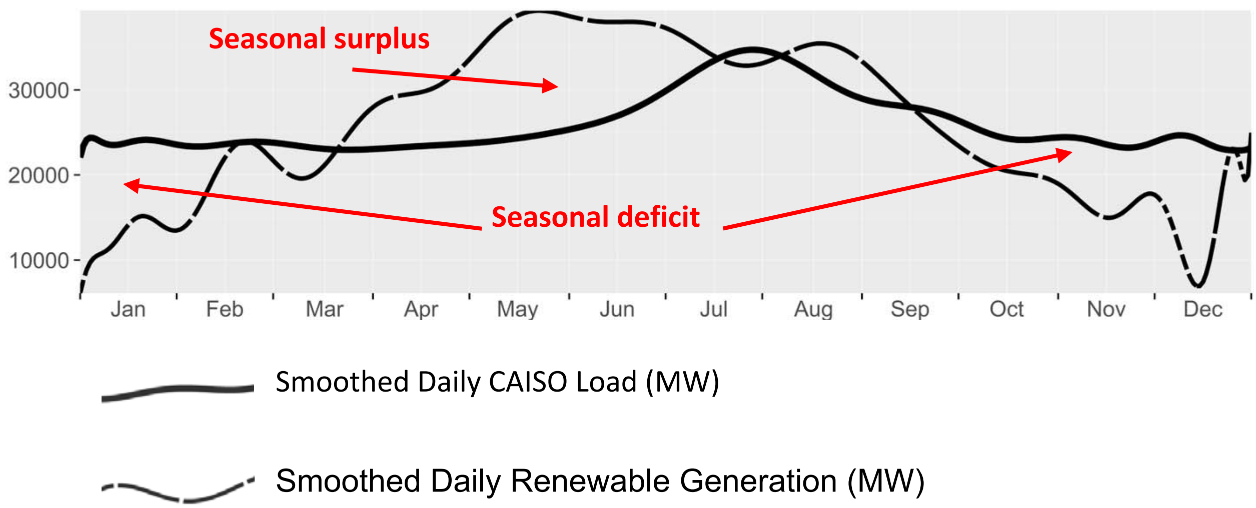


Figure 12

As you can see, there are multiple weeks of average surplus above demand during the summer months but substantial deficits September through February.

The consequence of this seasonal variation is that, even when California procures enough wind and solar output to meet total electricity demand on an ***annual average*** basis, ***roughly 27% of hours of the year cannot be served by wind and sun.*** This is shown in the "heat map" below, Figure 13, in which yellow, orange and red hours are unserved by variable wind and sun:

Percent of Hourly Load Served, Mixed 100% Wind and Solar Scenario

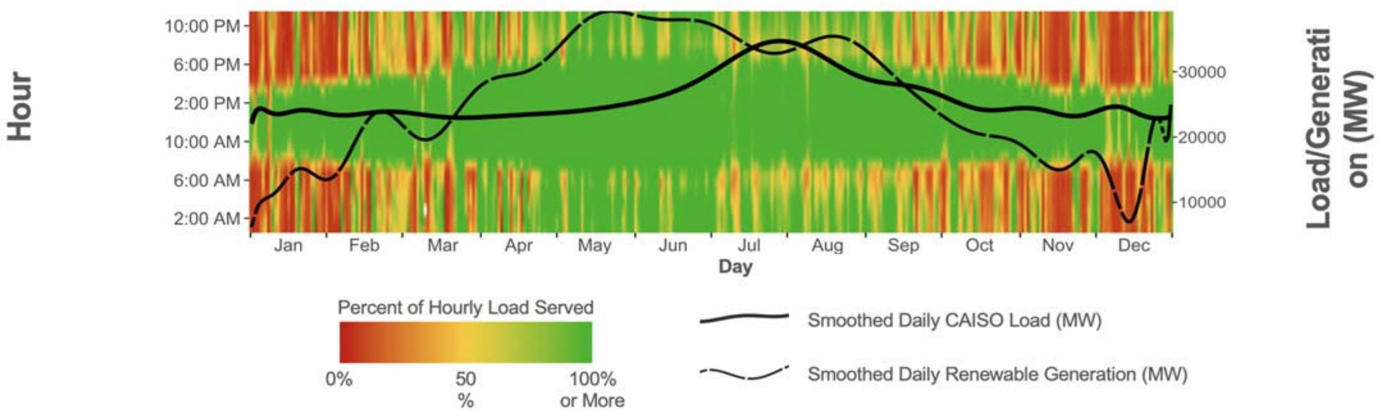


Figure 13

In theory, we could use battery storage to harvest surpluses and use them in deficit periods. But this is where cost comes in. The sheer amount of storage that must be built to capture maximum surplus, and then utilized infrequently, becomes cost prohibitive, even at very low storage costs.

In Figure 14, we see that the accumulated surplus during the year equals 35,946,633 MWh, or roughly 14% of the California's annual electric usage. To contain that much energy at peak storage time, you would need a storage system equivalent in instantaneous capacity larger than the generating capacity of the entire US electric grid.

