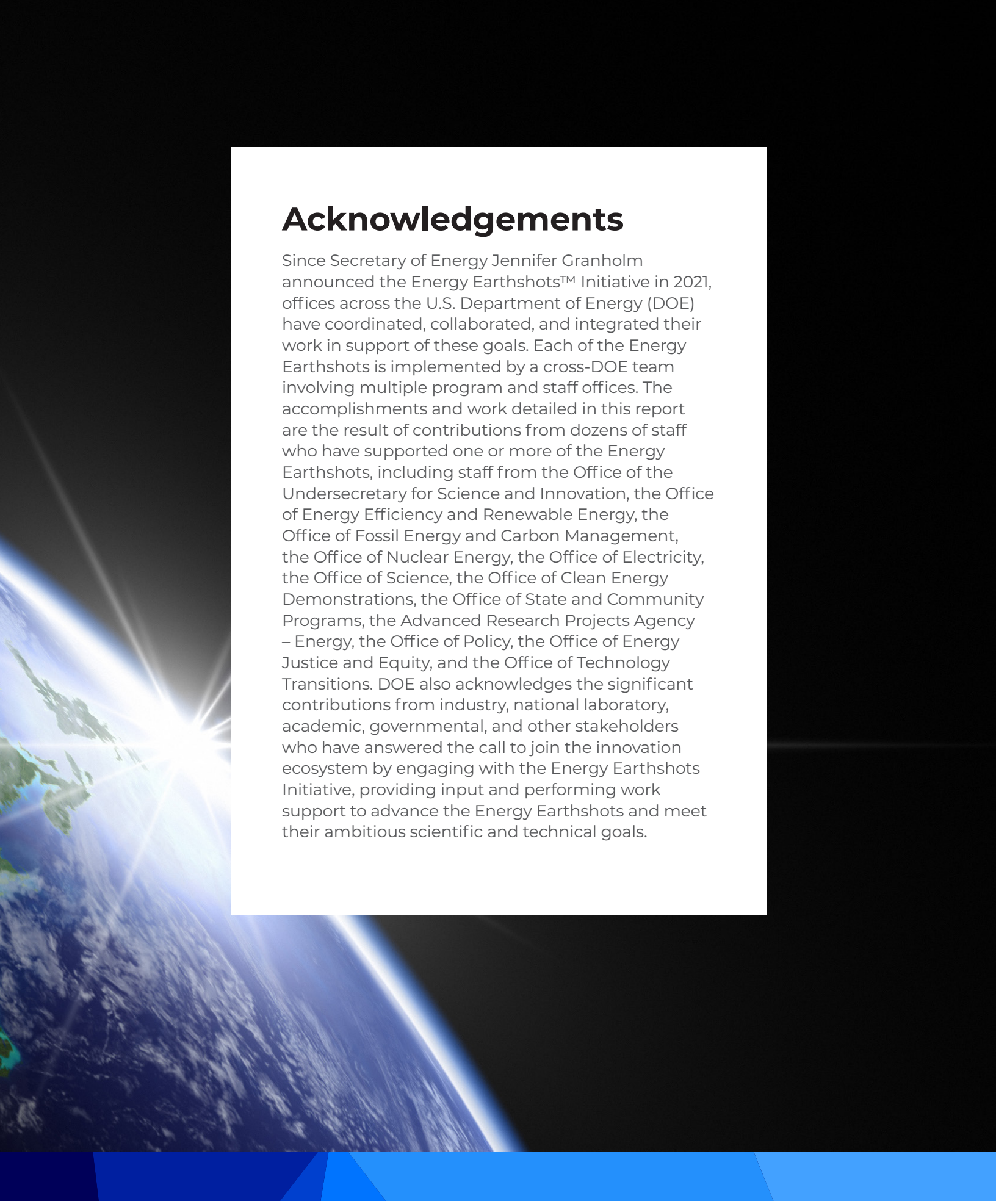
ENERGY earthshots
U.S. DEPARTMENT OF ENERGY

