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Innovation Amplifiers: Getting More Bang for the Buck on GHG Reductions

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The pace of GHG reductions needs to greatly accelerate. Recent investments are a great start but are not sufficient. We need to amplify the current investments to achieve clean energy as the norm and improve competitiveness.

KEY TAKEAWAYS

- The pace of global GHG reductions is far from what's needed to stabilize the climate. Emissions are going up in contrast to projections and commitments that they'd be going down.
- The tax incentives in the recent IRA legislation will expand clean energy generation, distribution, and use but are insufficient to drive the RD&D needed to decrease the costs of low-carbon technologies, support infrastructure, and implement solutions.
- For the current portfolio of investments, DOE and other agencies need to capture significantly more value from the resources they commit by adopting knowledge and application amplifiers with goal-directed research.
- DOE should develop high leverage capabilities (e.g., electrochemistry, composites, energy storage); pursue science and engineering to address crosscutting constraints; and rally diverse collaborator networks focused on audacious goals.
- DOE also should encourage spillovers into adjacent or unseen applications and markets; increase outreach and transparency to engage ecosystems of collaborators; and use the investments in hydrogen and CCUS hubs to utilize a range of amplifiers.

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EXECUTIVE SUMMARY

The world is behind the curve in addressing climate change. We need to amplify the impact of global greenhouse gas (GHG) reduction initiatives. Despite recent historic United States investments to spur clean energy technologies, we simply can't reduce GHGs fast enough with the limited resources committed globally—and additional massive funding is unlikely. We need bigger and faster GHG reductions from the funds already committed. But how?

Pursuing amplifiers is an underutilized approach that could cascade GHG reductions in multiple areas simultaneously. Amplifiers leverage resources and knowledge to greatly increase impact, remove constraints, or expand applications. They spur creative thinking that leads to innovative solutions to tough problems. Amplifiers such as spillovers increase the impact of innovations. For example, lithium-ion batteries developed for small consumer electronics are making an even larger impact powering electric vehicles and stationary batteries. Looking ahead, innovations in core capabilities such as electrochemistry could amplify GHG reductions in batteries, hydrogen fuel cells, and water electrolyzers, and converting carbon dioxide (CO_2) into value-added products.

Like increasing the power of amplifiers at a concert, we need to "crank it up" in terms of GHG reductions. The Department of Energy (DOE) and research partners can get more bang for the buck from recent investments by pursuing amplifiers in "Energy Earthshots."[1] DOE should engage diverse innovator networks across multiple partners to develop and apply expertise with high leverage potential (e.g., electrochemistry, composite materials, separations, energy storage).

Making big GHG reductions fast is vital. Using amplifiers to deliver those bigger reductions faster will be crucial to achieving audacious GHG reduction and sustainability goals.

INTRODUCTION

Society is way behind the pace when it comes to GHG reductions needed to avoid the worst impacts of climate change.[2] Recent investments provide a start for the transformation required but are far from the level currently needed. One way to achieve far greater impact from the limited resources available—get "more bang for the buck"—is by identifying and pursuing amplifiers to increase leverage and market pull.

The scale of the transformation needed across energy systems, manufacturing, buildings, transportation, supply chains, and the way that people use energy is colossal. The resources committed to this radical change in a very compressed time window are limited considering the scale of the change needed. This is a global problem, and the level of global investment needed will be enormous, but the consequences of not making the transformation are unthinkable. Estimates of the global investment needed are above $130 trillion through 2050.[3] Between 2021 and 2025, $2.6 trillion per year is needed—and this increases beyond 2025 to $4.5 trillion/year. By comparison, the $35 billion authorized for clean energy technology is merely a blip.[4] And prospects for additional funding in the next few years are dim, so making the most of the limited funds is vital.