Daily Renewable Energy Generation Surpluses and Deficits, Mixed Renewable Scenario

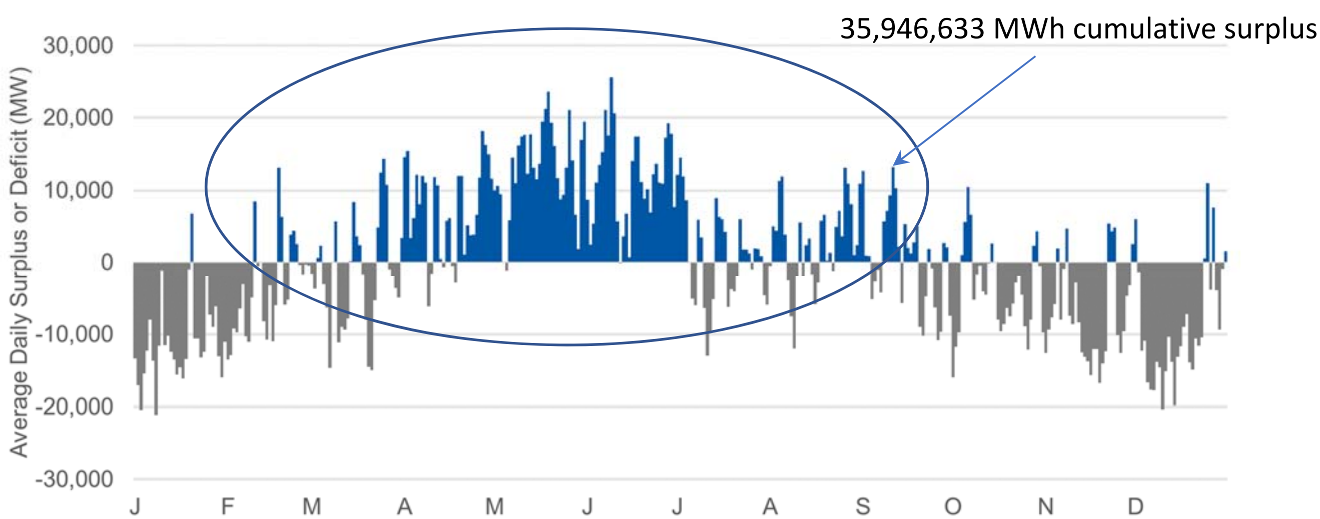


Figure 14: California surplus and deficit patterns under a 100% renewable energy scenario.

That much capacity will incur a very large capital expense. The US Department of Energy estimates the current cost of grid scale energy storage to be just under $500/kwh of capacity.[19] Let us assume we drop that cost by roughly 85% to $80/kwh. The total cost of such a battery storage system would be ***$2.9 trillion,*** or more than California's annual GDP of $2.7 trillion.

But that in some way understates the problem, because this storage capacity would be used at a very low rate – about 1% of capacity in an average year. That is because only a small amount of the storage capacity would be used regularly to balance daily variations in solar and wind output. Most of the storage capacity would need to be built to store peak seasonal surplus and thus only cycle seasonally. That means large capacity divided by little use, resulting in very large per unit costs for stored energy.

[19] US EIA, "U.S. Battery Storage Market Trends "(May 2018) https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage.pdf

The result, depicted in Figure 15 below, shows that the escalating costs of storage per unit output required, as wind and sun percentages become higher, drive very large system cost increases of roughly sevenfold as wind and sun go from 60% to 80% of energy supply, and roughly twenty four times as wind and sun provide all system energy.