Charting the Path: An Energy Earthshots Initiative Report

Measuring the Progress and Mapping the Future of the Energy Earthshots Portfolio

January 2025



Acknowledgements

Since Secretary of Energy Jennifer Granholm announced the Energy Earthshots™ Initiative in 2021, offices across the U.S. Department of Energy (DOE) have coordinated, collaborated, and integrated their work in support of these goals. Each of the Energy Earthshots is implemented by a cross-DOE team involving multiple program and staff offices. The accomplishments and work detailed in this report are the result of contributions from dozens of staff who have supported one or more of the Energy Earthshots, including staff from the Office of the Undersecretary for Science and Innovation, the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy and Carbon Management, the Office of Nuclear Energy, the Office of Electricity, the Office of Science, the Office of Clean Energy Demonstrations, the Office of State and Community Programs, the Advanced Research Projects Agency – Energy, the Office of Policy, the Office of Energy Justice and Equity, and the Office of Technology Transitions. DOE also acknowledges the significant contributions from industry, national laboratory, academic, governmental, and other stakeholders who have answered the call to join the innovation ecosystem by engaging with the Energy Earthshots Initiative, providing input and performing work support to advance the Energy Earthshots and meet their ambitious scientific and technical goals.

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Executive Summary

The U.S. Department of Energy's (DOE) Energy Earthshots™ Initiative targets the most difficult-to-solve technology barriers for net-zero greenhouse gas emissions and sets technical and cost goals for key next-generation clean energy technologies. The initiative is accelerating research, development, and demonstration breakthroughs of more abundant, affordable, and reliable clean energy solutions. When achieved, these targets will support the private sector launch of new clean energy industries, help create quality jobs, lower energy costs for families across the country, and avoid hundreds of millions of tons of greenhouse gas emissions. The portfolio of the Energy Earthshots features eight ambitious targets (Figure 1).