Getting more bang for the buck matters, as the innovations needed to enable the technological change are enormous and low-carbon technologies need to get to price and performance parity with incumbent solutions fast.[6] This will require large and durable research, development, and demonstration (RD&D) investments as adoption faces displacing well-entrenched, less-expensive technologies and processes. Sectors such as industry, aviation, and marine are very heterogeneous, while integration (e.g., complex linkages between inputs and outputs) and risks for implementation are high.

The needs for innovation to achieve net-zero emissions are profound. Nearly half the technologies needed to reach net zero by 2050 are still in prototype or demonstration stage.[5] Sectors such as industry, aviation, and marine are even more dependent on emergent technologies. Accelerated adoption will require demonstrations in multiple configurations, applications, and regional contexts, so innovation in implementation is important too.

The low-carbon approaches for transitioning energy use such as renewable hydrogen, converting CO_2 into useful products, electrifying manufacturing processes, and mitigating remaining emissions from hard-to-abate processes by carbon capture utilization and storage (CCUS) are significantly more expensive than incumbent solutions. That price gap will lead to slow adoption, which means it's essential to reach price parity while delivering the same performance.[6] There's a critical need to amplify our efforts given limited resources, a short time window, and myriad adoption challenges.

This report explores how to identify and pursue amplifiers to accelerate GHG reductions, highlighting policy enablers and ways agencies can expand the impact of funds provided by the Inflation Reduction Act (IRA) and Bipartisan Infrastructure Law (BIL).

WHAT IS AN AMPLIFIER?

Amplifiers are approaches to program management that leverage resources and knowledge to greatly increase the impact of inputs, remove constraints, or expand a range of applications. In the context of GHG reductions, an amplifier greatly expands the magnitude of emissions reductions for the resources available. Figure 1 shows the several categories of amplifiers, followed by illustrative examples for each. But as there are many ways amplifiers can be creatively applied, this list is not meant to be exhaustive.

Figure 1: Categories of amplifiers

Improved Clarity and Fewer Constraints

There are multiple ways in which removal of constraints (capital, risk, technical issues, etc.) and improved clarity can yield amplified impact. Operation Warp Speed (OWS) in the United States was successful in removing RD&D and regulatory risk to accelerate COVID-19 vaccine development.[7] RD&D often has associated risks regarding whether offerings will meet the needs of customers and if they'll purchase the product developed. The government largely eliminated those risks by guaranteeing the purchase of the vaccines and providing financing regardless of regulatory approval. Normal regulatory processes for medical products can take years—a cloud of uncertainty for product developers' approval timing and application constraints. The government minimized these risks by fast-tracking approval for the vaccines and aided contracting and distribution, further minimizing risks. Multiple agencies and private sector companies partnered to speed development and deployment while effectively addressing hurdles.

The Defense Advanced Research Projects Agency (DARPA) played an early role by seeing the potential for the mRNA technology for vaccines, supporting development, building networks of researchers, and lowering technical risks—starting eight years before the pandemic.[8] DARPA has a history of pioneering innovations that have been picked up by markets. Examples include the Internet, miniaturized global positioning system (GPS) devices, unmanned aerial vehicles (drones), and flat screen displays.[9]

Knowledge Spillovers

Spillovers increase the rate of learning and application in areas that were not the original target of innovation activity.[10] Knowledge spillovers incorporate new principles into other applications increasing the rate of innovation in the new area. One example, as noted is the adoption of semiconductor manufacturing processes and leveraged silicon production with photovoltaic (PV) cells. This contributed to the dominance of PVs (over competing thin films) after 2000 with polysilicon costs dropping to 10 percent that of the 1975 level.[9] Another aspect of these spillovers occurs when researchers pursue innovations in unfamiliar fields in which they can develop new insights. These interlopers can be "cross-pollinators" that help develop innovative ideas.[11] The diversity in thinking at the intersection of fields, culture, and experiences can yield unique perspectives. For example, the emergency room (ER) staff at a hospital who were seeking innovative, nontraditional methods to minimize mistakes observed car racing pit crews under pressure—not ERs at other hospitals.[12]