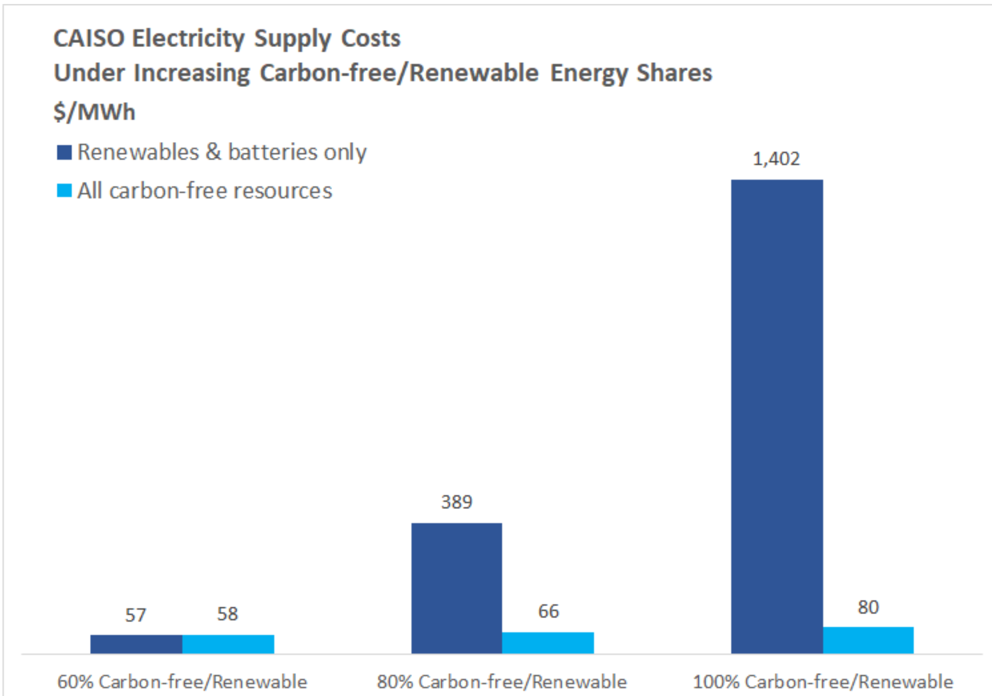
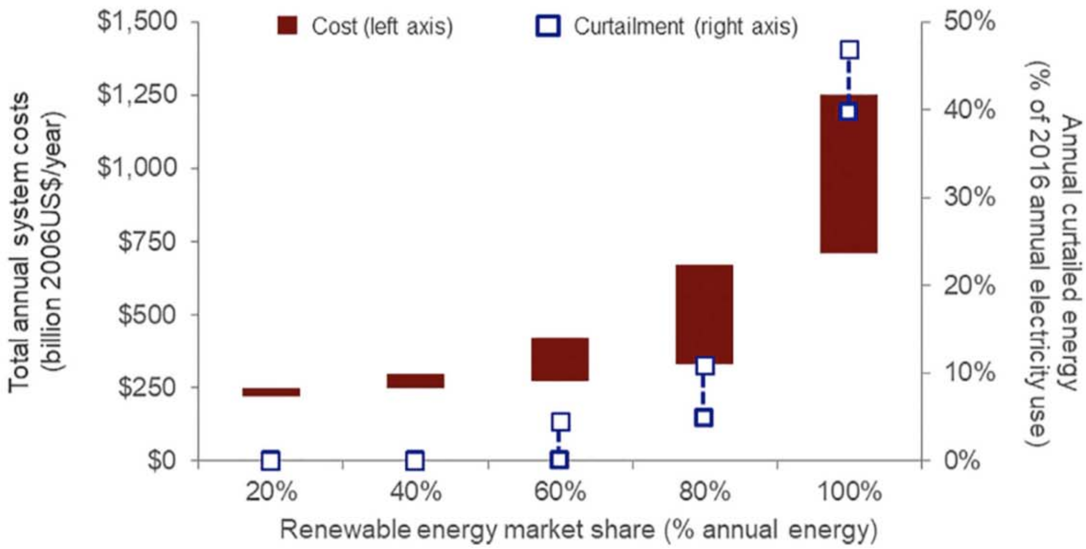


Figure 15. California energy systems costs with increasing shares of wind and solar, versus a mixed system including firm zero-carbon sources such as nuclear energy. Source: Clean Air Task Force calculated from CAISO data and aggressive assumptions on renewable energy and storage cost reductions.[20]

A similar cost escalation pattern has been seen in national studies, such as a recent one conducted by National Renewable Energy Laboratory analyst Bethany Frew, which also assumed a transcontinental electric grid and optimal demand response mechanisms (see Figure 16 below).

[20] The analysis assumes very aggressive further cost reductions in wind and solar energy compared to current projections by the US Energy Information Administration. Specifically, the analysis assumes that wind costs drop from $1,624 per kw to $1,000/kw and that solar PV drops from $1,969/kw to $700/kw.



Jenkins et al., Getting to Zero Carbon Emissions in the Electric Power Sector, Joule (2018), https://doi.org/ 10.1016/j.joule.2018.11.013, adapted from Frew, Bethany A., Jacobson, M. et al. "Flexibility mechanisms and pathways to a highly renewable US electricity future." *Energy* 101 (2016): 65-78.

Figure 16: Costs of supplying power in a national study of increasing shares of wind and solar. (Source: see Figure description above).

While these costs can be reduced by curtailing solar and wind output rather than storing all surplus electricity, note that that approach would leave the system in need of some other carbon free power to fill the void. As one can see from Figure 15 and 16, a system with substantial curtailment that provides 70-80% of energy from wind and sun rather than 100% still incurs steep costs – and still leaves the system in need of a back-filing zero carbon technology. Curtailment solves one problem, but creates another.

None of this analysis is to gainsay a substantial role – likely greater than 50%, or six times today's share – for wind and solar energy in cost-effectively achieving the electric system portion of the grid decarbonization challenge. And it is always possible that technological breakthroughs could occur that would make it possible to increase the percentage of economically affordable wind and solar to very high levels.[21] But supporting policies to bring other zero-carbon options to market will provide greater certainty of success.[22]

b. Technology diversity increases the chances of building the necessary infrastructure in time

Cost, however, is not the only issue. There is the question of whether we can achieve the necessary build-out by mid-century if we restrict ourselves just to one family of technology such as wind and solar, or nuclear, or carbon capture.