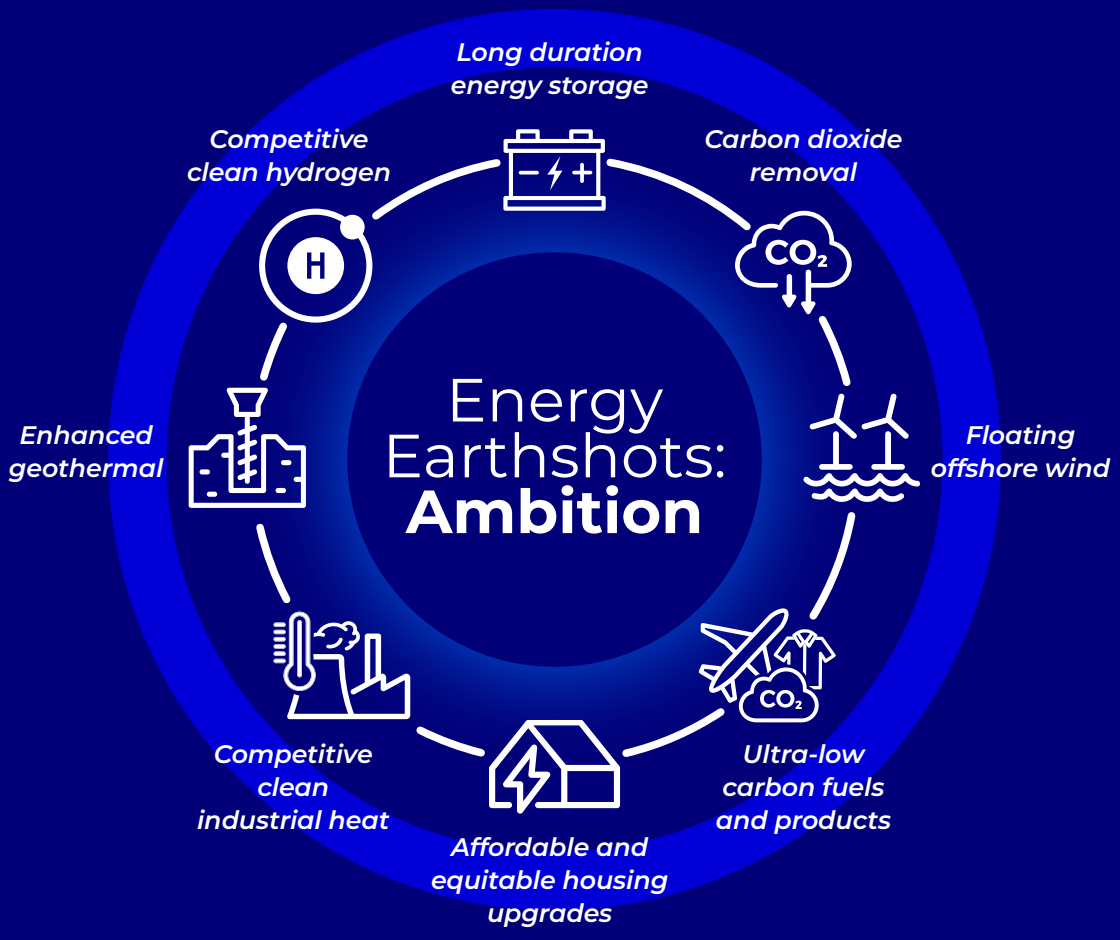


Figure 1. The Energy Earthshots drive integrated program development across DOE to address the toughest technological challenges and drive down the costs of our most promising next-generation clean energy technologies. The Energy Earthshots Initiative includes long duration energy storage, carbon dioxide removal, floating offshore wind, ultra-low carbon fuels and products, affordable and equitable housing upgrades, competitive clean industrial heat, enhanced geothermal, and competitive clean hydrogen.

Each of the Energy Earthshots was identified, scoped, and set through extensive analysis, including a set of ideation forums with the DOE national laboratories. Execution of the Energy Earthshots is guided by the mission, strategic alignment, and implementation elements detailed in this report. Delivering on these elements ensures that DOE is driving innovation to unlock transformative technologies, strengthen the clean energy economy, and ensure the achievement of long-term climate goals.

Modeling conducted by Evolved Energy Research, convened by independent organization Third Way, projects that achieving the first six Energy Earthshots simultaneously could avoid the release of approximately 3,900 million metric tons of carbon dioxide (CO_2) and save $850 billion in energy system costs by 2050 (Londagin et al. 2023).

The Energy Earthshots enable accelerated progress through better integration of the basic science research of the Office of Science with the applied research, development, and early demonstration work of the applied energy offices (Office of Electricity, Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy and Carbon Management, Office of Nuclear Energy), and by facilitating appropriate connections with DOE's large-scale demonstration and deployment activities.

Today, the Office of the Under Secretary for Infrastructure is demonstrating and deploying infrastructure built on decades of science and innovation, taking key steps towards decarbonizing and transforming the nation's energy economy.

Achieving the ambitious, decadal scale targets of the Energy Earthshots requires a continuous focus and investment in the basic science challenges that need to be addressed to overcome the technical barriers of today and launch the new energy technologies of tomorrow.

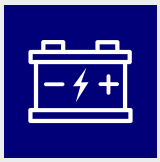
Resources for testing and validation of promising new technologies and pathways that emerge through early-stage applied research and development today will ensure DOE's investments prime successful technologies for commercial viability and accelerate their ability to gain market traction.

Since 2021, DOE has released dozens of strategy documents and technical reports, convened numerous workshops, summits, and stakeholder engagement events, and accelerated innovation with billions of dollars of financial assistance for projects and programs that support the Energy Earthshots portfolio.

This report lays out five distinct elements to assess progress for each of the Energy Earthshots, defining their goals, setting baselines for these goals, measuring progress against the baselines, tracking actions and accomplishments toward their goals, and roadmapping their paths to success.

The **Hydrogen Shot™** seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in one decade (i.e., 1-1-1 by 2031). Affordable clean hydrogen is a key enabler across industrial, transportation, and stationary power sectors, enabling energy security, resiliency, and both economic and environmental benefits.

