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An Innovation Agenda for **Hard-to-Decarbonize** *Energy Sectors*

Clean energy innovation has bipartisan public support and has proved successful in expanding the use of solar and wind power. Now it's time to tackle the hard stuff.

Technological innovation is essential for fighting climate change. In the United States, both political parties actually agree on this key point, but neither party has yet developed an innovation agenda that matches the scale and urgency of the climate challenge.

For progressives, the Green New Deal (GND) has elevated climate change and clean energy as a national priority, prompting multiple hearings on climate change in the Democratically controlled House and forcing all major candidates for the Democratic presidential nomination to develop their own climate policy.

But the GND is silent on the role of innovation. The resolution offered by Senator Ed Markey (D-MA) and Representative Alexandria Ocasio-Cortez (D-NY) acknowledges the limits of existing technologies, using the phrase "to the extent technologically feasible" to qualify its ambitious emissions reductions goals. But the GND does not diagnose those limits, nor does it offer a plan to expand what is technologically feasible through innovation.

Congressional Republicans have responded to the GND by touting innovation to fight climate change. But their proposals generally consist of tax cuts or deregulation that would deepen the nation's fossil-fuel dependency, possibly coupled with modest increases in funding for research and development (R&D) for select technologies.

Although neither camp has outlined a comprehensive innovation agenda, congressional leaders could yet come together around a grand bargain for clean energy innovation that is both ambitious and politically viable—if not in this presidential campaign year, then starting in 2021.

Clean energy innovation is overwhelmingly popular, with polling finding that the vast majority of Americans support greater investment in clean energy R&D. And lawmakers have already taken modest, bipartisan steps to advance energy innovation. They boosted funding for research, development, and demonstration (RD&D) in clean energy, and supported loan programs for first-of-a-kind projects, including an advanced nuclear plant and a clean methanol production facility. And they are currently debating a flurry of bills to create new programs that would accelerate innovation in energy storage; atmospheric carbon removal; carbon capture, utilization, and storage (CCUS); next-generation renewable energy; and advanced nuclear power.

Congress should build on these successes, and elevate innovation in clean energy as a national priority. Many technologies that now make major contributions to both US and global energy systems were created through federal investments and public-private cooperation. Federal support for shale-gas resource characterization and directional drilling in the 1970s and 1980s led to the boom in production of low-cost natural gas that helped it supplant coal as the nation's number one source of electricity generation. And decades of federal investment in solar power have helped drive cost reductions to the point where solar power is now the cheapest source of electricity in parts of the country with good solar resources.

But current funding levels do not match the urgency and scale of investment needed to put the United States and the world on a path to net-zero carbon emissions, and there are signs that the clean energy transition is beginning to stall, just when the nation needs it to accelerate. The US Department of Energy (DOE) currently invests about $7 billion annually in RD&D, of which about $2.8 billion is in basic research and $4.2 billion is in applied research. This investment is well below historical levels—Congress invested nearly $10 billion (in 2017 dollars) in DOE's energy RD&D programs when the department was created in 1978—and far from the level needed to address climate change. Globally, the majority of new energy demand is being met with fossil fuels, a sure sign that clean energy remains more expensive than fossil fuels for most applications and in most parts of the world. And after peaking in 2012, global patent applications in clean energy have been declining, suggesting that the pace of innovation is slowing down.

Clearly, more investment will be needed to close the gap between the current emissions trajectory and a pathway that would take the United States to a net-zero emissions energy system by midcentury. But more funding by itself will not be enough. Policy-makers will have to tackle hard-to-decarbonize sectors of the economy and create new programs that address gaps in the current federal clean energy RD&D portfolio.

And now for the hard part

The energy innovation agenda of the past 10 years has focused, with considerable success, on reducing the cost and expanding the use of wind and solar resources for electricity generation. These trends appear likely to continue. Greater penetration of wind and solar may result in near-term carbon emissions reductions in the electricity sector (though their impact could be muted by any loss of carbon-free generation from closing nuclear plants).

It is now time for policy-makers to expand the clean energy portfolio to address gaps in the current innovation agenda. In particular, a recent study published in the journal *Science* on net-zero emissions energy systems identified three sources of difficult-to-eliminate emissions that will require fundamental breakthroughs and greater attention from policy-makers as they seek to develop low-carbon solutions: firm, dispatchable electricity; hard-to-electrify transport; and industrial-sector emissions.