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[21] It is sometimes argued that "demand response," that is, the ability to curtail customer load, will alleviate the surplus and deficit problems outlined in this testimony. While this resource can be valuable, it is a question of scale and duration. Today, the California grid operator reports that the system has in place 350 MW of maximum load reduction/demand response — representing less than 1% of peak demand. See California ISO, 2018 Annual Report on Market Issues and Performance, http://www.caiso.com/Documents/2018AnnualReportonMarketIssuesandPerformance.pdf, pp. 29, 42. These agreements are generally understood to require interruptions for a few hours a few times a year. By contrast, as Figure 12 demonstrates, 100% wind and solar scenarios produce power deficits equal to as much as 75% of demand ***over many weeks***. It is not likely that California businesses, industries and consumers would effectively agree to multi-week and seasonal curtailment of demand, or that this would be good for the California economy if they did.

It also may be argued that interconnection of California to other control areas will alleviate the surplus and deficit problem. While greater interconnections can help at the margins, we must assume that other regions will be pursuing similar levels of decarbonization and are likely to adopt similar levels of variable energy. And wind and solar tends to be highly correlated on a daily and weekly across the nation. As a result, even with seamless national interconnection, as is assumed in the study referenced in Figure 16, substantial surplus and deficit problems are experienced at very high levels of wind and solar, with the resulting cost impacts shown in the figure.

[22] Zero carbon technology innovation policies range from R&D investments that focus on state of the art designs and construction methods, de-risking technologies for investors by supporting commercial demonstrations through purchase power agreements or contract for differences, driving costs down through deployment by performance-based tax incentives, and creating the infrastructure and regulatory pathways needed to build the new industry. See e.g., "Derisking Decarbonization: Making Green Energy Investments Blue Chip, Steyer Center for Energy Policy and Finance (2017) at: https://energy.stanford.edu/sites/g/files/sbiybj9971/f/stanfordcleanenergyfinanceframingdoc10-27_final.pdf; Sectoral policies that can help deploy zero-carbon energy technologies include "Clean Energy Standards" for the power sector and "Low Carbon Fuel Standards" for the transportation sector. Industrial decarbonization may require a suite of targeted policies depending on the emissions and process characteristics of the industry in question and may need to include boarder adjustment mechanisms. See: "Reducing CO2 Emissions from Heavy Industry, Briefing Paper #7" Grantham Institute for Climate Change (2012) at: https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/Reducing-CO2-emissions-from-heavy-industry---Grantham-BP-7.pdf

For example, Figure 17 below depicts the amount of zero-carbon energy that would need to be added each year to the California grid to meet the state's mid-century zero-carbon target, compared to various historical addition rates. To achieve these targets on wind and solar alone would require California to deploy those sources at five times the best historic rate, every year for the next 25 years – the equivalent of nearly ten of the world's largest onshore or offshore windfarms ***every year***. In nuclear terms, this would amount to construction of more than one Diablo Canyon size plant (2256 MW) every year. Figure 18 shows similar national figures for various technologies.

Illustrative zero-carbon energy deployment rates to achieve California grid decarbonization target