DOE has published or is in the process of publishing comprehensive technology assessments covering a portfolio of technology pathways to achieve the target of the Hydrogen Shot through thermal conversion, water electrolysis, and advanced pathways. DOE has made significant progress toward meeting the Hydrogen Shot goal, including supporting a 25-fold increase in electrolyzer installations (planned and installed) across the United States since the Hydrogen Shot launch (from 0.17 gigawatts in 2021 to 4.5 in 2024).



The **Long Duration Storage Shot™** established the target to reduce by 90% the cost of grid-scale energy storage that can provide 10+ hours of energy by 2030. Grid-scale long-duration energy storage (LDES) is a key option to provide vital grid services to enable renewable generation while also increasing local control of the power system and building resilience.

In August 2024, DOE published assessment reports on the critical technical barriers and research, development, and deployment pathways to result in the lowest costs of LDES across 10 technologies. Since 2021, the industry has made steady progress toward the Long Duration Storage Shot goal. According to an analysis by Standard & Poor (Kim 2024), a range of technologies—including sodium, flow, and lithium batteries—have seen 10%–30% cost reductions between 2021 and 2024.

The **Carbon Negative Shot™** establishes a target for technologies and approaches that will remove CO_2 from the atmosphere and store it at meaningful scales for less than $100 per net metric ton of CO_2-equivalent. Carbon dioxide removal (CDR) has a critical role in helping the United States address the climate crisis and achieve net-zero emissions by 2050.

The Carbon Negative Shot's progress will be measured based on analyses and quantitative evaluations of the costs of relevant CO_2 removal pathways, including direct air capture with storage, soil carbon sequestration, biomass carbon removal with storage, enhanced mineralization, marine CO_2 removal, and afforestation, reforestation, and revegetation. DOE-supporteds research, development, and deployment activities have accelerated since the announcement of the Carbon Negative Shot, including the launch of a voluntary CDR purchase prize, the creation of direct air capture hubs, and a suite of Carbon Negative Shot pilot projects.

The **Floating Offshore Wind Shot™** is an initiative to drive U.S. leadership in floating offshore wind design, development, and manufacturing, led by DOE, the U.S. Department of the Interior, the U.S. Department of Commerce, and the U.S. Department of Transportation. The Floating Offshore Wind Shot seeks to reduce the cost of floating offshore wind energy by more than 70% by 2035 for deep-water sites far from shore.

The strategic framework for the Floating Offshore Wind Shot focuses on five pillars: technology innovation; supply chain development; expanded, just, and sustainable deployment; transmission development; and co generation opportunities. In addition to ongoing planning, leasing, and other supporting actions, the Floating Offshore Wind Shot federal partners have supported over $950 million in research, development, demonstration, and deployment efforts associated since this Energy Earthshot was announced in September 2022.

The **Enhanced Geothermal Shot™** aims to dramatically reduce the cost of enhanced geothermal systems by 90% to $45 per megawatt-hour by 2035. Reducing the costs of enhanced geothermal systems will spur investments in the technology, in turn unlocking the nation's significant heat resources to provide secure, firm, flexible power for the equivalent of more than 65 million American homes.

To drive toward these cost goals, DOE has identified six primary research areas: exploration and characterization; subsurface accessibility; subsurface enhancement and sustainability; resource maximization; data, modeling, and analysis; and geothermal integration and awareness. Since the launch of the Enhanced Geothermal Shot in 2022, there have been significant advancements. At DOE's Utah Frontier Observatory for Research in Geothermal Energy (FORGE) facility, for example, in August 2024, a team completed a successful full-scale 30-day circulation test. In addition to the stimulation success, FORGE also realized a seven-fold increase in on-bottom drilling rates.

The **Industrial Heat Shot™** seeks to develop cost-competitive industrial heat decarbonization technologies with at least 85% lower greenhouse gas emissions by 2035. Developing these technologies will put the American industrial sector on course to reduce its carbon-equivalent emissions by 575 million metric tons by 2050.