Firm, dispatchable electricity. As costs of electricity from wind and solar are continuing to decline, they are projected to meet a growing share of electricity demand in the coming decades. But there are limits to the amount of variable generation from wind and solar that the grid can accommodate. Nearly all deep decarbonization studies identify the need for "firm" low-carbon electricity to balance both variability in electricity demand and variable output from wind and solar. Firm electricity refers to electricity that can be generated and dispatched as needed in all seasons and over periods of weeks or longer.

Batteries combined with variable generation may be able to help manage shorter-term imbalances on hourly and sub-hourly scales, and the present enthusiasm in the climate and energy communities about systems that combine lithium-ion (Li-ion) batteries with renewables is understandable. These batteries can fill in gaps of up to a few hours when the sun is not shining or the wind is not blowing. But battery storage technologies using current Li-ion chemistries are unlikely to be able to manage the large weekly and seasonal variations in generation from wind and solar. For example, in 2017 California experienced 90 days with little to no wind, including 10 consecutive days in December when output from wind turbines was essentially zero. Similarly, the solar resource in a California winter is on average less than half what it is in the summer.

Variability on these timescales has traditionally been balanced by flexible generation from natural gas power plants. However, full decarbonization of the electricity system will require low-carbon firm, dispatchable electricity that can manage variability across all timescales, from hourly, to weekly, to seasonal.

Hydropower plants with high-capacity reservoirs, geothermal power, and biomass- and biogas-fueled power plants can all provide firm, dispatchable low-carbon electricity. But hydropower and geothermal are constrained by geography and have limits on the total capacity that can be installed with current technologies. And large-scale reliance on biomass for power generation competes with other land uses, including agriculture, as well as the use of biomass for fuels in the transportation and industrial sectors.

Maintaining reliable grid operations will require new, low-carbon suppliers of firm, dispatchable electricity. Options include long-duration energy storage that can store large quantities of electricity on weekly and seasonal timescales; nuclear power plants that are operated flexibly; and fossil fuel power plants equipped with CCUS technologies.

Hard-to-electrify transport. In the transportation sector, low-carbon electricity is emerging as a promising alternative for petroleum fuels for light-duty cars and trucks. Market analysts project that as the cost and performance of Li-ion batteries continue to improve, electric vehicles will capture growing shares of new sales for passenger vehicles.

The Electric Power Research Institute projects that the annualized total cost of ownership for electric passenger cars and other light-duty vehicles will reach cost parity with conventional internal combustion engine vehicles between 2020 and 2030.

However, batteries will not be able to replace petroleum-based fuels in all transportation sectors. Petroleum-based fuels have both high volumetric energy density (energy per volume) and high gravimetric energy density (energy per weight), both of which are important for transporting large volumes of goods or numbers of people. The Li-ion batteries that enable electrification of light-duty passenger vehicles are several orders of magnitude away from matching the energy density of current liquid fuels, and are unlikely to ever meet the performance requirements for aviation, shipping, and long-distance road transport.

Instead, air travel, shipping, and long-haul trucking will likely continue to rely on liquid fuels for the foreseeable future. Biofuels may offer a lower-carbon bridge to a net-zero transportation system, but they are not carbon-neutral themselves. The fertilizer used to grow energy crops, the energy used to harvest and transport crops to a biorefinery, the energy used to drive the biomass conversion process, and the fermentation of biomass all result in net-positive greenhouse gas emissions, which are themselves difficult if not impossible to completely remove.

Eliminating emissions from air travel, shipping, and long-haul trucking will therefore require carbon-neutral fuels. Hydrogen produced from water electrolysis (using carbon-free electricity from renewables or nuclear power), synthetic fuels made from ambient carbon dioxide, and carbon-neutral ammonia are all possible solutions.

Industrial-sector emissions. The industrial sector is especially challenging to decarbonize, due to two sets of emissions sources that are difficult, if not impossible, to eliminate using existing technologies.

First, the high-temperature heat used in many industrial processes is primarily generated by combusting fossil fuels. Calcination of limestone to make cement requires temperatures of roughly 2,500 degrees Fahrenheit, melting iron ore to produce steel requires roughly 2,200 degrees, and steam cracking to produce ethylene, a key feedstock for plastics and other petrochemicals, requires roughly 1,500 degrees—and all use fossil fuel combustion to generate the high temperatures. There are few low-carbon options capable of generating heat at these temperatures. Electrification of heat can be used for lower-temperature applications, such as washing and sterilizing, but electrification of high-temperature heat, generally considered anything over 750 degrees Fahrenheit, poses cost and technical barriers, and may require significant changes to industrial processes.