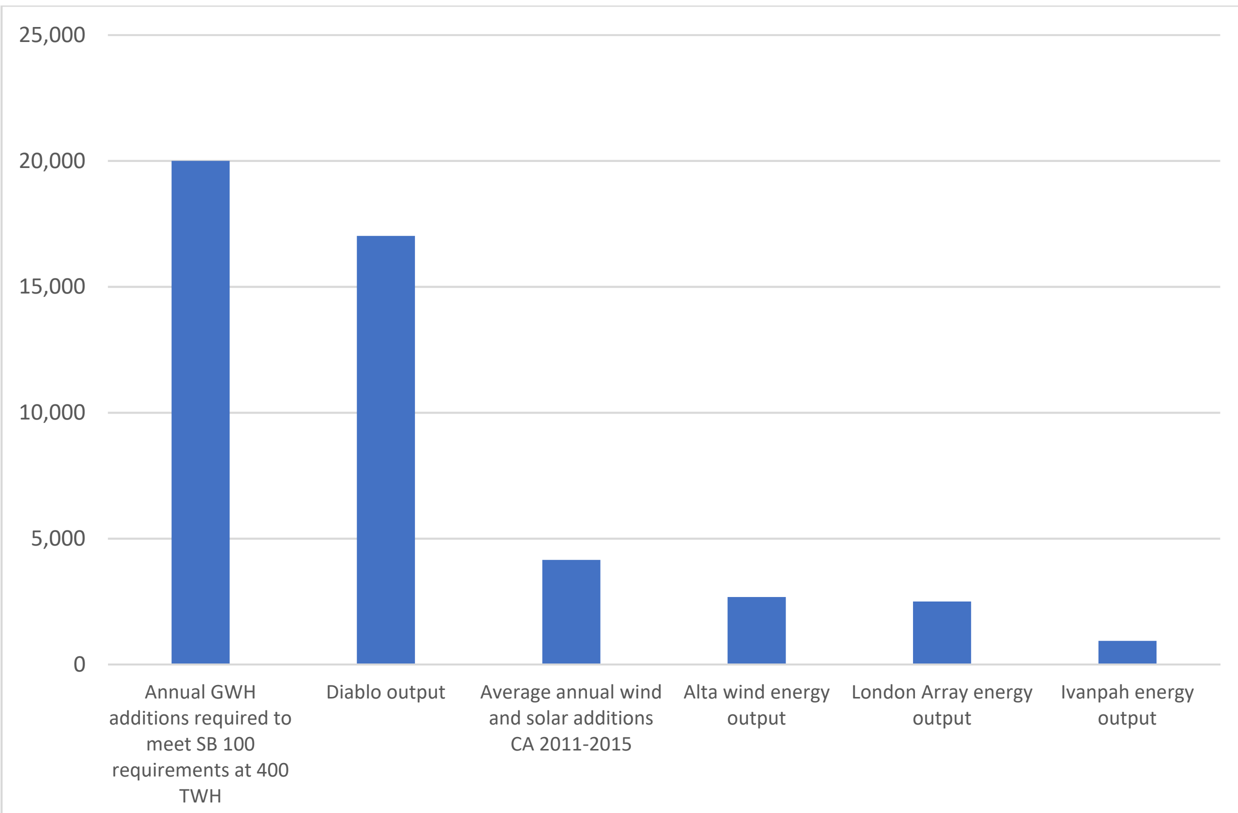

Figure 17: Annual zero-carbon energy deployment rates required to meet California's 2045 zero-carbon grid requirement starting in 2020, assuming increased electrification. It is assumed that all current zero-carbon energy infrastructure would need to eb replaced by midcentury. (Source: Clean Air Task Force calculated with historical data from published reports of the California Energy Commission, California PUC)

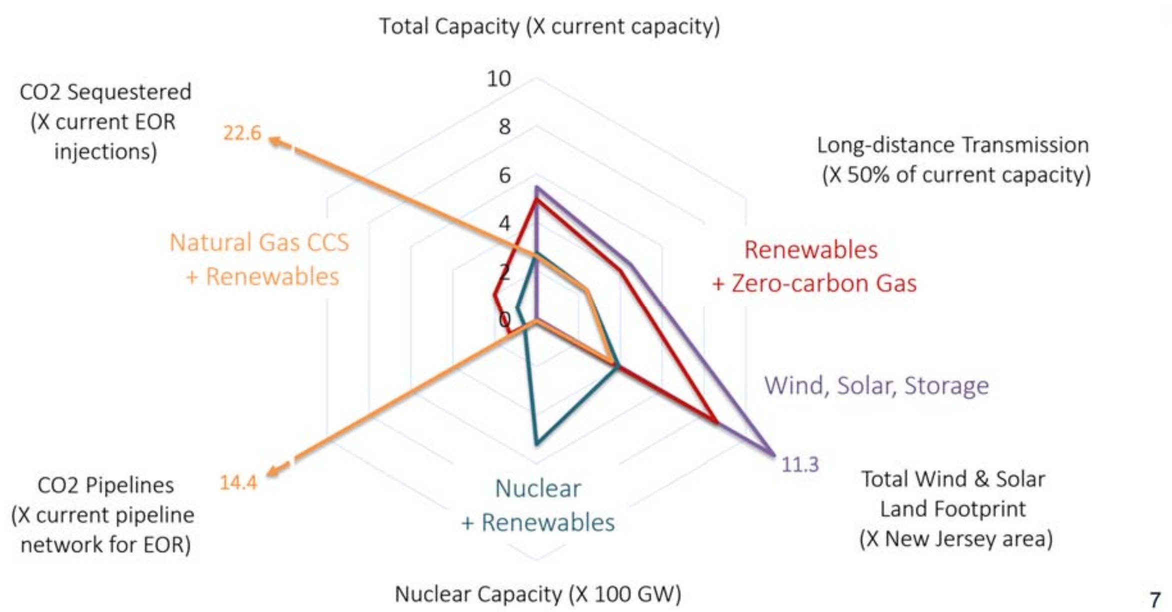

Figure 18: National buildout required for 100% carbon-free electricity, by technology. Source: J. Jenkins, *Critical bottlenecks in decarbonization of the U.S. electricity grid*, Jesse D. Jenkins, PhD, Princeton Rapid Switch Workshop (June 12, 2019), used by permission of author

By any measure, this is blistering and unprecedented pace of energy system buildout. It would be challenging enough to imagine achieving this with all of the available options. The difficulty increases as options are increasingly taken off the table.

The sheer engineering feat required is complicated further by public acceptance issues. Around the nation, and even, or especially, in more environmentally oriented states such as California, there have been substantial battles and delays over siting renewable energy infrastructure, and associated transmission.[23] Additional transmission needed to knit together diverse wind, sun and hydro resources are especially dramatic as renewable energy shares increase – requiring as much as a twenty-fold increase in US transmission capacity and interties for very high renewable energy scenarios, according to the National Renewable Energy Laboratory (see Figure 19 below). Just one such transmission line, in New England, has recently consumed roughly a decade of environmental debate, and is still not resolved.[24]

[23] See P. Field, et al, Resolving Land Use and Energy Conflicts (2018). https://www.cbsnews.com/news/new-york-wind-turbines-face-uphill-battle/ and https://friendsofmainesmountains.org/?category=Anti-Wind+Groups

[24] https://www.bostonglobe.com/metro/2018/11/22/plans-bring-hydropower-from-canada-cornerstone-state-energy-policy-faces-mounting-obstacles/3j6iBavrm4Libx8QdpX67M/story.html

