U.S. Innovation to Meet 2050 Climate Goals

Assessing Initial R&D Opportunities

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THE WHITE HOUSE
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Five Priorities to Launch the Net-Zero Game Changers Initiative

The Biden-Harris Administration is committed to supporting game-changing innovation to meet its climate goals — including the U.S. nationally determined contribution target of reducing greenhouse gas (GHG) emissions by 50-52% from 2005 levels by 2030 and the national goal of reaching net-zero emissions by no later than 2050. The Administration created an interagency working group to identify, prioritize, and accelerate innovation in game-changing net-zero technologies. The working group first identified 37 net-zero R&D opportunities, which are described in this report. **The Administration then prioritized five areas[1] to launch the Net-Zero Game Changers Initiative**:

- **Efficient Building Heating and Cooling**, including refrigerants with low global warming potential;
- **Net-Zero Aviation**, cost-competitive with conventional aviation, including electric and hybrid aircraft and sustainable aviation fuels production;
- **Net-Zero Power Grid and Electrification**, including advanced transmission and distribution systems;
- **Fusion Energy at Scale**, cost-competitive with conventional energy; and
- **Industrial Products and Fuels for a Net-Zero, Circular Economy**, including secure supply chains and alternative pathways for producing low-carbon steel, aluminum, cement, chemicals, industrial heat, clean water, and electrofuels.

These solutions are all key areas where transformative progress can help the United States reach its 2050 climate goal and support global decarbonization. They build on existing clean energy priorities at Federal agencies, such as the Department of Energy (DOE) Energy Earthshots™, which are necessary to achieve the 2030 emissions reduction goal. This set of priorities will strengthen the U.S. innovation ecosystem, cutting across economic sectors and U.S. Government research and development (R&D) programs. The priorities include opportunities for near-term wins, investments in underserved communities through the Justice40 initiative, and long-term transformation of the energy system. Leveraging the strength of U.S. science institutions including Historically Black Colleges and Universities and Minority Serving Institutions, the Net-Zero Game Changers Initiative enables the development of a next-generation clean energy workforce that looks like America.

With inclusive and intentional innovation, these initial five priorities can have significant co-benefits and advance environmental justice, enhance energy security, ensure U.S. leadership in the next generation of energy technology, and grow good-paying jobs in the United States. As a first step to accelerate rapid innovation on these priorities, the Biden-Harris Administration is:

- Enhancing coordination between Federal departments and agencies that are creating these critical climate solutions, drawing expertise from the United States' unparalleled public and private innovation ecosystem;

- Roadmapping pathways from early-stage research to widespread deployment of these game changers; and

- Leveraging clean energy innovation investments made under the Bipartisan Infrastructure Law, the CHIPS and Science Act, and the Inflation Reduction Act.

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About the Interagency Process

The creation of this document was coordinated through an interagency process under the Net-Zero Game Changers Working Group. This group is a subset of the Climate Innovation Working Group of the National Climate Task Force. The Net-Zero Game Changers Working Group is co-chaired by the White House Office Climate Policy Office, Office of Science and Technology Policy, and Office of Management and Budget, and includes members from the departments and agencies listed in Appendix A.

The list of technologies and their evaluations are a result of robust discussions across Federal departments and agencies. However, this should not be considered a final or exhaustive list of game-changing technologies. Commercial deployment of many of these technologies is critical for the United States to meet its 2050 net-zero emissions goal. Ongoing work to assess current levels of support and analyze gaps will help to determine appropriate investment levels. Nothing in this report shall be construed to impair or otherwise affect the function of the Director of the Office of Management and Budget relating to budgetary, administrative, or legislative proposals.

The Need for a Net-Zero Innovation Portfolio

Limiting warming to 1.5 ^{o}C above pre-industrial levels is the official goal of the United States in its domestic efforts as well as its work with international partners. Today, the United States and over 80 other nations — together representing almost 75% of global GHG emissions in 2019 — have committed to reaching net-zero GHG emissions around mid-century.[2] If these and other commitments are met, the world could be on a path to limiting warming to less than 2 ^{o}C.[3,4]

To limit warming to 1.5 ^{o}C will require *even faster* technology innovation, scale-up, commercialization, and deployment. **Success will require nearly complete transformation of today's energy system** — which relies on fossil fuels that emit carbon dioxide (CO_2) to meet 80% of global demand — to one that relies on zero- or negative-emission technologies. Success will also require addressing industrial, agricultural, and land management-related emissions.

Globally, the International Energy Agency (IEA) projects that by 2050 "**almost half the reductions [needed to achieve net-zero] come from technologies that are currently at the demonstration or prototype phase**."[5] In addition, many technologies needed to achieve net-zero emissions are unable to compete with incumbent fossil-based technologies without considering the cost of emissions. Technology innovation is thus needed to drive down costs, making clean energy an easy choice in the United States and across the globe.

To meet its climate commitments, the United States has a threefold action plan (as illustrated in Figure 1) to invest in:

1. Early-stage R&D for a portfolio of game-changing innovations to ensure an adequate suite of technologies to reliably, affordably, and equitably achieve net-zero emissions no later than 2050;
2. Demonstration and early deployment of technologies that are available today, but not at commercial scale; and
3. Policy measures, including regulation and financial incentives, to accelerate deployment and adoption of technologies that are available today.

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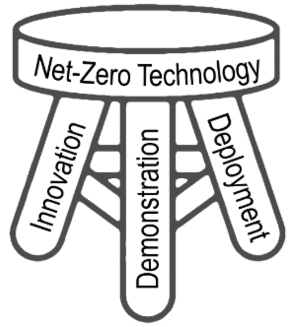
Figure 1: Threefold Strategy for Technologies Needed to Achieve Net-Zero GHG Emissions by 2050



Three recent Federal laws work together to rapidly advance these goals: the CHIPS and Science Act of 2022 expands budget authorities for R&D that can include earlier-stage net-zero innovation; the Bipartisan Infrastructure Law of 2021 enables demonstration of clean hydrogen, carbon removal, and other game-changing climate-aligned infrastructure with appropriations over several years; and the Inflation Reduction Act of 2022 accelerates deployment by pulling clean energy technology to the market through tax credits, loan guarantees, grants, and rebates. While the United States continues to demonstrate and deploy more established technologies, this report focuses on the need to **maintain a robust early-stage development pipeline of emerging technologies** which will make it substantially easier or cheaper to reach net-zero.

With a projected 13% of global GDP spent on energy in 2022[6] and over $2 trillion of annual investment (of which over half is in clean energy),[7] the economic opportunity of this once-in-a-century transformation is enormous. Nations and companies around the world are poised to seize this opportunity, and **the race for technological leadership in a decarbonized future is well underway**. With expanded public and private sector investments in climate and clean energy innovation and supportive policies to rapidly scale up commercialization and manufacturing, the United States can lead the world in the climate and energy industries of the 21st century.

This document summarizes the **national approach for the United States to identify, prioritize, and accelerate innovation in game-changing net-zero technologies** to tackle the climate crisis, support national security, advance American leadership in the future global economy, and promote equity and justice.

A Whole-of-Government Strategy for Net-Zero Innovation

Addressing every emissions source by 2050 will require unprecedented effort, scale, and creativity. GHG emissions are generated from every sector of the U.S. economy: transportation, electricity generation, industry, homes and businesses, and agriculture. Many of the U.S. Federal agencies have a critical role to play, as they have unique R&D capabilities, expertise, regulatory authorities, and procurement powers that enable them to contribute to the development and implementation of a pathway to net-zero emissions. By coordinating these efforts, the U.S. Government can increase the impact of existing investments, fill innovation gaps, and enable a competitive net-zero innovation ecosystem that delivers a sustainable, equitable, cost-effective, and secure energy system.