Application Spillovers

Application spillovers involve a technology developed for one application being picked up by another application or adjacent market. For example, gas turbines originally developed and applied for jet engines were later adapted for natural gas turbines.[13] Spillovers can share a common scientific base, manufacturing techniques, and operation skills. The multitude of application spillovers from the NASA moonshots are prime examples.[14] The increased impacts and accelerated speed from spillovers were also important for the rapid preparation of materials for World War II, where they enabled collaboration to turn failures into successes in other applications and accelerated progress in the face of scarce inputs.[15]

Clear Solution Paths

Amplifiers can also reveal new knowledge that allows for a clearer path to solutions. The development of vaccines by OWS enabled the mapping of supply chains for the rapid manufacture, transportation, and deployment of vaccines. This mapping was a key part of the rapid response to the pandemic, as it identified vulnerabilities and was used along with manufacturing forecasting and investing to close gaps before they arose.[7] This also uncovered that Pfizer knew its supply chain, as did Sanofi, but knowledge of the entire supply chain needed for manufacture and distribution was unknown. This is an example of finding clarity on how to utilize a complex production and delivery process more effectively from end to end.

There are also examples wherein new insights can come from more clearly seeing how to orchestrate solutions in complex, nonlinear, or multivariate systems. Analyses of patents associated with complex areas show the disproportionate benefits of science uncovering previously unrecognized relationships. Science can help inventors both find their way to unfamiliar places and convince others that what they found is valuable.[16]

Strategic Use of Resources

Greater impact is realized when the value is leveraged across multiple organizations. For example, a company with the rights to build roads, bridges, or communications networks can operate more efficiently in moving its goods or information. This impact, however, can be far greater if the technology is shared among multiple companies connecting more producers, sellers, and end consumers. In another example, systems engineering challenges were not readily divisible during technology development associated with WWII, so the development of radar was concentrated at the Massachusetts Institute of Technology.[15] Conversely, parallel efforts were favored for fission and the development of penicillin and medicines to address malaria.

Intersectional Thinking

Frans Johannsen, in *The Medici Effect,* explained that increased creativity comes when talented people with different backgrounds and disciplines collaborate, yielding step-change improvements.[11] Creativity will flourish when people with diverse background, cultures, educations, and values collaborate. At these intersections of thinking, new approaches and breakthroughs can occur. People outside a certain field of study don't have the same assumptions or are able to challenge those already present, and ideas can be combined in new ways.

DARPA promotes this intersectionality in the teams they build and interactions they spur among networks. The Advanced Research Projects Agency-Energy (ARPA-E) promotes it at their innovation summits where technology developers from all over the globe working on diverse problems have an opportunity to interact.[7] Successes from the ARPA-E program include wide-band gap semiconductors and mobile detection for methane leak detection among the 135 companies, more than 1,000 patents, and over 300 licenses resulting from supported programs.[17]

Support Networks

Support networks enable the rapid exchange of knowledge and spur creativity between researchers in overlapping disciplines, encouraging cross-fertilization and innovation. When these networks are focused on a common goal, progress can be accelerated by the community of collaborators that expand expertise and drive durable progress.

For example, DARPA is known for building strong networks of collaborators that focus on a goal, with the networks tapping a broad range of expertise and disciplines.[7] The networks can range from academia to emerging technology firms that lack experience as defense contractors. In another example, the United States government spurred the development of public-private networks leading to numerous PV inventions/innovations in the 1970s.[7] However, at the same time, a similar federal program encouraging public-private networks and innovation ecosystems to drive the application of technology was largely absent, allowing Germany, Japan, and Spain to have the upper hand in installations per capita.

Goal-Directed Research

Creative innovation will make the greatest difference in addressing climate stabilization, if directed toward that cause. This aligns with prior learnings. Goal-directed research was vital to the United States Office of Scientific Research and Development (OSRD) development of innovative solutions to challenges during WWII such as the Manhattan Project.[12] That experience also showed the tensions between the needs for very rapid innovation in multiple areas, severe time constraints/urgency, limited resources, and high costs. Discovering unusual combinations of ideas via amplifiers may be relatively inexpensive, but commercializing those breakthroughs may require more time to fully deploy, as these unique solutions are still relatively new and untested.