Second, "process" or "feedstock" emissions result directly from industrial processes and are independent of the source of energy used to drive the process. For example, the calcination of limestone to make cement releases carbon dioxide directly, regardless of the source of energy used. Fermentation of corn to produce ethanol also releases carbon dioxide. And ammonia production, which uses natural gas as a feedstock, results in direct emissions of carbon dioxide. Because these emissions are the result of chemical transformations and are independent of the energy used, they cannot be eliminated by switching to low-carbon energy sources.

Carbon capture, utilization, and storage may be the only option for mitigating these types of process emissions. Hydrogen produced from electrolysis of water using zero-carbon electricity (or other carbon-neutral fuels) could be combusted to generate high-temperature heat. Additionally, some advanced nuclear concepts operate at higher temperatures than the current light-water reactor designs, and could provide heat for some industrial processes.

Technology for hard-to-decarbonize sectors

These three hard-to-decarbonize sectors are not sufficiently represented in the federal energy RD&D programs, and constitute gaps in the federal clean energy innovation agenda. To fill these gaps, I propose six key areas for expanded federal investment. In many cases, a single technology can address more than one set of hard-to-decarbonize sectors.

Long-duration grid storage. Technologies that can store large quantities of electricity from daily to seasonal timescales could enable variable renewables to provide firm, dispatchable low-carbon electricity year-round.

But current RD&D programs at the Department of Energy and the Department of Defense focus primarily on short-duration (hourly) storage across a limited range of technologies. To accelerate innovation in long-duration grid storage, policy-makers will need to establish new R&D programs across a diverse portfolio of alternatives—such as flow and liquid-metal batteries, thermal storage, and new approaches to pumped hydropower storage—so viable options are available when Li-ion batteries reach their limit. Additionally, policy-makers will need to help promising technologies make the transition between lab-scale prototype and first-of-a-kind commercial demonstration, and between demonstration and widespread deployment.

Energy storage enjoys broad support within the administration and across both parties. But current proposals to stimulate innovation lack the appropriate scale of ambition or pursue a limited set of technologies. The administration under DOE Secretary Rick Perry has proposed new crosscutting storage initiatives in the past two budget cycles—the Beyond Batteries initiative in 2019, and its successor, the Advanced Energy Storage Initiative in 2020—that have done a good job of identifying connections across the technology silos to enable greater synergies. Additionally, Congress has begun debating investment in tax credits for storage, and the Senate Energy and Natural Resources Committee at its June 2019 hearing examined grid-scale energy storage options. But long-duration storage will need a broader coalition of supporters and a sustained commitment from Congress—likely for more than a decade—to realize its potential role in decarbonizing the nation's energy system.

Advanced small modular nuclear reactors. Nuclear power accounts for 20% of US electricity generation and still produces more carbon-free electricity than hydropower, wind, and solar combined. However, the development of nuclear technologies has stagnated, and nuclear power capacity has not grown in decades. High construction costs, site-specific designs, and inflexible grid operations make the current large-scale baseload model a poor fit for the electric grid of the future. New small modular designs can lower upfront capital costs, provide more flexible grid operations, and, it is hoped, enable the cost reductions from economies of replication that most technologies see with greater levels of deployment.

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To jump-start innovation in nuclear energy, policy-makers should prioritize advanced small modular reactors with standardized designs and lower capital costs, and should commit to the demonstration of at least one advanced reactor concept at commercial scale. The federal government should also provide the research infrastructure that can unlock private-sector innovation, such as the construction of a versatile test reactor user facility that will enable private companies to assess their structural materials and fuel designs in a reactor environment. Finally, the federal government should expand the nuclear research portfolio to include other applications (beyond electricity generation) for nuclear energy, including providing high-temperature heat for industrial processes such as hydrogen production and desalination.

The political outlook for many of these reforms is favorable. During the past budget cycle, the administration proposed a new R&D program focused on advanced small modular reactors, which Congress funded at $100 million in its 2019 budget. And a bipartisan group of 19 senators, led by Energy and Natural Resources Committee chair Lisa Murkowski (R-AK) and Ranking Member Joe Manchin (D-WV), recently introduced the Nuclear Energy Leadership Act, which adopts many of these proposals. However, the role of nuclear energy in addressing other hard-to-decarbonize sectors, such as carbon-neutral fuels production or heat for industrial processes, has received less attention from lawmakers. And of course, lawmakers will have to find a political and technical solution for safe geologic storage of used nuclear fuel in order to ensure that nuclear energy remains a viable option in a low-carbon future.

Carbon capture, utilization, and storage. By capturing the carbon emissions from fossil fuel combustion for subsequent use or sequestration, CCUS technologies have the ability to turn fossil fuels into low-carbon energy sources, enabling coal and natural gas power plants to provide low-carbon firm, dispatchable electricity. CCUS is also currently the only option for decarbonizing many industrial processes—such as the production of ethanol, fertilizers, plastics, cement, and steel—for which low-carbon alternatives do not exist.