This is a living document that outlines key technology innovations needed for the United States to reach its goal of a net-zero GHG emissions economy by no later than 2050 and support other nations around the world in doing the same. The Climate Innovation Working Group will continually inform the National Climate Task Force about not just GHG reduction potential of net-zero technologies, but also potential benefits and challenges related to the environment, equity and justice, the economy, and security — representing **the first multi-attribute assessment of Federal net-zero R&D efforts.**

Net-Zero Game Changers

This report is focused on identifying **emerging technologies that hold promise to change the game on the path to a net-zero economy by 2050**. Game changers include the following.

- <u>New Technologies</u>: Technologies or approaches with no current commercial adoption that use physical, chemical, biological, or other processes in new ways to produce energy or provide an energy service (e.g., fusion energy).
- <u>Significantly Improved Technologies</u>: Disruptive changes in existing technologies or approaches that will make scale-up and deployment significantly more efficient, cheaper, and faster (e.g., direct air capture or efficient water treatment processes).
- <u>Critical Enabling Technologies</u>: Novel technologies or approaches that facilitate the integration of *New* or *Significantly Improved* technologies into the energy system (e.g., distributed energy resource management).
- <u>Multi-Objective Technologies</u>: *New, Significantly Improved,* or *Critical Enabling* technologies that simultaneously enable the transition to net-zero emissions and significantly improve supply chains, energy security, equitable energy access,[8] or some other weakness in the existing technology or approach (e.g., advanced battery chemistries, supply chains, and recycling).

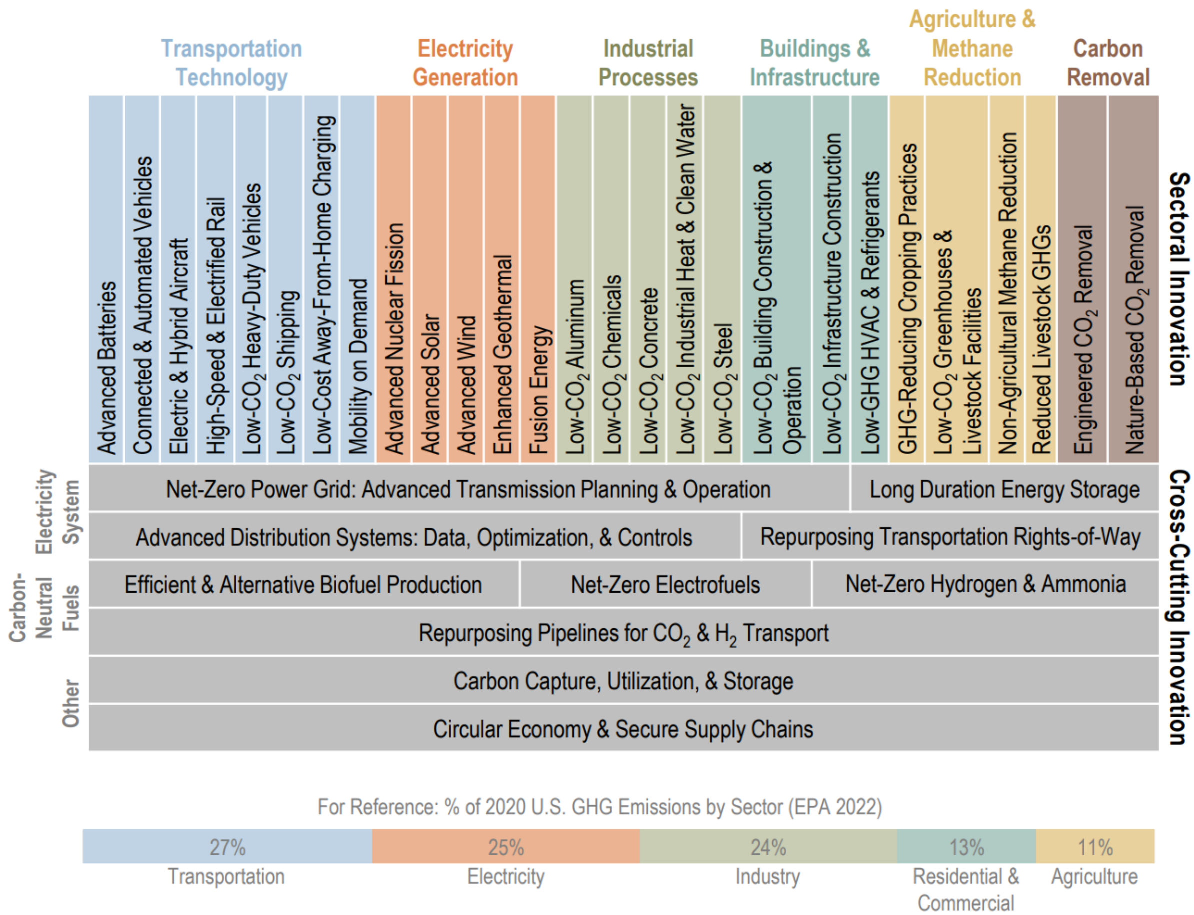
Due to the urgency of the climate crisis and the scale of the challenge, the United States must invest in multiple technological pathways to net-zero. Therefore, **a diversified portfolio is needed to ensure success** in meeting our climate commitments and capturing the opportunity for American industries to lead the global energy transition. Such a portfolio must span high-risk, high-reward technologies (such as fusion energy) to lower-risk, necessary technologies (such as low-cost away-from-home vehicle charging). It must also include nascent technologies and more established technologies in need of further improvement.

Additionally, while not a focus of this document, solutions like existing photovoltaic (PV) solar, land-based wind, energy efficiency, electric vehicles, and other commercially available technologies will still be primary drivers of decarbonization. These technologies should receive robust funding across the research, development, demonstration, and deployment continuum to increase their impact through continuous cost and performance improvements. This will ensure that U.S. and global climate goals can be achieved and the worst impacts of climate change can be avoided. Additionally, it is critical to maintain robust investment in fundamental sciences and discovery-based research that will continue to create new options for the future.

In this first iteration of this report, the Net-Zero Game Changers Working Group identified the innovations shown in Figure 2. Some game changers — referred to as cross-cutting innovations — can eliminate emissions from multiple sources (e.g., a net-zero power grid and biofuels).

Other innovations address a particular end-use sector such as net-zero steel and concrete. The diverse portfolio of solutions below — which includes both cross-cutting and sector-specific innovations — could **provide options for eliminating most, if not all, emissions across the U.S. economy, and for removing CO_2 from the atmosphere.**

Figure 2: Portfolio of 37 Net-Zero Game Changers Identified from Across the U.S. Interagency



Innovations categorized as cross-cutting (shown in gray) affect multiple sectors of the economy and therefore contribute to the foundation of a decarbonized energy system. Colors represent the sector each solution addresses, as indicated by the headings. See Appendix B for full descriptions of each of the net-zero game changers.

Prospective Benefits of Net-Zero Game Changers

The game changers and their potential impacts are summarized in Figure 3. Experts across the participating agencies performed a qualitative assessment of all of the game changers to determine their potential benefits to the environment, economy, equity, and security if they meet established cost and performance targets. Consequently, this is not an assessment of the likelihood of success, which may vary considerably, but solely the impacts if each is successful. Based on this assessment, these game changers are categorized as Transformational, Broad, or Targeted as defined below.

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- Transformational Impact: These innovations have the largest system-wide and cross-cutting benefits and will lead to major advances in emissions reductions, environmental quality, justice and equity, the economy, and security and reliability.
- Broad Impact: These innovations have benefits for one or more sectors of the economy and will lead to advances in several objectives.
- Targeted Impact: These innovations have benefits for targeted subsectors of the economy.

This categorization does not imply that broad and targeted technologies are less worthy of investment than transformational technologies. Rather, they fulfill an important but more limited role in meeting our climate goals. The urgency of the climate crisis requires a full portfolio of solutions to ensure success.