The Human Genome project's success with private RD&D directed toward a societal goal changed the way biomedical research is structured.[18] The evolution of "grand challenges" provides additional steering for research.[19] The notion of challenge-based research has been picked up in Europe to create a research agenda with society and active participant stakeholders.[20]

HOW CAN WE FOSTER AMPLIFIERS?

There are several routes to bolster amplifiers. Projects and events that gather experts from different fields of study encourage cross-fertilization of ideas, learning, and collaborations that lead to new combinations of approaches to solutions.

Gathering innovators in multiple fields across art, sciences, literature, etc. harkens back to the Medicis, a wealthy banking and merchant family that spurred innovation in 16th century Florence via this method. The resulting nexus of intellectual thinking contributed to Europe's renaissance.[21] The collision of different perspectives, life experiences, and cultures can lead to experimentation outside the bounds of previous thought patterns—which sometimes are constrained by the established "rules" of a field of practice. People that consider problems in areas that are new to them don't have the biases and therefore don't have to unlearn "traditional" learning. This allows people working at these interfaces to spontaneously connect disparate concepts, ideas, ingredients, approaches, etc.

Diverse networks, collaborations, and partnerships form when people with divergent experiences and perspectives come together. A key to fostering intersectional thinking is to gather people from different fields and focus their creative thinking on a challenge (e.g., goal-directed RD&D). People who are naturally curious and interested in topics beyond their expertise and training—and ask lots of thought-provoking questions and enjoy pursuing them—are good candidates.

The strategy of fostering networks is central to DARPA, and it intentionally brings together a range of experts from multiple disciplines and focuses them on a challenge.[22] This model is also employed in the National Network for Manufacturing Innovation (NNMI), where the involvement of networks to address crosscutting opportunities is recognized.[23] Expansion of networks to include international peers in overlapping fields can speed the transfer of knowledge, identify innovation gaps, and avoid duplication of efforts. Existing multilateral programs include the International Energy Agency's (IEA's) technology collaboration programs, Mission Innovation, and the Clean Energy Ministerial.[6]

Spurring development of new insights in complex areas is another route. This can occur in areas that are well covered—where new approaches, tools, or re-examination of assumptions can yield new paths to solutions. Or it can occur in unexplored areas. The improved ability to model myriad parameters quickly with emerging artificial intelligence (AI), machine learning, quantum computing, etc. is expected to provide greater understanding of how to optimize complex systems and dynamically adjust to changing market needs and opportunities. Understanding how to connect market push and pull mechanisms, and how to optimize interactions across complex supply chains, presents additional opportunities in this area.[24] Expanding access to information or using the voluminous level of digital data available to identify trends and interpret them for more rapid decision-making fits here as well.

Encouraging new approaches and business models is yet another approach. For example, increasing the scale of production aids the ability of companies to compete. This leads to larger and larger facilities in centralized locations. The pandemic, however, exposed several supply chain gaps with that model and inherent vulnerabilities with just-in-time-delivery. A converse approach is pursuing smaller modular units closer to customers (shorter supply chains) that are nimbler and can achieve scale by stacking production from identical units. Those pursuing distributed manufacturing tout the increased opportunities for radically different business models in which data-driven open innovation provides greater flexibility and the ability to customize, and meet fast delivery requirements of customers.[25]

Inspiring the development of deep expertise in areas with broad applicability is central to amplification. There are multiple opportunities where shared expertise could benefit clean energy innovation. For example, the area of electrochemistry is central to innovation in batteries, electrolyzers (e.g., generation of renewable hydrogen), fuel cells, and many other clean technology applications.[9] Development of expertise in this area and encouraging experts to move from one application area to another is a way to encourage innovation. Other areas where expertise could be central to innovations could include energy storage, separations, lightweight materials, quantum computing, AI, advanced manufacturing/automation, and biotechnology.