Current CCUS programs focus primarily on coal-fired power plants. Policy-makers should now turn their attention to other sources, and should prioritize carbon capture demonstrations at natural gas power plants and cement and steel production facilities, to address the technical challenges unique to each type of operation. Research to turn captured carbon into fuels, building materials, plastics, and other products would expand the market for carbon dioxide, essentially turning carbon dioxide emissions into a valuable product. And DOE should continue to support geologic storage of carbon dioxide in saline aquifers and depleted oil and gas fields.

Support for CCUS technologies is growing. Members of Congress from states with large fossil fuel deposits are increasingly coming to view carbon capture as a means of enabling the continued use of fossil fuels in a low-carbon energy system. On the political left, skepticism about CCUS is thawing, as prominent scientific bodies (such as the Intergovernmental Panel on Climate Change) and respected nongovernmental organizations (such as the World Resources Institute, Clean Air Task Force, and Center for Climate and Energy Solutions) view CCUS as an essential part of a balanced mitigation strategy. The result has been bipartisan legislation such as the USE-IT Act, the EFFECT Act, and the LEADING Act, which would expand federal programs in carbon capture, utilization, and storage. Though a positive sign, current proposals are piecemeal, and they omit key industrial sources such as cement and steel production that cannot otherwise be decarbonized.

Carbon-neutral fuels. Fuels such as hydrogen, ammonia, and synthetic hydrocarbons that are made using energy from renewables or other low-carbon energy sources could play a role in multiple hard-to-decarbonize sectors. Hydrogen made from splitting water with excess renewable electricity can be stored and converted back to electricity when needed, providing a form of long-duration electricity storage. It can also be combusted to provide high-temperature heat for industrial processes. Synthetic hydrocarbons made from carbon dioxide captured from the air can be used as transportation fuels in conventional engines. And ammonia—already synthesized in large quantities for fertilizer use—can be used as a fuel in combustion turbines or fuel cells.

Until now, DOE's clean fuels program has focused primarily on fuel cell electric vehicles that use hydrogen. But plummeting battery costs have made battery electric vehicles the most promising technology for decarbonizing light-duty cars and trucks. Policy-makers should shift their focus to applications of carbon-neutral fuels for which batteries are ill-suited. In the transportation sector, this includes aviation, shipping, and long-distance road transport. In the industrial sector, this includes using carbon-neutral fuels as a source of high-temperature heat for industrial processes. On the production side, policy-makers should expand existing programs beyond hydrogen to develop low-carbon processes for manufacturing ammonia and synthetic hydrocarbons.

The nation will need multiple policies acting in tandem across the entire innovation system to help emerging clean technologies reach commercial scale.

But carbon-neutral fuels have not yet received much attention from the administration or from Congress, and are unlikely to be widely available in the near future. Support for such fuels, however, does not appear to be politicized, so it may be possible to build bipartisan support for more investment in R&D. The biggest challenge may be that policy-makers will associate hydrogen, the most well-known carbon-neutral fuel, exclusively with hydrogen fuel cell electric vehicles and write it off as a technology that has not lived up to its potential. Climate and clean energy advocates will have to continue to make the case to policy-makers and the public about the need for these fuels in addressing hard-to-decarbonize sectors.

Carbon dioxide removal. Carbon dioxide removal refers to a suite of technologies and processes that remove carbon dioxide directly from the atmosphere for subsequent use or storage. Carbon removal is distinct from CCUS and other conventional mitigation approaches because it removes carbon dioxide that is already in the atmosphere, rather than preventing the gas from being emitted in the first place. Approaches range from technologies that capture carbon dioxide directly from the air to natural solutions such as no-till agriculture that increase the carbon dioxide absorbed in soils.

As greenhouse gas emissions have continued to climb, awareness of the need for carbon removal is growing. Indeed, the most prominent strategies for emissions reductions depend on the large-scale deployment of these as-yet-unproven technologies for meeting these targets. And even the most stringent emissions reductions scenarios cannot remove non-carbon dioxide greenhouse gases (e.g., methane and nitrous oxide) from hard-to-decarbonize sectors such as agriculture. Atmospheric carbon removal will be necessary to counter such emissions.