Figure 3: Identification of Net-Zero Innovations with Transformational, Broad, and Targeted Impacts

Transformational Impact	Broad Impact	Targeted Impact
Advanced Distribution Systems: Data, Optimization, & Controls	Circular Economy & Secure Supply Chains	Repurposing Pipelines for CO_2 and H_2 Transport
CO_2 Capture, Utilization, & Storage	Efficient & Alternative Biofuel Production	Repurposing Transportation ROWs
Long Duration Energy Storage	Net-Zero Electrofuels	Electric & Hybrid Aircraft
Net-Zero Hydrogen & Ammonia	Connected & Automated Vehicles	Low-CO_2 Shipping
Net-Zero Power Grid: Advanced Transmission Planning & Operation	High-Speed & Electrified Rail	Low-CO_2 Aluminum
Advanced Batteries	Mobility on Demand	Low-CO_2 Cement
Low-CO_2 Heavy-Duty Vehicles	Advanced Nuclear Fission	Low-CO_2 Chemicals
Low-Cost Away-From-Home Charging	Advanced Solar	Low-CO_2 Steel
Fusion Energy	Advanced Wind	Low-CO_2 Greenhouses & Livestock Facilities
Low-GHG HVAC & Refrigerants	Enhanced Geothermal	
Engineered CDR	Low-CO_2 Industrial Heat & Clean Water	
Nature-Based CDR	Low-CO_2 Building Construction & Operation	
	Low-CO_2 Infrastructure Construction	
	GHG-Reducing Cropping Practices	
	Non-Agricultural Methane Reduction	
	Reduced Livestock GHGs	

Legend

Cross-Cutting Innovation	Transportation Technology	Electricity Generation	Industrial Processes	Buildings & Infrastructure	Agriculture & Methane Reduction	Carbon Removal

Note that the technologies are grouped by sector and appear in alphabetical order.

This is a **first step towards a coordinated and accelerated national net-zero innovation strategy.** As this is a living document, the list of innovations will be updated as technologies advance and markets evolve. Further analyses will determine the innovations that require renewed or expanded U.S. Government effort.

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Ongoing Efforts

The unparalleled technical abilities of the U.S. public and private R&D ecosystem represent a competitive advantage in the 21st century economy. **With scaled-up investments in a diverse portfolio of game-changing technologies outlined here, the United States can leverage that ecosystem to achieve its climate objectives and improve the lives of all Americans.**

The ongoing efforts for the Net-Zero Game Changers Working Group include enhancing coordination on the five initial priorities as described above. Over the longer term, the working group will continue to track progress on these innovations, scan the horizon for emerging technologies, refine the evaluation process, and advance additional game-changing technologies.

Meeting the 2050 net-zero emissions goal of the United States requires deliberate action to accelerate the time from proof-of-concept to commercialization and radically increase the pace of deployment. To accomplish this, parallel efforts are needed to: cultivate demand for new technologies; develop supply chains; train a skilled workforce that looks like America; develop an appropriate regulatory environment; broaden public support and ensure equity, justice, and inclusion; and scale up deployment and adoption. The historic climate actions already taken by the Biden-Harris Administration — which accelerate deployment of existing technologies and demonstrate technologies on the cusp of commercialization — set the stage to super-charge the U.S. energy innovation ecosystem. **Now is the time to develop the next generation of net-zero game changers that will get us and the rest of the world quickly to net-zero emissions.**

Appendix A: Net-Zero Game Changers Interagency Working Group

Co-chairs: White House Climate Policy Office (Ali Zaidi and Sonia Aggarwal), Office of Science and Technology Policy (Sally Benson), and Office of Management and Budget (Candace Vahlsing and Tali Bar-Shalom)

Participants:

- Council of Economic Advisors (CEA)
- Department of Defense (DoD)
- Department of Energy (DOE)
- Department of Housing and Urban Development (HUD)
- Department of Labor (DOL)
- Department of State (State)
- Department of Transportation (DOT)
- Environmental Protection Agency (EPA)
- General Services Administration (GSA)
- National Aeronautics and Space Administration (NASA)
- National Economic Council (NEC)
- National Oceanic and Atmospheric Administration (NOAA)
- National Science Foundation (NSF)
- National Security Council (NSC)
- Office of the National Cyber Director (ONCD)
- United States Department of Agriculture (USDA)
- White House Office of General Counsel

Appendix B: Net-Zero Game Changers Descriptions

Cross-Cutting Innovations: Electricity System

Advanced Distribution Systems: Data, Optimization, and Controls

Today's distribution grid in most regions of the United States was designed to deliver power as demanded by homes and businesses, and it was constructed to meet peak demand with a reserve margin. With electricity demand and distributed generation increasing and climate change threatening system reliability, the requirements facing the distribution system are rapidly changing. Transformational change in electricity distribution is now needed to enable: widespread electrification of vehicles, appliances, and industry; effective integration of customers' generation, storage, and flexible demand resources (including vehicle-grid integration); and new grid architectures that improve reliability and resilience (including via dynamic management with large-scale transmission system-level resources). By providing increased flexibility for electrification and integrating variable renewables, these changes will cost-effectively reduce GHGs and other emissions. Technology needs include developing the sensors, controls, communication networks, protocol standards, data analytics through machine learning, data privacy standards, control strategies, location-specific architectures, business models, and equity strategies. DOE is leading R&D for planning, technology, and institutional issues. EPA, DOT, DOI, NOAA, and many other agencies bring critical perspectives due to their roles in siting, permitting, electrification, energy justice, and other fundamental issues associated with transformational change in the grid.

Low-Carbon, Low-Cost Long Duration Energy Storage (Daily, Weekly, Monthly, and Seasonal)

Long duration energy storage is essential to enable a 100% decarbonized power system, as it provides flexibility between when electricity is generated and when it is used. This is critical as more variable renewable electricity is deployed on the grid. While today's batteries are increasingly attractive for shifting loads a few hours (e.g., shifting solar generation to the evening peak), innovation is needed to reduce the cost and improve the performance of large-scale, long-term storage. DOE is exploring many pathways to long duration storage — including chemical, mechanical, and thermal concepts or combinations of these — and has set an Energy Earthshot™ target to reduce the cost of grid-scale energy storage by 90% for systems that deliver 10+ hours of duration within the decade.[1] Technology and manufacturing innovation to improve cost and performance will enable long duration storage, in tandem with other clean resources, to compete with flexible fossil fuel generation. It will also support expanded U.S.-based manufacturing.

Net-Zero Power Grid: Advanced Transmission Planning, Operation, and Optimization

Effective transmission expansion and grid modernization is a key enabler of a 100% clean electricity grid, allowing cost-effective and reliable integration of clean energy while meeting increased demands and improving system resiliency. Innovations are needed in transmission planning, grid-enhancing technologies, grid architecture, and operational control. Improved planning is needed at international, national, and regional levels to maximize the benefits of integrating increasingly widespread resources (including distribution-connected resources). Grid technologies (e.g., advanced sensors, controls, and dynamic line rating) are needed to improve system management and control. This allows more effective use of existing wires and electrical infrastructure and provides the flexibility needed to respond to dynamic supply and demand. DOE is leading R&D for planning and technology issues. As with advanced distribution systems, EPA, DOT, DOI, NOAA, and many other agencies bring critical perspectives on transformational change in the grid.