The Industrial Heat Shot focuses on three pathways to decarbonize industrial heat: generating heat from clean electricity, integrating clean heat from alternative sources, and innovating low- or no-heat process technologies. Additionally, there is a need for enabling cross-cutting technologies, like thermal energy storage and advanced materials. DOE has published various analyses and strategic documents related to advancing technologies along these pathways. DOE is pursuing analysis to identify and explore pathways to grow the U.S. industrial sector and sharpen the nation's competitive edge and national security globally while bending the sector's trend in reducing greenhouse gas emissions.

The **Clean Fuels and Products Shot™** aims to decarbonize the fuel and chemical industries through alternative sources of carbon with a goal of developing cost-effective technologies from alternative feedstocks that reduce greenhouse gas emissions by at least 85% compared to a 2019 baseline of petroleum-based products by 2035. The Clean Fuels and Products Shot will advance the vision of using sustainable carbon resources to meet a significant portion of projected 2050 demands: 100% of aviation fuel; 50% of maritime, rail, and off-road fuels; and 50% of carbon-based chemicals.

DOE has invested in and now tracks technology development from basic science to applied research and development to pilot and demonstration stages in three key areas: fuel production pathways, chemical production pathways, and resource mobilization. Over the course of the 18 months since the Clean Fuels and Products Shot was launched, multiple offices across DOE have announced new funding opportunities and selections.

The **Affordable Home Energy Shot™** aims to reduce the upfront cost of upgrading a home by at least 50% while reducing energy bills by 20% within a decade. This goal relies on enabling upgrades to American homes and improving energy affordability. Nearly one in four households nationwide experiences high energy burdens; as a result, more than 20% fell behind on their energy bills in 2023.

On Oct. 12, 2024, the Affordable Home Energy Shot celebrated its one-year anniversary. Throughout its inaugural year, DOE has advanced funding opportunities to promote research, development, and deployment of cutting-edge energy technologies that will be instrumental in reaching Affordable Home Energy Shot goals. These investments are designed to drive down costs and enhance accessibility, particularly for underserved communities.

In addition to reporting across the eight individual Energy Earthshots, this report discusses efforts across the Energy Earthshots to ensure that DOE is enlisting the full innovative ecosystem in pursuit of these goals with strong connections to DOE's Pathways to Commercial Liftoff efforts and international collaborations with Japan (Floating Offshore Wind Shot), India (Hydrogen Shot), and Australia (Long Duration Storage Shot).

Introduction

Launch and Motivation

The United States has set an ambitious climate goal of reaching a net-zero greenhouse gas emissions economy by 2050. Achieving this goal will require breakthroughs in clean energy and climate technologies in multiple sectors in this decade. The U.S. Department of Energy (DOE) is well positioned to drive these breakthroughs with its history of stimulating energy innovation encompassing foundational science, applied energy, and demonstration programs through its network of national laboratories, academic institutions, and private sector entities. DOE's Energy Earthshots™ Initiative aims to harness these capabilities for the most difficult-to-solve technology barriers for net-zero emissions and sets technical and cost goals in key next-generation clean energy technologies. The initiative is accelerating research, development, and demonstration breakthroughs of more abundant, affordable, and reliable clean energy solutions. When achieved, these targets will support the private sector launch of new clean energy industries, help create quality jobs, lower energy costs for families across the country, and avoid hundreds of millions of tons of greenhouse gas emissions. The portfolio of the Energy Earthshots features eight ambitious targets, which are the:

- **Hydrogen Shot™**, announced June 7, 2021, which sets an ambitious and achievable cost target to accelerate innovations and spur demand of clean hydrogen by reducing the cost by 80%, to $1 per 1 kilogram of clean hydrogen within one decade.
- **Long Duration Storage Shot™**, announced July 14, 2021, which aims to achieve affordable grid storage for clean electricity by reducing the cost of grid-scale energy storage by 90% for systems that deliver for a duration of 10+ hours by 2030.
- **Carbon Negative Shot™**, announced Nov. 5, 2021, which aims to achieve innovation in technologies and approaches that will remove carbon dioxide (CO_2) from the atmosphere and durably store it at meaningful scales for less than $100 per 1 net metric ton of CO_2-equivalent (CO_2e) within a decade.