Supporting early markets is key. It's challenging for entrepreneurs to commercialize inventions. Encouragement in targeted areas of market or societal challenges can decrease the hurdles and speed innovation. DARPA uses this approach by serving as an early market for information technology (IT) products. By encouraging "connected RD&D," DARPA provides not only insights into customer needs but also connections to interested parties willing to trial concepts.[26] DARPA and the Department of Defense (DOD) were the first adopters of IT advances for workstations (Sun Microsystems, Silicon Graphics) and Internet forerunners ARPANET and MILNET.[27] DARPA provided a critical assist to the launching of Sun by extending funds to academic institutions, thereby permitting them to acquire workstations. Orders from DARPA-connected academic partners accounted for 80 percent of the orders received by Sun in its first year of business.[34] DARPA relied on its connections and ties to larger innovation systems to nurture internal and external multilayered networks to spur innovation while engaging a diverse range of researchers and end users.[28]

There's also the approach of offering prizes to spur innovation, which would seem to support innovation by entrepreneurs. There's been a boom in large prizes since 1970, with inducement prizes accounting for 78 percent of total prizes.[29] Yet, quantitative evidence for the effect of prizes is not strong. Where prizes are chosen, they may be particularly appropriate for developing technology to break critical technological barriers, achieve higher performance, or stimulate the diffusion or commercialization of technologies.[30] These areas align with amplifier use, so careful selection of goals and metrics in the design of prizes could be considered to inspire those pursuing early markets.

Be alert for adjacent markets and applications. Goal-oriented RD&D should recognize that while innovations are targeted for one area, there may be adjacent markets or applications with even larger impact or a more direct pathway to adoption.

Often innovators have tunnel vision—focused on meeting a market need that justifies their time and energy in developing a solution—but are unaware of adjacent or unseen markets, as noted by Peter Drucker decades ago.[31] Amplifiers can reveal a broader market to innovators augmenting the business case and providing greater scale. The company that developed the first computer, Univac, saw that it would be great for scientific research but didn't see the market for business, let alone personal computing. Several markets connected with electrochemistry may be modest today, but when combined with the potential for leverageable innovations, become quite attractive. The global market for electrolyzers is $1.2 billion in 2023 but expected reach $24 billion by 2028 (a compound annual growth rate (CAGR) of 80 percent).[32] The global market for hydrogen fuel cells was $14.7 billion/year in 2021 and is projected to be a $80 billion/year market by 2030 (CAGR 21 percent).[33] The market potential in chemicals and fuels is immense given the array of products and need to decarbonize.[34] The global market for ethylene (one of the largest commodity chemicals) in 2021 was $176 billion and is projected to reach $287 billion by 2030.[35]

Entrepreneurs can spur disruptive innovation by reorganizing a current market or creating a new one through the application of existing technologies to new processes or business models. The latter is hard to understand, as it's difficult to do research on a market that doesn't exist yet. Nevertheless, unseen markets can be the path to success and should be tapped by amplifiers.

HOW ARE DOE, DOD, AND OTHER AGENCIES USING AMPLIFIERS?

Several agencies recognize the benefits of leveraging innovations across multiple areas. For example, the National Energy Technology Laboratory (NETL) has a long-running crosscuts program. It focuses on high-performance materials, sensors/controls/cybersecurity, simulation-based engineering, waste management, and energy storage.[36] The program reaches out to the private sector by incorporating comprehensive risk assessments and techno-economic analyses. Several programs have international collaborators, such as the materials RD&D area, which collaborates with experts in high-temperature materials in the United Kingdom.[37]