Repurposing Transportation Rights-of-Way for Energy Infrastructure

Repurposing existing transportation rights-of-way (ROWs) that exists between, underneath, above, or adjacent to roadways or railways offers the opportunity to accelerate siting and reduce costs of expanding the transmission system and other energy technologies. Today's Interstate Highway System extends across the United States in a 48,000-mile grid pattern, with a road density that largely mirrors population density and electricity usage. In addition, the United States boasts nearly 140,000 miles in freight rail infrastructure. Using existing transportation ROWs for transmission expansion — which is needed to affordably achieve 100% clean energy — will also strengthen the electric grid in transportation corridors to support ubiquitous electric vehicle charging. Tools and technologies should be developed to maximize and scale climate-aligned uses of transportation ROWs, such as overlaying favorable solar sites. R&D to facilitate the use of transportation ROWs includes advanced construction methods for undergrounding high-voltage and high-capacity AC and DC cables, the development of modular interconnection power electronics for grid stability and reliability, and novel energy usage technologies such as inductive charging embedded in the roadway. DOT will take the lead with potential involvement from DOE and other agencies.

Cross-Cutting Innovations: Carbon-Neutral Fuels

More Efficient and Alternative Biofuel Production

Sustainable, cost-competitive biofuels are potential near-term supplements or replacements for fossil fuels in a variety of applications (e.g., hard-to-electrify transportation and electric generation) and potential long-term enablers for CO_2 removal from the atmosphere via bioenergy with carbon capture and storage (BECCS). Innovations are needed in biomass supply, transport, and conversion to increase efficiency and decrease environmental impacts. USDA is conducting research to improve the economics of biofuel production by turning byproducts of the typical conversion process into marketable energy and non-energy products. DOE is performing research on coproducts that can be used to decarbonize the industrial and chemical sectors. EPA leads assessments of the full life cycle GHG reductions for the Renewable Fuel Standard Program, which determines qualification under that program. Additional R&D on alternative biofuel production pathways, bio-based sustainable aviation fuels, and BECCS will likely involve USDA, DOE, DOT, and EPA, along with other agencies.

Net-Zero Electrofuels, at Scale and Cost-Competitive with Conventional Fuels

Electrofuels are hydrocarbon fuels and feedstocks created by electrochemical conversion of captured CO_2 and hydrogen. Electrofuel production can be net-zero or net-negative depending on the electricity source used for the conversion process. While it is expected that most light-duty personal transportation will be electrified, some heavy-duty trucking, shipping, and aviation are likely to require energy-dense fuels such as electrofuels for the foreseeable future. These sectors collectively accounted for about 10% of 2020 GHG emissions. Electrofuels burn cleaner than fossil fuels and can be used as drop-in substitutes for jet fuel, gasoline, and diesel (potentially with additional additives or minor component retrofits). While processes exist today to create electrofuels, major improvements are needed, including better catalysts, lower-cost CO_2 capture, alternative conversion approaches, manufacturing advances, cleaner combustion processes (or non-combustion uses), abundant renewable energy, and high-performance computing for materials discovery. DOE leads this R&D with potential for future collaboration with DOI, EPA, Commerce, DoD, DOT, and other agencies.

Net-Zero Hydrogen and Ammonia, at Scale and Cost-Competitive with Conventional Fuels and Feedstocks

Net-zero hydrogen and ammonia can support decarbonization of a wide range of transportation, buildings, agriculture, and industrial systems.[2] Today, most hydrogen production in the United States uses natural gas reforming, which contributes to both CO_2 and methane emissions, and almost all hydrogen use is in industrial settings.[3] DOE's Hydrogen Shot™ is addressing the challenge of clean hydrogen production, seeking to reduce the cost of clean hydrogen by 80% to $1 per kilogram in one decade. However, additional R&D is needed on ammonia production as well as hydrogen and ammonia transport, storage, end-use technologies, pollution abatement, and leakage reduction. The DOE Hydrogen and Fuel Cell Technologies Office is leading R&D in this space, with recent efforts including the development of a draft DOE National Clean

Hydrogen Strategy and Roadmap and a draft guidance for a clean hydrogen production standard in compliance with the Bipartisan Infrastructure Law.[4] Additional R&D on breakthrough approaches to reduce the cost of ammonia production has been funded by DOE's Advanced Research Projects Agency–Energy (ARPA-E). Offices throughout DOE, including the new Office of Clean Energy Demonstrations, are funding R&D to advance the use of hydrogen in diverse sectors, including industry, heavy-duty transportation, and energy storage.

Repurposing Pipelines for CO_2 and Hydrogen Transport

Clean hydrogen and captured CO_2 are critical for reaching net-zero by 2050. They also both require specialized transport approaches, one of which is in pipelines. Repurposing existing pipelines using in-situ construction and modernization techniques can facilitate this emerging alternative fuel enterprise, reduce the requirement for large amounts of new construction materials, and accelerate the net-zero transition. The United States has a very comprehensive existing pipeline network for the transport of natural gas as well as liquids (including crude and finished petroleum products such as diesel fuel and gasoline). An improved understanding of materials compatibility, development of in-situ pipeline repair processes and/or coatings, and new methods of robotic construction can facilitate conversion of pipelines for hydrogen and CO_2 transport. DOT (including its Pipeline and Hazardous Materials Safety Administration, PHMSA) and DOE (including its natural gas blending initiative, HyBlend; Hydrogen Materials Compatibility Consortium, H-Mat; and its evaluation of repurposing existing oil and gas infrastructure for CO_2 transport) will take the lead with potential support from the Department of Commerce and others.

Cross-Cutting Innovations: Carbon Capture, Utilization, and Storage

Point-source carbon capture, utilization, and storage (CCUS) is a cross-cutting solution that can be used to decarbonize industrial processes such as steel, cement, hydrogen, aluminum, and chemical production, as well as electricity production. The U.S. Long-Term Strategy anticipates between about 400 and 1,300 million metric tons (MMT) per year of CCUS will be needed in 2050 to meet our net-zero goals. Today, 27 projects around the world are capturing and storing 36 MMT/year of CO_2 in subsurface geological formations.[5] While technologies for capture, utilization, and storage exist today, they add considerable costs to manufacturing operations and electricity generation. If the cost for CCUS could be reduced to less than $30/ton for dilute sources, the cost difference would be sufficiently small to have only a minor impact on the price of electricity or final manufactured goods. In addition to reducing cost, innovation could lead to improved technologies, processes, or approaches for CCUS that further reduce or eliminate air emissions, reduce or eliminate water consumption, accelerate mineralization or other stabilization processes in the subsurface, and provide uses for captured CO_2 as permanent storage alternatives. DOE is leading development and demonstration of CCUS technology in collaboration with EPA, with support from USDA (CCUS associated with biofuel production) and DOI (projects on public lands).

Cross-Cutting Innovations: Circular Economy Innovation and Secure Supply Chains

Circular Economy Innovation (CEI) involves designing products and processes to increase recirculation of materials and products. CEI can reduce hard-to-abate emissions associated with goods production and land management, which account for nearly half of all global GHG emissions.[6] At the same time, it can help alleviate supply chain issues, reduce environmental justice concerns from mineral extraction, and reduce waste and pollution. This is particularly important as the United States scales up deployment of renewables, batteries, and other advanced technologies whose supply chains rely on critical materials. CEI is not a single solution — for every sector of the economy, there is a set of needed innovations related to materials, products, and systems. A comprehensive analysis of circular economy innovations and applications as well as an overall national framework are needed. This effort will require a coordination between many Federal agencies, including but not limited to DOE, NSF, EPA, USDA, NOAA, NIST, and the Department of State.