> "The **Energy Earthshots™** are an all-hands-on-deck call for innovation, collaboration, and acceleration of our clean energy economy by tackling the toughest remaining barriers to quickly deploy emerging clean energy technologies at scale."
>
> Secretary of Energy
> Jennifer Granholm,
> June 7, 2021

- **Enhanced Geothermal Shot™**, announced Sept. 8, 2022, which sets an ambitious and achievable target to dramatically reduce the cost of enhanced geothermal systems by 90% to $45 per megawatt-hour by 2035.
- **Floating Offshore Wind Shot™**, announced Sept. 15, 2022, which aims to reduce the cost of floating offshore wind energy by more than 70% by 2035 for deep-water sites far from shore, to help usher in a clean energy future by driving U.S. leadership in floating offshore wind design, development, and manufacturing.
- **Industrial Heat Shot™**, announced Sept. 21, 2022, which aims to develop cost-competitive industrial heat decarbonization technologies with at least 85% lower greenhouse gas emissions by 2035.
- **Clean Fuels & Products Shot™**, announced May 24, 2023, which focuses on decarbonizing the fuel and chemical industry through alternative sources of carbon to advance cost-effective technologies with a minimum of 85% lower greenhouse gas emissions by 2035.
- **Affordable Home Energy Shot™**, announced Oct. 12, 2023, which aims to accelerate innovative breakthroughs and reduce costs to decarbonize our nation's residential buildings by lowering the upfront cost of upgrading a home by at least 50% while reducing energy bills by 20% within a decade.

The Energy Earthshots Framework

The approach to setting and achieving the Energy Earthshots targets is based in part on DOE's highlight successful SunShot (Solar Energy Technologies Office 2011), which set out in 2011 to slash the cost of solar energy by 75% within a decade and did so three years early. The Energy Earthshots take the SunShot concept of time-bound technical and cost goals to a new level of ambition by simultaneously targeting innovation across multiple technologies and sectors.

When the initiative launched in early 2021, DOE anticipated six to eight Energy Earthshots. Each of the Energy Earthshots was identified, scoped, and set through extensive analysis, which included a set of ideation forums with the DOE national laboratories. Senior leadership across DOE developed the Energy Earthshots framework to define the mission, strategic alignment, and implementation of the Energy Earthshots.

Each of the Energy Earthshots targets was designed to meet four **mission** elements. Energy Earthshots are:

- **Ambitious.** The Energy Earthshots targets is bold and aspirational at the scale of 2030 and 2050 necessity. The targets are focused on a goal to have new technologies ready to deploy within a decade. They will require acceleration of innovated research, development, and deployment on an ambitious but achievable timeline.
- **Technology focused.** Each of the Energy Earthshots establishes a cost, performance, or other target in a specific DOE technology space. They were designed to address the hardest technology barriers within these spaces to drive the cost and performance improvements to bring these technologies to the market.
- **Purposeful.** Each of the Energy Earthshots targets one of the highest emitting sectors of our energy economy, and is singularly focused on reducing emissions at scale. Energy Earthshots target transformation in sectors of the economy that are foundational to the U.S. clean energy agenda.
- **Leading the way.** Each of the Energy Earthshots targets places DOE and the United States as central thought leaders of the global clean energy trajectory. Individual Energy Earthshots include goals for U.S. leadership in new clean energy industries and have catalyzed international collaboration in line with Energy Earthshots goals.