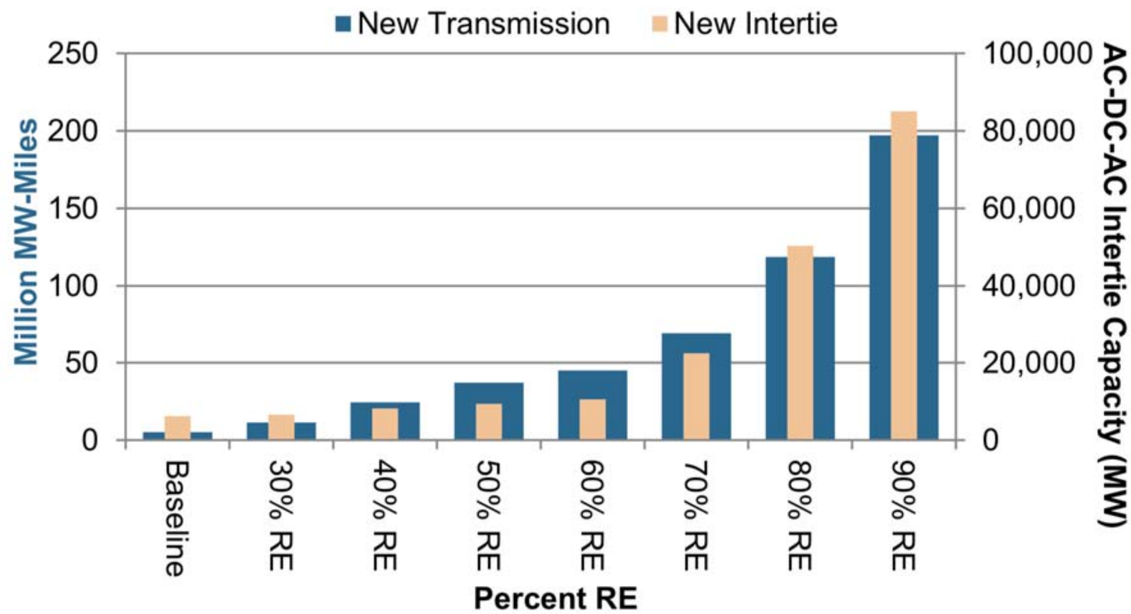

Figure 19: Transmission required for various levels of renewable energy deployment. Source: National Renewable Energy Laboratory, "Renewable Electricity Futures Study," Executive Summary, p. 26.

c. Conclusion: Allow and Support Developing Firm Zero-carbon Electricity Options

A diverse approach provides resiliency to the strategy by proving optionality in case insurmountable hurdles are faced in one pathway. As we have discussed, in addition to cost issues, a large build-out of wind and solar energy capacity, along with the substantial increase in transmission capacity that would be necessary to serve a wind- and sun-dominated system, may well face substantial and well organized opposition which has already emerged around relatively small scale proposals. Nuclear energy, while comprising the vast majority of the nation's zero-carbon energy today, has recently experienced cost overruns in the building of new first of a kind U.S. plants, and continues to face public concern around waste disposal and safety. The use of natural gas with carbon capture and careful methane emissions management, although based on well-demonstrated technologies, will likely face challenges from those opposed to the use of any fossil fuels for reasons including local health and environmental effects. The more options we have, the greater will be our chance of success, so Clean Air Task Force supports incentives and other policies to bring additional zero-carbon options to market.

3. Eliminating Super-Pollutants such as methane is a critical component of any plan to manage climate change

I want to close with one last important point. True climate protection requires attention to carbon pollution *beyond* carbon dioxide. Methane, black carbon, hydrofluorocarbons (HFCs), and others represent highly-potent "super-pollutants" that, pound for pound, have a much greater warming impact than carbon dioxide.[25]

As noted above, one possible path to decarbonization of electric and fuels involves the use of natural gas, with carbon capture and sequestration. However, to play a role in climate mitigation, natural gas will need to virtually eliminate its collateral emissions of the super pollutant methane.

If released into the atmosphere (rather than combusted), methane—which is the primary component of natural gas—is a climate pollutant 87 times more powerful than CO_2 over a 20-year period and 36 times more powerful over a century time scale. Methane pollution is responsible for about a quarter of the warming we are currently experiencing. And concentrations of methane are surging in the atmosphere.[26] This methane rise has pushed the world off course of meeting the Paris Agreement goals.[27] If governments and companies fail to take action on non-CO_2 climate pollutants, it will be impossible to deeply decarbonize the world's energy systems.