Transportation Technology Innovation

Advanced Battery Chemistries, Supply Chains, and Recycling, at Scale and Cost-Competitive with Today's Energy Storage

The battery market is expanding to support a range of applications, but its supply chains are heavily reliant on raw materials that are rare and have environmental and humanitarian concerns. For one of the major growth sectors, passenger electric vehicles (EVs), raw material costs may limit further reductions in battery costs. Innovation is needed to further improve battery cost and performance, as well as address environmental and social concerns with supply chains of cobalt, lithium, copper, and other minerals. Innovative battery recycling processes that are easier, safer, and more efficient can also reduce demand for critical materials altogether. Improved battery costs, performance, and lifetimes will accelerate their use in light-, medium-, and heavy-duty vehicle fleets as well as stationary storage to support variable renewable electricity, microgrids, and residential and commercial applications. Additionally, these applications have varying needs that can be met by alternative battery chemistries. For lithium battery concepts, DOE has developed a National Blueprint for Lithium Batteries[7] which summarizes the status and Administration goals to 2030. Future research could explore whether advanced battery development can be directed to difficult-to-decarbonize subsectors where current battery technology is considered insufficient and low-carbon fuel applications have limitations. DOE's Vehicle Technologies Office and national laboratories are primarily leading on R&D for advanced batteries and recycling.

Connected and Automated Vehicles

Connected vehicles (CVs) use advanced sensors, digital infrastructure, and interoperable connectivity capabilities to enable sharing of precise location data and other information between vehicles and infrastructure. This can enable efficient routing, reduce congestion, and avoid crashes.[8] Automated vehicles (AVs), which may or may not be connected, shift some or all driving functions from human drivers to the vehicle, and could reduce energy use through eco-driving, platooning, reducing crashes, enhancing transit, and increasing ridesharing, but could also increase energy use through additional travel. Estimates on the fleetwide energy and emissions reduction potential of CVs and AVs are uncertain, with a range of negative 60% to positive 200% depending on assumptions and the implementation of policies to encourage shared rides.[9] When combined with policies that maximize vehicle utilization, minimize empty miles, and incentivize using electricity or zero-carbon fuels, AVs have significant potential to decarbonize the transportation system, as road vehicles emit 22% of all U.S. GHGs. In addition to policy innovation and processes to ensure equity, technological developments are needed in the following areas to achieve the full emissions reduction potential of CVs and AVs: infrastructure digitalization and interoperable connectivity, sensing, systems integration, and communications. DOT leads on the R&D for CVs and AVs with potential involvement from DOE, DoD, NIST, and others.

Electric and Hybrid Electric Aircraft (Including Batteries and Fuel Cells), Cost-Competitive with Conventional Aviation

Air travel represented about 4% of U.S. GHG emissions and 11% of U.S. transportation emissions in 2020,[10] and emissions from the sector are expected to continue to grow in the United States and around the globe. About 90% of the world's population does not yet travel by air, underscoring the need for carbon-free solutions in this sector.[11] Opportunities to decarbonize aviation include sustainable aviation fuels (which are described under the carbon-neutral fuels section above) and electrification. Currently, some small electric, hybrid, and fuel cell planes are in the experimental, prototype, and certification stages. These types of electrified propulsion systems are also used by the advanced aerial mobility community, which is developing small electric vertical takeoff and landing aircraft, with and without human operators. The motor and electric system development from the smaller aircraft applications can also inform implementation of hybrid electric propulsion systems on large transport aircraft. Improvements in engineering, materials, energy storage, performance, safety, and costs are needed for viable commercial electric, hybrid, and fuel cell aircraft at scale. In 2019, NASA and DOE performed a joint assessment of research and development needs to accelerate the commercialization of electric propulsion.[12] NASA leads on aeronautics research, with potential involvement from DOE, DOT, and EPA.

High-Speed Rail and Railroad Electrification

Rail is a very safe and efficient transportation mode and the backbone of freight movement in the United States. Rail accounts for about 2% of U.S. transportation emissions[13] and is significantly more amenable to electrification than aviation or marine transportation. Widespread development and adoption of inter-city high speed rail (and even traditional inter-city rail to a lesser degree) in the United States has the potential to reduce the demand for energy- and GHG-intensive transportation modes such as short-haul aircraft trips, truck freight, and long-distance passenger car travel. Additionally, rail electrification paired with a clean electricity grid offers a zero-emission transportation option. However, access to rights-of-way for new passenger and freight rail lines remains a challenge. R&D is needed to advance domestic rail electrification, including innovative new electric traction motors, power electronics, and high-precision rapid construction techniques that employ both traditional and emerging materials. Additionally, the United States needs to rebuild domestic rail equipment supply chains to manufacture next-generation electric and alternative fuel locomotives, rolling stock, infrastructure, and fuels. DOT leads on R&D for rail electrification.

Low-Carbon Shipping, Cost-Competitive with Conventional Shipping

Ocean freight shipping currently accounts for 3% of global emissions,[14] and there are no scaled solutions to substantially reduce emissions. Zero-carbon shipping fuels or electrification could address the carbon emissions and air pollution associated with the shipping sector, but one fuel or technology application will not fit all vessels. Retrofitting ships to run on zero-carbon fuels is feasible but costly, and the ease of conversion will vary based on fuel type and operating profiles. Further research and innovation are required for vessels, fuels, and infrastructure to bring down costs, ramp up performance, abate pollutants, reduce leakage of gases with high global warming potential (GWP). Innovation is also needed to accelerate the transition to lower-carbon fuels, address market gaps, and build needed infrastructure. DOT's Maritime Environmental and Technical Assistance (META) program has supported a wide array of R&D efforts that address GHG reductions within the maritime sector, including collaborative efforts with DOE and other agencies. In addition, DOE performs shipping R&D through its Vehicle Technologies Office and Hydrogen and Fuel Cell Technologies Office.

Low-Carbon Heavy-Duty On- and Off-Road Vehicles

Heavy-duty vehicles (HDVs) include on-road vehicles such as freight trucks and delivery vehicles as well as off-road construction, mining, and agricultural equipment. Together, these vehicle types accounted for about 11% of U.S. emissions in 2020.[15] The transition of the HDV sector to zero-emission vehicles is not only essential for decarbonization, but also to reduce the air pollutants that contribute to poor air quality (especially in overburdened communities) and to maintain U.S. economic competitiveness. Decarbonizing HDVs is possible through continued improvements in vehicle and fuel technology performance and cost, with potential solutions including battery and fuel cell electric vehicles and carbon-neutral fuels. A deeper understanding of real-world operation and requirements is needed to identify viable pathways at the vehicle and system level, including the opportunities for improved energy efficiency (e.g., through energy recovery on repetitive motions). For on-road vehicles in particular, widespread deployment is also dependent on the availability and cost of charging and fueling infrastructure. Further, integrated simulation of freight traffic demands on distribution and transmission systems is needed to adequately plan for proactive construction of grid upgrades. DOE’s Vehicle Technologies Office and national laboratories lead with on- and off-road HDV decarbonization R&D, and several additional agencies such as DOT, DoD, EPA, and USDA also contribute in this area.

Low-Cost Away-From-Home Vehicle Charging

Light-duty vehicles (LDVs) contributed 57% of 2020 transportation sector GHGs.[16] The transition of the LDV sector to zero-emission vehicles powered by clean electricity is not only essential for decarbonization. It can also help reduce household energy burdens, support broader end-use electrification, and increase electric system resiliency. Widely available charging infrastructure in public spaces and at long-dwell locations is essential for EV adoption among drivers who lack access to home charging. Achieving very low-cost, accessible charging requires maintaining a low cost of delivered electricity as well as a drastic reduction in the time to deploy charging infrastructure. Required innovations include: reduction in costs of equipment, electrical hardware, controls software, and permitting; testing for, and the standardized acceptance of, reliable load management systems that avoid coincident demand on a circuit; and innovative concepts such as combining wireless or robotic charging with Level 4 and Level 5 automation, bidirectional and vehicle-to-vehicle charging, or battery swapping. DOE leads vehicle charging R&D through its Vehicle Technologies Office, and the Joint Office of Energy and Transportation between DOE and DOT will support deployment.