Activities in support of the Energy Earthshots are carried out in accordance with three **strategic alignment** elements. DOE ensures that its activities around Energy Earthshots are:

- **Aligning resources.** The Energy Earthshots drive integrated program development across DOE's Office of Science and applied energy offices. DOE ensures that resources are aligned with each of the Energy Earthshots through internal coordination and communication around budget requests and activities.
- **Informed with strategic planning.** Each of the Energy Earthshots must be supported by a comprehensive strategic planning effort that integrates basic science through applied energy and develops appropriate connections to large-scale demonstration and deployment to set both near and long-term research, development, demonstration, and deployment vision and strategy. This strategy should be periodically analyzed and reassessed along the decadal timeline.
- **Engaging stakeholders.** Energy Earthshots seek to enlist the entire innovation ecosystems. Stakeholders from DOE national laboratories, universities and other academic and research institutions, and industry are engaged at every stage of the Energy Earthshots.

Four **implementation** elements ensure that activities carried out toward Energy Earthshots goals will have maximum impact. Efforts around Energy Earthshots must demonstrate:

- **Clear communication.** Energy Earthshots are a central part of DOE's innovation story. They must be clearly communicated with compelling, highly-visible core messages around the ambition and importance of the target.
- **Measurable progress.** Innovation progress must be evaluated against benchmark targets, and assessments of progress toward the Energy Earthshots goals must be regularly produced and communicated.
- **Jobs, economic, and energy justice impacts.** Energy Earthshots are designed to enable significant opportunities for jobs, equity, and the domestic economy. These impacts must be assessed and communicated.
- **Decisive.** Implementation of Energy Earthshots activities must be done in ways that allow DOE to become more risk tolerant, streamlined, and prioritized around achieving these targets.

Although each of the Energy Earthshots was launched at a different time and involves multiple and different offices across the DOE (and, in one case, across the federal government), each adheres to all the elements of the Energy Earthshots framework.

Meeting the Mission

Delivering on the four mission elements of the Energy Earthshots framework—with targets that are ambitious, technology focused, purposeful, and with DOE leading the way—ensures that DOE is driving innovation to unlock transformative technologies, strengthen the clean energy economy, and achieve long-term climate goals.

Modeling conducted by Evolved Energy Research convened by independent organization Third Way projects that achieving the first six Energy Earthshots simultaneously could avoid approximately 3,900 million metric tons of CO_2 and save $850 billion in energy system costs by 2050 (Londagin et al. 2023). This modeling underscores the transformative potential of the Energy Earthshots, which surpasses even the ambitious achievements anticipated from the Inflation Reduction Act's (IRA's) energy provisions. As reported, "the energy provisions in the IRA—the largest investment in clean energy and climate change in U.S. history—is valued around $370 billion and is expected to reduce emissions by about 2,500 to 2,800 million metric tons by 2030." (Larsen et al. 2022; Hill 2022; Mahajan et al. 2022).

Furthermore, Third Way's report showcases the interlocking nature of the energy system and synergistic benefits of the Energy Earthshots Initiative's portfolio approach, wherein innovation toward one target drives progress in other sectors and contributes toward meeting other Energy Earthshots goals. Achieving these targets will require focused investment and planning, but the historic benefits of reduced costs and emissions make the Energy Earthshots a pivotal step in the transition to a clean energy future.

The All-Hands-On-Deck Approach

The Energy Earthshots are focused on accelerating research, development, and demonstration (RD&D) breakthroughs to realize abundant, affordable, and reliable clean energy and carbon-management solutions on an extremely ambitious timeline in recognition of the scale and urgency of the climate crisis.

Cross-cutting teams spanning DOE are engaged in coordinating, innovating, and tracking progress in support of the entire portfolio of Energy Earthshots goals. Each of the Energy Earthshots is led and implemented by a cross-department (or interagency) team chartered by the Under Secretary for Science and Innovation that reports regularly to DOE senior leadership. Internal DOE coordination across these teams fosters collaboration in approach across all Energy Earthshots. Activities are guided by the strategic alignment and implementation elements of the Energy Earthshot framework.