Carbon removal technologies are far from commercial, and current public investment in carbon removal RD&D is small and sporadic. Congress will have to establish new programs across multiple federal agencies to address all R&D needs. In October 2018, the National Academies released a detailed RD&D agenda for carbon removal, providing guidance to policy-makers as they seek to develop new federal programs. The USE-IT Act and EFFECT Act bills that would expand RD&D in CCUS would also create new programs in direct air capture and bioenergy with carbon capture and storage. However, no proposals encompass the full suite of carbon removal approaches at the funding levels recommended by the National Academies. A comprehensive carbon removal program will require an interagency program that builds on the skills and resources of multiple federal agencies, including DOE, the Department of the Interior, the Department of Agriculture, the Environmental Protection Agency, the National Science Foundation, and other supporting agencies. The new interagency program—perhaps modeled after the National Nanotechnology Initiative—should be structured to address all carbon removal needs.

Basic energy sciences. Each technology mission requires fundamental advances in basic energy sciences. Better catalysts can lower the energy requirements for hydrogen and ammonia production. New solvents and membranes could make carbon capture—whether from power plants or directly from the atmosphere—cheaper and more efficient. New battery chemistries will be needed to improve the energy density and storage duration of batteries. Mission Innovation—an international consortium of 24 countries and the European Union aimed at accelerating clean energy innovation—recognizes the importance of fundamental research, and has identified the discovery of new clean energy materials as one of its core "Innovation Challenges." Just as the basic science research conducted decades ago is beginning to transform energy systems of today, investment in basic science today is needed to seed new technologies and create new options for the energy systems of the future.

But the political outlook for greater investment in use-inspired basic research is mixed. Support for basic research spans the political spectrum, but increases in the past few decades have mostly gone to biomedical research at the National Institutes of Health and the broad academic portfolio of the National Science Foundation. The uncertain payoffs and long lag-time between fundamental research and technology breakthroughs make it challenging to draw a connection between basic research in energy-related sciences and reducing greenhouse gas emissions.

Beyond RD&D

Accelerating energy innovation requires a suite of policies acting together across the innovation spectrum. For technologies that are far from commercialization, public investment in basic and applied research and technology development is necessary to improve the performance and drive down the cost of emerging technologies to the point that entrepreneurs and corporate R&D units jump in.

As technologies mature, successful demonstration at commercial scale may be necessary to establish cost, reliability, and performance characteristics and provide confidence to more risk-averse investors and the public that the technology works as intended. Additional tools such as loan guarantees for first-of-a-kind commercial projects, time-limited tax incentives, and clean energy standards tend to incentivize greater private-sector investment to commercialize technologies, which in turn should push them further down the cost curve. Tax-advantaged structures such as master-limited partnerships (combining aspects of publicly traded companies and private partnerships) and private activity bonds (which are tax exempt but may support projects carried out by private entities) can give innovative companies access to low-cost capital. The Export-Import Bank can help expand markets for domestic technologies overseas.

The dramatic cost decline in solar photovoltaic (PV) technologies offers a classic example of smart public policy in accelerating innovation, and the synergistic interactions between public and private investment. In the 1970s and 1980s, government and university R&D was responsible for most of the performance improvements and cost reductions in solar PV modules. The nascent solar industry was supported by the emergence in the public sector of niche applications—primarily for use in satellites—at NASA and the Defense Department that were relatively insensitive to cost. As the technology matured and the solar industry expanded, "market pull" policies such as tax incentives, net metering, feed-in tariffs, and state portfolio standards helped expand the market for solar and also incentivized greater private-sector investment. In 2011, DOE provided loan guarantees to the first five utility-scale solar PV facilities larger than 100 megawatts. Greater deployment has enabled the solar industry to take advantage of economies of scale and learning-by-doing, driving further cost reductions. The combination of technological innovation, market-expanding policies in the United States and globally, and China's subsidies for solar manufacturing have driven a 99% decline in the cost of solar PV over the past four decades.

The solar example serves as a guide for how to accelerate innovation in other technologies. Public investment in R&D is essential, but it's not enough. The nation will need multiple policies acting in tandem across the entire innovation system to help emerging clean technologies reach commercial scale. This is especially the case for the hard-to-decarbonize sectors where the emissions challenges cannot be solved by today's technologies, however affordable they may become.

Even in today's political climate, innovation policy offers the potential for bipartisan action. Legislators of both parties recognize that innovation can be a win-win-win: it drives down energy costs for consumers and businesses, enables domestic clean energy companies to compete in the rapidly growing global clean energy sector, and reduces the greenhouse gas emissions that cause climate change. The challenge now is to launch a comprehensive innovation strategy that is appropriately scaled to the urgency of the climate challenge, fills gaps in the clean energy portfolio while building on current successes, and makes use of the full suite of policy tools at the government's disposal to accelerate innovation.

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Recommended reading

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