Mobility on Demand

Public mobility options, specifically buses and shuttle buses, are relatively efficient in terms of energy consumed per passenger-mile of service and are amenable to electrification due to the relatively short distances traveled by each vehicle per hour of operation. Improving access to and service of public transit encourages mode switching from individual passenger vehicles (which account for 16% of all U.S. emissions),[17] making it an essential pathway to reducing transportation GHGs. On-demand transit — which involves smaller buses and vans combined with dynamic routing — could reduce costs, increase energy efficiency, and address a variety of other transit problems which limit equity and access.[18] When combined with electrification, it can further reduce emissions. Beyond the electrification of the public mobility fleet, advances are needed in the dispatching and routing of on-demand vehicles. New and highly computationally efficient eco-routing algorithms need to be developed and implemented to improve the cost, utility, and efficiency of on-demand transit. Other research needs include developing cost-effective, purpose-built smaller transit vehicles (which can be conventional or automated vehicles) and exploring opportunities for on-demand transit vehicles to extend and complement existing public transportation systems. DOT leads on R&D for mobility on demand.

Electricity Generation Innovation

Advanced Nuclear Fission

Advanced fission reactors incorporate numerous innovations relative to existing nuclear plants, including: smaller sizing (including small modular reactors and microreactors); additional safety features such as alternative coolants, accident-tolerant fuels, and digital controls; and reductions in nuclear waste volumes and decay periods. Advanced fission reactors require low amounts of area per megawatt and the siting does not depend on availability of local energy resources such as sun or wind. As a result, advanced fission reactors could directly replace emitting firm generation sources, thereby potentially reducing the need for transmission expansion and providing a new source of jobs for legacy energy communities. As heat sources with wide ranges of possible sizes and temperatures, they can serve the specific needs of hard-to-abate industrial sectors such as petroleum refining, chemicals, and steel. Advanced fission reactors can also be used for heating and cooling and to produce hydrogen and other alternative fuels. The main technological next steps are ensuring adequate nuclear fuel supply (specifically high-assay low-enriched uranium for most types of advanced reactors), building demonstration units, and establishing a long-term nuclear waste strategy. This work is led by DOE's Office of Nuclear Energy.

Advanced Solar Power

The United States commercialized the solar panel during the Space Race, and while the solar industry has since grown exponentially, the percentage of solar panels manufactured in America has declined from 13% in 2004 to less than 1% today.[19] Over the past twenty years, one technology has dominated the solar PV market: silicon solar cells. Silicon PV far exceeded expectations for performance improvements and cost reduction. However, new innovation can deliver even cheaper and more versatile solar power technology that can be competitively produced in America. Innovative thin-film solar cells, including solid-state perovskite, use materials that are abundant and could be easier and less energy-intensive to manufacture. They also show potential to have higher efficiencies than traditional silicon PV cells, and could have even higher efficiency when used in tandem with silicon.[20] To achieve a step-change in solar power technology, R&D is needed to further improve performance, stability, durability, and manufacturing and validation processes for these next-generation solar concepts.[21] DOE is leading this work through its Solar Energy Technologies Office.

Advanced Wind Power

Advanced wind technology, including both offshore and next-generation land-based concepts, can have a vital role in meeting national and state net-zero goals. U.S. *offshore* wind potential alone is estimated at about 2,500 gigawatts,[22] and the Biden-Harris Administration has a goal of 30 gigawatts of offshore wind operating in 2030. As offshore deployments are accelerating around the world, the United States has been at the forefront of floating technology in particular, and can build on its talented labor force and revitalize its manufacturing, maritime, and transmission sectors to bring this technology to its shores. Additional R&D is needed to lower manufacturing and material costs, reduce the weight of mooring and array design, increase energy production, and advance high-voltage direct-current technologies and control systems for long distance transmission. In addition, to support this nascent industry, U.S. port infrastructure must be developed and U.S.-flagged crew and supply vessels must be constructed. To advance these efforts, DOE launched a Floating Offshore Wind Shot™ to reduce the cost by at least 70% to $45 per megawatt-hour in deep waters by 2035. Beyond expanded offshore wind capacity, the United States can also unlock significant additional onshore resources by transforming land-based wind technology to be a cost-effective option in every region in the nation. Examples of critical innovations needed are in next-generation materials, advanced manufactured designs, and AI-driven control systems, as well as distributed form factors. This R&D is led by DOE's Wind Energy Technologies Office.

Enhanced Geothermal Systems

Geothermal energy fills a critical clean-firm energy need as an available low-waste, carbon pollution-free, and dispatchable power source. It is estimated that over 5,000 gigawatts of potential continuous, zero-emission geothermal power exists within the United States.[23] However, less than one-thousandth of this potential is currently deployed and those resources are limited to a few states in the western United States.[24] Unlocking the vast potential of geothermal energy requires significant cost reductions through technology improvements in Enhanced Geothermal Systems (EGS). In addition to power generation, these technology advancements could enable utilization of geothermal energy for industrial process heating, district heating and cooling, and underground thermal storage. Further, advances in subsurface engineering can have spillover benefits for CCUS and nuclear waste disposal technologies. EGS projects require the skills and geological engineering expertise that already exist in America's oil and gas workforce and thus present opportunities for these workers. EGS R&D should target three critical areas: high-precision subsurface observation and prediction with improved sensors and computational tools; durable, efficient reservoir development with advanced drilling; and expansion of the large-scale demonstration portfolio. To advance this, DOE launched an Enhanced Geothermal Shot™ with a cost target of $45 per megawatt-hour by 2035. This work is currently led by DOE through its Geothermal Technologies Office, and the Department of the Interior can contribute in the future.

Fusion Energy at Scale

Fusion energy has the potential to be a globally scalable, on-demand, and sustainable zero-carbon source of primary energy that can support a worldwide energy transition. Fusion can offer energy diversity and security for nations, and potentially ease the expansion of renewables by offering grid stability. Fusion uses abundant fuels (e.g., deuterium and lithium) and could potentially be designed to produce little or no long-lived radioactive waste. It may require less land than renewables and could potentially be sited near or within population centers. As costs come down, fusion can address an increasingly large fraction of the electricity market and help decarbonize other energy sectors that rely directly on process heat, such as industrial processes, synthetic fuel production, and desalination. Much R&D remains to be done, especially in the following areas: achieving a net-gain fusion plasma for longer durations; developing the first-wall materials and operating scenarios for handling extreme heat and particle exhaust with acceptable maintenance cycles, economics, and waste management; and developing a sustainable, safe, and licensable fuel cycle. Within the past decade, significant market pull (represented by over $5 billion of cumulative private investments) and technical readiness of the science and enabling technologies warrants a new U.S. strategy for fusion energy R&D. This was discussed at a recent White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy,[25] at which DOE announced a new Department-wide, cross-cutting initiative to coordinate fusion energy R&D activities.

Industrial Processes Innovation

Low-Carbon Aluminum Production, at Scale and Cost-Competitive with Conventional Pathways

Primary aluminum production involves difficult-to-abate process emissions stemming from the use of carbon electrodes, but most of its emissions are indirect electricity emissions. It is a highly energy-intensive process, requiring about ten times as much energy per metric ton to produce as steel, for example.[26] Efforts to decarbonize the aluminum industry involve reducing energy intensity, switching to zero-carbon electricity sources, and developing alternative anode materials. Not only does reducing the energy intensity help with decarbonization, but it also gives the United States a competitive advantage in aluminum production, as about one-third of production costs are from energy.[27] Solutions for reducing energy intensity include increasing efficiency, increasing the proportion of recycled materials, and scaling up alternative pathways to aluminum production that can reduce energy consumption and accommodate more variable electricity sources. DOE leads R&D in this space through the Advanced Manufacturing Office.