Addressing methane emissions for the natural gas industry, where rampant and higher than reported methane leaks across the supply chain substantially erode the climate benefit of gas as compared to other fossil fuels, is of paramount importance.[28] According to the current best science, methane emissions from oil and gas in 2017 were more than 12 million metric tons,[29] or more than 1,000 million metric tons CO2-equivalent over a 20 year period. This is equivalent to the CO_2 emissions from more than 250 coal fired power plants.[30] According to the International Energy Agency (IEA), reducing fugitive methane emissions from the oil and gas sector is one of the highest-impact strategies to reduce global greenhouse gas emissions over

[25] Due to total volume of emissions, CO2 has the greatest total impact of average global temperatures. On a per ton basis, however, methane warms the atmosphere 28-36 times more than a ton of CO2 over a 100-year basis. Nitrous Oxide (N2O) has a GWP 265–298 times that of CO2 for a 100-year timescale. A number of gases, including chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6), are many thousands of times more potent per ton than CO2. See EPA (2017) https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[26] NOAA. (2019). Annual Greenhouse Gas Index. Available at: https://www.esrl.noaa.gov/gmd/aggi/aggi.html

[27] Nisbet, E.G., Manning, M.R., Dlugokencky, et al. (2019). Very Strong Atmospheric Methane Growth in the 4 Years 2014–2017: Implications for the Paris Agreement. Global Biogeochemical Cycles, 33 (3), 318-342. https://doi.org/10.1029/2018GB006009

[28] R.A. Alvarez, D. Zavala-Araiza, D.R. Lyon, D.T. Allen, Z.R. Barkley, A.R. Brandt, *et al.* (2018). Assessment of methane emissions from the US oil and gas supply chain
Science 361 (6398), 186-188. DOI: 10.1126/science.aar7204.

[29] U.S. Environmental Protection Agency. Inventory of U.S. Greenhouse Gas Emissions and Sinks, 2019. Chapter 3. Available at: https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-chapter-3-energy.pdf.
Alvarez, R.A., et al. (2018) "Assessment of methane emissions from the U.S. oil and gas supply chain," Science, Vol. 361, Issue 6398, pp. 186. Available at: https://science.sciencemag.org/content/361/6398/186.

[30] U.S. Environmental Protection Agency. Greenhouse Gases Equivalencies Calculator - Calculations and References. Available at: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references#coalplant.

the next several years. Furthermore, the IEA has documented that low-cost technologies exist today to reduce emissions by 75 percent.[31]

Reducing flaring, which produces methane, black carbon, and carbon dioxide emissions alike, is another serious climate issue for the oil and gas sector. For example, flaring of natural gas in the Permian Basin is shooting up - it rose about 113 percent last year,[32] pushing the U.S. to number four globally for flaring, ahead of Nigeria.[33] In addition to wasting more than enough gas to supply all of Texas' home heating demand, flaring is a serious climate issue. Permian flaring pumps more CO_2 into the air than did any of the four Texas coal-fired power plants that retired in 2018, in addition to methane and black carbon. Flaring is also a source of local air pollution that can harm public health. Alternatives exist for most instances of wasteful and polluting flaring of natural gas, such as ensuring that gathering pipelines are present to take associated gas or otherwise capturing and beneficially using the gas.[34]

4. *Conclusion: building a 100% carbon-free energy economy by midcentury is tough but achievable*

Achieving a carbon-free energy and industrial system requires many things, some of which I have not discussed in detail in this testimony, such as electrification and energy efficiency. A full set of solution pathways can be thought of as a jigsaw puzzle that needs to be assembled, as shown in Figure 20 below.

[31] International Energy Agency. (2017). World Energy Outlook. Available at: https://www.iea.org/weo2017/.
[32] Rystad Energy. "Permian Natural Gas Flaring and Venting Reaching All-Time High," June 4, 2019. https://www.rystadenergy.com/newsevents/news/press-releases/Permian-natural-gas-flaring-and-venting-reaching-all-time-high/.
[33] The World Bank, Global Gas Flaring Reduction Partnership. "Top 30 flaring countries - table (2013-2018)." Available at: http://pubdocs.worldbank.org/en/603281560185748682/pdf/Gas-flaring-volumes-Top-30-countries-2014-2018.pdf.
[34] Carbon Limits. (2015). Putting Out the Fire: Reducing Flaring in Tight Oil Fields. Available at: https://www.catf.us/resource/putting-out-the-fire/.

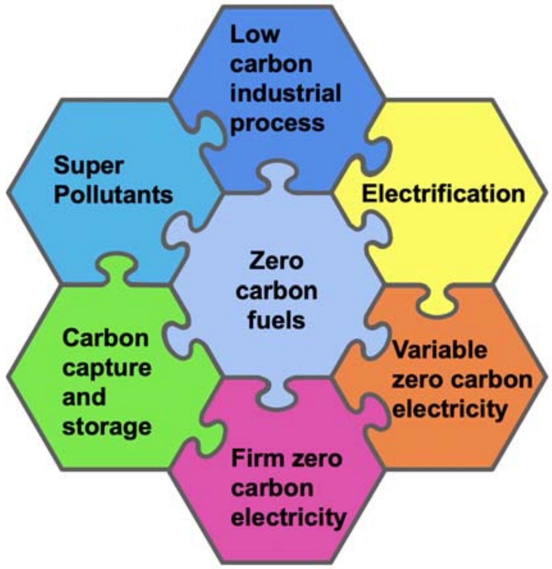

Figure 20: Decarbonizing the energy and industrial system will require assembling many different puzzle pieces.