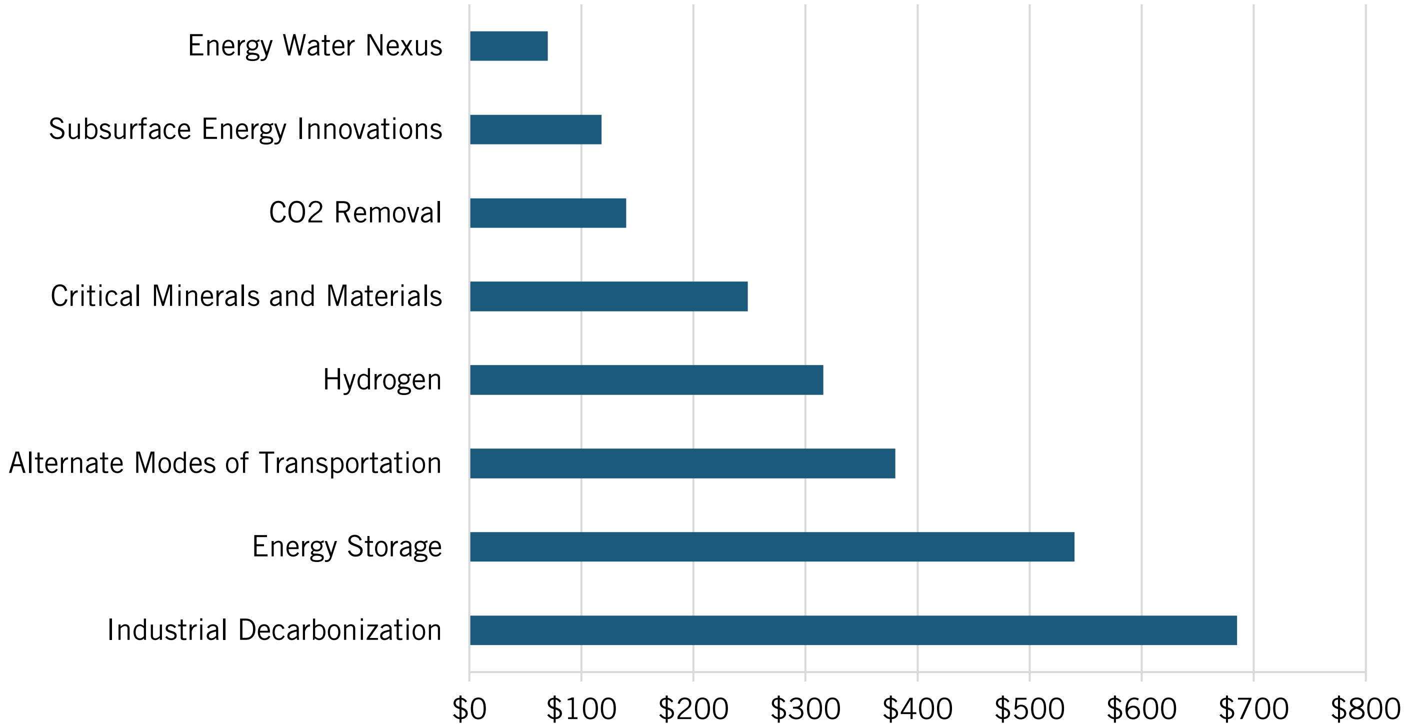
Across multiple departments, DOE has organized multi-office crosscutting research and development (R&D) programs to address common challenges/objectives, streamline hand-offs from earlier-stage research to more applied programs, and avoid unintended overlap in programs.[38] Crosscut teams launched in February 2023 work in areas where there's an opportunity to effectively leverage impact on big projects.[39] The crosscut initiatives have objectives, action areas, and ties to BIL and IRA funding.[40] Some of these teams specifically support the Energy Earthshots, whose intention is to accelerate progress on aggressive targets and increase communication and diverse thinking on the problems/opportunities. To support the fundamental research connected with the multiple Energy Earthshots, DOE announced $150 million in funding over three years for small teams focused on the common challenges. It is open to academia, private sector companies, and nongovernmental organizations (NGOs).[41] Additionally, there are joint strategy teams that coordinate efforts DOE-wide.