Low-Carbon Chemical Production, at Scale and Cost-Competitive with Conventional Pathways

Chemical production in the United States generated more direct GHG emissions in 2020 than steel, aluminum, and cement combined, about 190 MMT of CO_2-equivalent (CO_2e).[28] Further, demand for many chemicals is expected to increase over the next decades, especially plastics. Chemical production is a diverse industrial category including many different processes which each require different decarbonization solutions. However, there are approaches that can reduce emissions across many chemical types, including circular economy efforts to reduce overall demand, low- or zero-carbon feedstocks, and carbon capture. The United States is home to many leaders in advanced and high-value chemical production and can explore expanding low-carbon practices through industrial hubs. DOE is a leader in chemical production R&D through its Advanced Manufacturing and Bioenergy Technologies Offices, including initiatives such as the plastics innovation challenge and the BOTTLE consortium.

Low-Carbon Concrete Production, at Scale and Cost-Competitive with Conventional Pathways

Emissions from cement production are driven by both fossil fuel combustion and the chemical process itself. Cement production in the United States generated about 70 MMT CO_2e in 2020.[29]

The U.S. cement industry is highly centralized and has not pursued any net-zero-aligned pathways at scale to date. While there are no mature solutions, there are several pathways in the development stage, including alternative cement chemistry, switching inputs, using alternative heat sources, or carbon capture and storage. As with aluminum and chemicals, DOE will be a likely leader on cement decarbonization. DOT will also play a leading role in scale-up through its large concrete procurement power and Sustainable Pavements Program.

Low-Carbon Industrial Process Heat and Clean Water

Steel, cement, and chemical production, as well as water treatment and other energy-intensive industrial processes, all require process heat. Industrial process heat traditionally has been created by direct fossil fuel combustion. Direct burning of fossil fuels for industrial processes led to about 780 MMT CO_2e in 2020, a majority of which is attributable to process heat.[30] Near-term efforts are needed to maximize efficiency while industries transition to low-carbon solutions, including: electrification; alternative fuel sources such as hydrogen, concentrating solar power, or geothermal energy; or novel processes based on biology or alternative chemistry.[31] Systems and technological innovations are also needed for energy-intensive water processes such as desalination and wastewater treatment. Emissions from process heat have been difficult to abate from a technical as well as an economic perspective, due to the relatively low price of fossil fuels, capital intensity of manufacturing facilities, and long timelines associated with facility turnover on the order of 50 to 100 years. Alternative approaches must therefore be more efficient and significantly lower-cost to enable the industry to switch. To advance these efforts, DOE launched an Industrial Heat Shot™ to develop cost-competitive technologies with at least 85% lower GHG emissions by 2035. DOE is currently the leader on industrial process heating R&D through its Advanced Manufacturing Office. DoD, USDA, and NIST also support manufacturing R&D.

Low-Carbon Steel Production, at Scale and Cost-Competitive with Conventional Pathways

The traditional process for producing primary steel from iron ore is heavily dependent on fossil fuels. About half of the emissions from primary steel is inherent to the chemical process and the other half is caused by fossil fuel combustion to reach high temperatures, both of which are difficult to abate. A significant portion of U.S. steel production is now secondary steel, which uses recycled materials in an electric arc furnace and has lower GHG intensity. All iron and steel production methods in the United States emitted about 70 MMT CO_2e in 2020.[32] As demand grows, there will likely not be a sufficient supply of recycled material to eliminate the need for primary steel production, so novel processes are needed for steel production. A number of solutions are under development, including carbon capture, direct reduction with hydrogen, and electrolysis. Further R&D is needed to make these alternative pathways technically feasible and cost-competitive with conventional methods, which is especially important to maintain global competitiveness. DOE is a leader in steel production R&D through its Advanced Manufacturing Office.

Buildings and Infrastructure Sector Innovation

Low-Carbon Building Construction and Operation at Comparable Cost, Including Carbon-Negative Construction Materials

The use of low-carbon or even carbon-negative building materials and construction processes, coupled with more efficient and electrified appliances, could significantly reduce the life cycle emissions of commercial and residential buildings while increasing energy and material efficiency. To make carbon-negative building materials market-competitive, additional R&D is needed to lower costs and improve performance. More sophisticated fabrication techniques, off-site manufacturing processes, and robotics could also help reduce the carbon footprint of building construction. New construction methods and building designs that maximize structural efficiency and reduce the amount of necessary material is an area ripe for innovation, as is the optimization of material size modules to minimize waste. The Federal Government has significant purchasing power for building materials and appliances, which could create new markets for climate-friendly alternatives. DOE already funds R&D for carbon-negative building materials and advanced construction techniques, but achieving net-zero buildings at a comparable cost and at scale will require additional effort and interagency collaboration with standard-setting organizations and state, local, and Tribal governments to establish technology-agnostic, performance-based standards.

Low-Carbon Concrete Infrastructure Construction, Cost-Competitive with Conventional Pathways

As demand for climate-resilient infrastructure increases in the coming years, reducing the carbon intensity of infrastructure construction will be increasingly important for reaching net-zero. While promising advances in the development of low-embodied carbon cementitious materials have been made in recent years, concrete construction methods have barely changed in decades, if not centuries. To reduce the life cycle energy consumption and emissions associated with infrastructure, novel concrete construction methods that move beyond conventional slip-forming, casting, or pre-casting methods are necessary to increase both energy and material efficiency. For example, the application of additive manufacturing techniques to cementitious materials has shown promise, but the structural properties of the end product must be improved. Reductions in construction waste, the use of recycled materials, and other methods could also be crucial to reduce the carbon footprint of infrastructure construction. DOT's Office of the Assistant Secretary for Research and Technology (OST-R) coordinates internal research efforts on this front, while DOE, DoD, NIST, and others are involved as well.

Low-GHG Building Heating and Cooling, Including Low-GWP Refrigerants

The commercial and residential sectors contributed about 13% of direct U.S. GHG emissions in 2020.[33] In this space, building heating, ventilation, and air conditioning (HVAC) is responsible more than half of residential building energy use and nearly a fifth of commercial building energy use.[34] Despite recent improvements to the energy efficiency of buildings, most electrical equipment in use today in the United States is still inefficient. In addition, conventional refrigerants are among the most potent greenhouse gases,[35] contributing about 13% of commercial and residential CO_2-equivalent emissions in 2020.[36] There are several approaches to reducing or eliminating GHG emissions from building HVAC, including air-source, water-source, and geothermal heat pumps[37] as well as district energy systems. Replacing traditional HVAC systems with any of these types of heat pumps, for example, could reduce GHG emissions while improving energy efficiency and lowering energy bills. However, innovation is required to reduce upfront costs to enable widespread adoption, especially in communities with high energy burden.[38] Another area for innovation is automated control systems that respond to grid signals, shifting their operating times to lower electric bills and increase grid reliability. Key challenges include the efficacy of air-source heat pumps in cold climates, the switch to refrigerants with low global warming potential (GWP), and the ability to retrofit existing buildings. Improving building envelope efficiency is also an important consideration for reducing heating and cooling loads and making heat pumps economic in more regions. DOE is the lead agency in this area, with NIST, HUD, EPA, and GSA as key supporting agencies.

Agriculture and Methane Reduction Innovation

Super-Sequestering Crops and Farm Practices that Dramatically Reduce GHGs

Crop cultivation in the United States contributes over half of agricultural GHG emissions and around 6% of total emissions.[39] In addition, nitrogen fertilizers are produced from methane and their use is associated with emissions of N_2O (a potent GHG), nitrogen contamination of ground water, and ozone depletion. One pathway to reducing crop cultivation emissions is developing perennial grain crops that sequester carbon, reduce energy required for annual planting, and are better at capturing soil nitrates, allowing reduced fertilizer inputs. Other solutions include enhanced photosynthesis, microbial amendments, and crops with root systems that store more carbon. To address emissions from nitrogen fertilizers, approaches include nitrogen-fixing crops such as cereals, cover crops that store nitrogen and nutrients, and biochar technologies that displace synthetic fertilizers and reduce open burning of wood waste. These mitigation pathways all can improve soil health and environmental quality, and some could create a net removal of CO_2 from the atmosphere. General areas where R&D is needed are genome sequencing and editing and microbe characterization. USDA and DOE (through the ARPA-E ROOTS program) currently lead R&D for GHG-reducing agricultural processes.