While much attention has been given by policy-makers to zero-carbon electricity, and especially renewable energy, less attention has been paid to other critical components such as:

- Firm zero-carbon electricity
- Zero-carbon non-electric fuels
- Zero-carbon industrial processes
- Eliminating super pollutants such as methane if decarbonized fossil fuels are to play a role

There is an important role for both innovation and regulation to meet these challenges and create more affordable options for decarbonization. In this endeavor, there is a very important role for policy to play, and Congress and the states have already taken some important first steps. We need to quicken the pace and expand the technology and policy toolkit by combining economy wide emission targets or carbon pricing calibrated to achieve zero-emissions by midcentury[35] with innovation policies to bring additional, scalable zero-carbon technology options to market in time. Clean Air Task Force looks forward to working with this subcommittee and the Congress in that effort.

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[35] See: Phillips and Reilly, "Designing Successful Greenhouse Gas Emission Reduction Policies: A Primer for Policymakers – The Perfect or the Good?" at: https://globalchange.mit.edu/sites/default/files/MITJPSPGC_Rpt335.pdf

APPENDIX 1: The Potential Role of Bioenergy in Deep Decarbonization

- An energy technology can only play a leading role in decarbonization if it is massively scalable. Scalability presents unique challenges for bioenergy, however, because it competes for land with forests and other natural systems that are already sequestering carbon. The incremental climate benefits of using bioenergy—whether liquid biofuels or biomass-based power generation—tend to decrease (or disappear altogether) as bioenergy production increases and the supply of climate-beneficial biomass feedstocks is exhausted.

- The International Energy Agency has suggested that nearly 20% of projected global final energy demand in 2060 could be met by biomass-fueled power plants and other bioenergy systems,[36] but to meet that goal the global agricultural sector would have to roughly double the amount of plant matter it currently harvests.[37] Land use change of that magnitude would threaten natural ecosystems around the world and could drastically undermine forests' capacity to absorb CO2.[38]

- Large-scale production of liquid biofuel from conventional feedstocks like corn, soybean, canola, and oil palm presents a similar scalability challenge. The production of biofuel feedstocks drives up overall demand for both commodity crops and arable land. This demand in turn reshapes agricultural markets and encourages farmers—even those with no direct connection to biofuel—to convert previously uncultivated landscapes into cropland.[39] The conversion process (clearing, plowing, etc.) transfers soil and plant carbon into the atmosphere and creates a "carbon debt" that must be repaid before biofuels can actually reduce net greenhouse gas emissions.[40]

- Bioenergy is most likely to contribute to climate stabilization when it is derived from post-harvest waste feedstocks, like corn stover and some forestry residues, rather than conventional feedstocks. The use of waste feedstocks can be climate-beneficial because it creates a supply chain for bioenergy that does not encourage additional land conversion. In addition, waste feedstocks are no longer growing (and thus no longer sequestering carbon) and their embedded carbon will return to the atmosphere regardless of whether the waste is harvested and converted into energy or left in place to decompose.

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[36] International Energy Agency. 2017. Technology Roadmap: Delivering Sustainable Bioenergy, at 26 (https://www.ieabioenergy.com/wp-content/uploads/2017/11/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf).
[37] Timothy Searchinger and Ralph Heimlich. 2015. Avoiding Bioenergy Competition for Food Crops and Land, at 13. Working Paper, Installment 9 of *Creating a Sustainable Food Future*. World Resources Institute (https://www.wri.org/publication/avoiding-bioenergy-competition-food-crops-and-land).
[38] Marshall Wise *et al*. 2009. Implications of Limiting CO2 Concentrations for Land Use and Energy, *Science* 324(1183):1183-1186; DOI: 10.1126/science.1168475.
[39] https://www.catf.us/wp-content/uploads/2019/07/BiofuelsMap.pdf
[40] Joseph Fargione *et al*. 2008. Land Clearing and the Biofuel Carbon Debt, *Science* 319(5867):1235-1238; DOI: 10.1126/science.1152747.

- The supply of economically-recoverable waste biomass is limited, so all such biomass should be used as strategically and efficiently as possible. For example, while multiple technological pathways can contribute to power sector decarbonization, there are few non-bioenergy pathways for decarbonizing the aviation sector. (Aside from biofuel, the most frequently mentioned option is synthetic jet fuel made from carbon that was removed from the atmosphere by direct air capture (DAC) systems.[41]) Accordingly, aviation fuel should be a high-priority use for any available climate-beneficial biomass feedstocks.

- In addition, as CCS systems make it increasingly possible to eliminate CO2 emissions from combustion processes, every bioenergy facility—whether existing or new—should eventually be required to install CCS, provided the facility can deliver its captured carbon to a sequestration site at a reasonable cost. Bioenergy with carbon capture and storage systems (BECCS) can potentially achieve negative CO2 emissions if they use climate-beneficial waste biomass feedstocks, but substantial research must be done to better understand the scale at which BECCS can be sustainably pursued.[42]

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[41] *See* OECD, *ITF Transport Outlook 2019* at 142 (https://bit.ly/2YYq3ej).
[42] Christopher B. Field and Katharine. J. Mach, 2017. Rightsizing carbon dioxide removal, *Science* 356(6339):706-707; DOI: 10.1126/science.aam9726.