Fostering networks to spur innovation while asking and pursuing difficult questions toward commercialization is a focus of the Embedded Entrepreneurship Initiative (EEI) funded by DARPA.[42] The aim is to build healthy ecosystems wherein companies with innovative concepts can coalesce while getting early guidance on what's commercially relevant and the steps needed to deliver a product to the marketplace. To tap the capabilities and creative nature of smaller companies, DARPA has a program specifically for small businesses to join a consortium looking at creative solutions to problems (e.g., an innovation "farm system," per the baseball analogy). DARPA also offers a two-year fellowship program for scientists within five years of their Ph.D.

The DARPA approach, used at ARPA-E to tap the research community and encourage entrepreneurs to pursue solutions aligned with areas of interest, has been successful.[49] ARPA-E projects have attracted more than $11.4 billion in private sector funding.[43] Both DARPA and ARPA-E have a relatively flat organizational structure, with a high degree of leverage to academia, entrepreneurs, and others to foster innovation and collect ideas from a broad community. Their support is instrumental in developing a diverse workforce and providing a breeding ground for young scientists and engineers.

Crosscuts are mentioned in funding streams for the various agencies. Figure 2 provides a look at the budgets for crosscut programs using public data. This view does not include IRA and BIL funds, which are defined to specific programs. This coarse analysis reflects the pivot of DOE toward decarbonization (industry, transportation), investments transforming energy (hydrogen, energy storage), and CO_2 mitigation. Critical minerals and materials are important to multiple areas (batteries, electrolyzers, catalysis, etc.) and are therefore a crosscut.

Figure 2: Funding for crosscutting areas at DOE (millions)



HOW COULD AMPLIFIERS MAXIMIZE THE IMPACT OF RECENT FUNDING?

Amplifiers should be used to maximize the funding impact from recent legislation. This includes:

1. **Developing capabilities in expertise areas with high leverage and impact potential.** For example, expertise in electrochemistry could be helpful in developing creative solutions for batteries, fuel cells, water electrolyzers, carbon capture, electro-swing absorption, selective catalytic conversion of non-petroleum-based feedstocks into chemicals and fuels, and more applications. These technologies share principles, materials and manufacturing approaches, and components, so advances in one area could benefit others. An analysis shows that advanced materials and manufacturing for electrodes could deliver 20–45 percent of the cost-reduction potential, while shared learning on the balance of plants could deliver another 25–45 percent of the improvement.[9] The importance of critical minerals and materials noted in figure 2 and substitution with chemistries allowing less-critical, lower-cost materials is clearly important. Continued development and application of skills in materials, surface chemistry, and nanotechnology can improve the performance and lifetime of materials solutions.

   Agencies should foster networks of diverse thinkers to pursue decarbonization. This could be integrated into several current offices and programs, including the Office of Energy Efficiency and Renewable Energy (EERE), the Vehicle Technologies Office, the Hydrogen program, the Fuel Cell Technology program, the Advanced Materials and Manufacturing program, and the Energy Earthshots program.