Net-Zero Greenhouses and Livestock Facilities

In addition to direct emissions from cattle management and crop cultivation, energy-related emissions from agricultural facilities must also be addressed to reach net-zero. Indoor facilities have a range of benefits for food production. For example, greenhouses offer a solution to increased food production demand and enable more efficient water and nutrient use, among other benefits. Climate-controlled livestock facilities can also increase animal comfort and productivity. Both of these types of climate-controlled facilities may become more important as the climate warms and heat waves become longer and more severe. However, these traditional facilities often use fossil fuels to operate, would benefit from efficiency improvements, have significant maintenance costs, and often have a short lifespan. USDA is exploring approaches to address greenhouse energy use with integrated solar power generation coupled with underground heat well systems. Solar integrated with heat wells also has many potential applications to infrastructure other than agricultural facilities, including residential buildings and parking lots.

Strategies to Reduce or Eliminate Non-Agricultural Methane Emissions

Landfills, abandoned mines, and abandoned oil and gas wells contribute an estimated 120 MMT CO_2e per year.[40] Coalbeds that outcrop or are near the surface also create significant but unquantified emissions. Further, reservoirs are the fourth largest anthropogenic methane source in some regions.[41] Methods to more cost-effectively and efficiently measure and reduce and/or capture these emissions are needed. For point-sources of emissions, such as from abandoned wells, locating and plugging them with cement can be an effective approach for reducing emissions. For landfills, GHG emissions can be reduced by eliminating organic wastes from entering the landfill through options such as separation and combustion or anaerobic digestion. Landfill gas (LFG) can also be captured, converted, and used – including for electricity generation and combined heat and power, for direct use in industrial applications, or for upgrading to more energy-dense renewable natural gas. More innovation is needed to advance new applications for landfill gas,[42] and also for measuring and reducing methane emissions from large diffuse sources such as oil and gas systems, coalbeds, abandoned well fields, and reservoirs. EPA leads on R&D for methane measurement and remediation and DOE also conducts research on methane capture and waste diversion strategies.

Strategies to Reduce or Eliminate Livestock GHG Emissions

Enteric methane emissions from ruminant livestock, mostly produced by microbial decomposition and fermentation of food in digestion and released through burps, comprise 28% of agricultural emissions and 3% of total U.S. GHG emissions.[43] Manure, which can be reused in fertilizer, is another significant source of methane and N_2O emissions at livestock facilities, accounting for 13% of agricultural emissions.[44] USDA is exploring multiple pathways to reduce these emissions. Enteric methane emissions can be reduced by drugs and feed additives. One approach is bacterial supplements that reduce negative side effects of nitrates in feed. While nitrates can prevent methane production in ruminants, they can result in poisoning if used in excess, are associated with decreased feed intake (and thus animal productivity), and also add cost. Another pathway is exploring algae-based food supplements, which show promise to improve feed efficiencies and milk yields while potentially reducing methane burps by more than 80% and offering a lower carbon footprint for feed production. FDA is an important partner in these efforts. For manure management, USDA is testing integrated bioreactor systems which reduce emissions and nutrient loss, potentially making fertilizer output more competitive relative to synthetic fertilizers.

Carbon Dioxide Removal

Engineered Carbon Removal Solutions Deployed at Scale

Engineered carbon dioxide removal (CDR) includes many pathways, such as: BECCS, direct air capture with storage (DACS), biological methods to produce long-lived bio-based products and biomass sequestration, ocean-based removal strategies,[45] and enhanced mineralization. Some CDR approaches still lack demonstrated verification techniques required for large-scale deployment, and the potential environmental consequences of deployment at scale have not been fully evaluated in some cases. The United States needs to reduce the costs of CDR, develop technologies and methods for rigorous measurement, reporting, and verification of full life cycle emissions, and ensure that secure geologic storage and enabling technologies can support removal at the gigaton scale. DOE has launched a Carbon Negative Shot™ target to achieve scalable CDR under $100 per metric ton within a decade. DOE already supports CDR R&D through its Offices of Energy Efficiency and Renewable Energy, Science, Fossil Energy and Carbon Management, and Clean Energy Demonstrations, as well as ARPA-E.

Nature-Based Carbon Removal Solutions Deployed at Scale

Nature-based CDR includes a wide range of approaches, including reforestation, afforestation, sustainably managed forests and long-lived wood products, restoration of coastal and wetland ecosystems, and ocean-based approaches. According to a recent study, the removal potential from U.S. terrestrial systems is over a gigaton of CO_2e per year, [46] or about 20% of 2020 emissions. Many of these nature-based approaches are designed to restore ecosystems and have significant co-benefits, including enhanced biodiversity, ecosystem services, and climate resilience. Capture costs for nature-based solutions are expected to be lower than current costs for engineered CDR, and many nature-based solutions are ready to deploy today. However, there will be additional costs for monitoring, reporting, and verifying the amount and permanence of the carbon removed from the atmosphere. R&D is needed to advance carbon cycle science, develop measurement and monitoring tools, and determine capital and operating costs, co-benefits, and risks. Standards are also needed for life cycle assessments and verification processes. The National Academies of Sciences, Engineering, and Medicine has also identified research priorities for nature-based CDR.[47] To advance efforts in this area, DOE has launched a Carbon Negative Shot™ target to achieve scalable CDR under $100 per metric ton within a decade. The current R&D activities are distributed across a number of agencies, including DOE, EPA, USDA, DOI, NOAA, and NSF.

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[1] Note that this list of 5 priorities consolidates some of the 37 net-zero game changers into larger coordinated research areas. The game changers included in each priority are listed after the bolded title.
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[7] IEA (2022). "World Energy Investment 2022." https://www.iea.org/reports/world-energy-investment-2022.
[8] Energy access includes access to electricity, building heating and cooling, and transportation for both residential and commercial uses. Access to these forms of energy is critical for economic development and improved quality of life.
[1] DOE (2022). "Storage Innovations 2030." https://www.energy.gov/oe/storage-innovations-2030.
[2] Henbest et al. (2021). New Energy Outlook. *BloombergNEF*. https://about.bnef.com/new-energy-outlook/#download.; IRENA (2020). "Global Renewables Outlook: Energy Transformation 2050." https://www.irena.org/publications/2020/Apr/Global-Renewables-Outlook-2020. On a global scale, studies indicate the potential for hydrogen to enable 10% to over 20% of global GHG emissions reduction based on market adoption across sectors.
[3] Alternative Fuels Data Center (2022). "Hydrogen Production and Distribution." https://afdc.energy.gov/fuels/hydrogen_production html.
[4] DOE is also implementing $9.5 billion in Bipartisan Infrastructure Law hydrogen-specific funding, including $1.5 billion for both electrolysis and clean hydrogen technology manufacturing and recycling, and $8 billion for at least four regional clean hydrogen hubs.
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[15] EPA. (2022). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020. U.S. Environmental Protection Agency, EPA 430-R-22-003. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020. The EPA inventory reports emissions for medium- and heavy-duty on-road vehicles (8% of U.S. emissions), but off-road vehicle emissions are attributed to the industry and agriculture sectors. For this report, off-road vehicle emissions were calculated to be about 3% of U.S. emissions based on data for off-road fuel use and fuel emissions factors that were reported in the EPA inventory.
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