2. **Identifying and pursuing fundamental science and technology to address constraints and other deep challenges in support of goals.** For example, improving the efficiency of thermal energy transfer is important to high-temperature applications for process heat via beneficial electrification. Improving the heat transfer efficiency at scale could open doors for electrification of steam crackers as well as steam methane reformers, methanol plants, etc.[44] Agency areas of application could include the following:
    a. The $150 million fund to advance the fundamentals for Energy Earthshots is a clear area where amplifiers across applied science and engineering could bring down costs so solutions can compete with incumbent technologies.
    b. For Basic Energy Sciences (BES), amplifiers should be pursued in Energy Frontier Research Centers, Computational Materials and Chemical Sciences, Energy Innovation Hubs (fuels from sunlight, next-generation batteries, and energy storage), and materials science and engineering.
    c. Connecting science, engineering, and applied/integration work is an opportunity. Incorporating applied science and engineering early on with the more basic sciences can help identify constraints so they can be addressed early in the concept development cycle.
3. **Rallying a diverse set of contributors around goal-driven research.** The Energy Earthshots are a great opportunity to focus the creativity of collaborators around a common goal. The Clean Fuels and Products Energy Earthshot is goal oriented and provides an excellent opportunity for pursuing amplifiers. Creating cross-functional teams in which individuals are assigned to a team for a targeted period, yet are still connected to the larger organization (e.g., island-bridge model), is a successful approach for innovation.[45] Our allies are wrestling with the same clean energy challenges, so this is a prime opportunity to collaborate to resolve constraints and develop solutions that can compete in the marketplace on both price and performance. Specific programs include the following:
    a. The Clean Hydrogen R&D program, wherein the BIL specifically calls out a crosscutting approach for a broad perspective (section 40313).
    b. Deployment of Technologies to Enhance Smart Grid Flexibility (section 40107, BIL) is also another where a broad network of contributors is needed.
    c. Energy Earthshot teams should leverage learnings from the COVID vaccine and competitive scenario approaches.[46]
4. **Encouraging spillovers.** This includes areas where multiple uses or adaptation of solutions is anticipated. Process heat solutions such as industrial heat pumps, electric boilers, microwave, infrared, and a host of others provide a space to be leveraged across heavy industries.[47] Additional opportunity areas include composite materials (applications in wind turbines, aircraft, road vehicles, batteries, etc.) and integration of heating and cooling.[48] General purpose spillovers (historical examples include steam engines, electric power, and IT) can drive productivity across the economy, so investment attention to spillovers could have very large returns.

5. **Increasing transparency of key information related to goals.** Agencies can increase transparency and information flow during projects rather than deliver a tome at end of projects well after the research was performed. Other routes to breakdown informational barriers could include having diverse networks engaged with projects in-flight even if they're not the parties that are funded. Connecting "market pull" and "technology/science push" is important here as well. For example, success for Organization for Economic Cooperation and Development's (OECD's) demonstrations is dependent on rapid learning of how to lower costs and improve performance while moving solutions to full scale. It is important to have an agile and transparent approach, which entails communicating about interim information on the objectives, key noncommercial data, and indicators of success.[49]
6. **Supporting clusters, hubs, and the opportunity for multiple amplifiers.** DOE has set the course with Hydrogen and CCUS hubs as an approach for focused technology development and deployment and cultivating new markets. Clusters and hubs are a target-rich environment for pursuing amplifiers, as there's a ready market to pick up solutions, an attentive/interested audience to provide input on needs and how to lower costs.

Agencies can stimulate amplifiers at clusters and hubs by intentionally creating networks that engage on the challenges and solutions, being transparent and communicating interim results, and not shying away from "failures," but rather, rapidly learning from them.

CONCLUSIONS AND RECOMMENDATIONS

Amplifiers are approaches to increase the leverage, impact, and speed of innovation by engaging a diverse ecosystem of insightful thinkers to focus on a very challenging societal or business problem. Ingenious solutions are needed to bring the costs down and performance up for low-carbon solutions and to invent technologies that close the gap to net-zero GHG emissions. The recent investments in the clean energy options are great, but the pace of GHG reductions needs to greatly accelerate and more leverage needs to be squeezed from the current investments. This is the opportunity for amplifiers to yield more bang for the buck.

DOE and DOD should:

1. Communicate the opportunities for amplification throughout agencies.
2. Drive the practice of goal- oriented, cross-functional teams dedicated to achieving goals.
3. Utilize networks with diverse capabilities to contribute unique and helpful perspectives aligned with the goal-oriented areas.
4. Apply intersectional learning, nurture inputs, and foster a broad range of collaborators to spur creative innovation.
5. Be transparent and agile, and foster rapid learning and application across teams and networks DURING projects.
6. Identify areas with spillover potential and of common science, engineering, and market challenges.
7. Invest in basic RD&D to solve the problems and apply solutions.

8. Track the magnitude of amplification effects and utilize the information in future budget requests.

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