This cross-cutting approach enables accelerated progress through better integration of the basic science research of the Office of Science with the applied and early RD&D work of the applied energy offices (Office of Electricity, Office of Energy Efficiency and Renewable Energy, Office of Fossil Energy and Carbon Management, and Office of Nuclear Energy), and by facilitating appropriate connections with DOE's large-scale demonstration and deployment activities that are overseen by the Office of the Under Secretary for Infrastructure.

Today, DOE is demonstrating and deploying infrastructure built on decades of science and innovation, taking key steps towards decarbonizing and transforming the nation's energy economy. These efforts have been supported by the IRA and Bipartisan Infrastructure Law (BIL), which are revitalizing the U.S. energy system by investing in American energy supply chains, clean energy job creation, emissions reduction, and consumer energy savings. Achieving the ambitious, decadal scale targets of the Energy Earthshots requires a continuous focus and investment in the basic science challenges that need to be addressed to overcome the technical barriers of today and that will launch the new energy technologies of tomorrow.

Many of the Energy Earthshots will require further advances in fundamental science, in areas such as materials discovery, which will better enable technology in extreme environments that Energy Earthshots target; atomic and molecular understanding of materials and chemical reactions that can underpin new energy efficient processes and systems at larger scales; and innovations in measurements, sensing, and computational modeling of systems.

Resources for testing and validation of promising new technologies and pathways that emerge through early-stage applied R&D will ensure that today's DOE investments prime successful technologies for commercial viability and accelerate their ability to gain market traction.

Tracking Innovation Progress

Since the Energy Earthshots were first announced in 2021, DOE has released dozens of strategy documents and technical reports, convened numerous workshops, summits, and stakeholder engagement events, and accelerated innovation with millions of dollars of financial assistance supporting new innovative projects and programs that support the Energy Earthshots portfolio.

One aspect of tracking the impact of Energy Earthshots efforts and a key aspect of the Energy Earthshots framework is measurable progress. Tracking action and evaluating progress toward each decadal-scale goal informs strategic alignment and sets a path of the highest chance of success.

This report lays out are five distinct elements in assessing progress of the Energy Earthshots thus far, which are to::

- **Define.** How is the goal defined?
- **Measure.** What is the baseline? How can we measure progress against that baseline?
- **Analyze.** What is our progress toward the target thus far?
- **Track.** What actions and accomplishments have we achieved in support of the goal?
- **Roadmap.** What are the priorities to keep us on the path to success?

The findings in this report represent the culmination of, in some cases, several years of analytical capabilities, as well as clear strategies for how DOE can continue to make and track progress on each of the Energy Earthshots over the next decade.

Hydrogen Shot

1 dollar

1 Clean Kilogram

1 decade

The first Energy Earthshot—the Hydrogen Shot™—was announced on June 7, 2021, and sets an ambitious yet achievable target to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade.

Defining the Goal

The Hydrogen Shot, launched on June 7, 2021, seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kilogram (kg) in one decade (i.e. by 2031). Affordable clean hydrogen is a key enabler across industrial, transportation, and stationary power sectors, enabling energy security, resiliency, and both economic and environmental benefits.

Meeting the Mission

Achieving the Hydrogen Shot goal could result in at least a five-fold increase in the use of hydrogen—50 million metric tons per year by 2050, aligned with the *National Clean Hydrogen Strategy and Roadmap* (Hydrogen Fuel Cell Technologies Office 2023)—which could enable up to 10% reduction in U.S. emissions relative to 2005. In addition to enabling clean hydrogen for existing markets, such as refining and domestic ammonia production, it would create new markets for clean hydrogen including heavy-duty transportation; additional industrial uses, such as steel manufacturing; and long-duration energy storage for renewables. Progress toward meeting the Hydrogen Shot also enables a transition from today's conventional hydrogen production to 10 million metric tons of clean hydrogen annually by 2030, with the potential for 100,000 net new direct and indirect jobs in the building of new capital projects and infrastructure.

Measuring: Target Baseline and Assessment Approach

Currently, clean hydrogen can be produced using renewable energy at a cost above $5 per kilogram. Hydrogen can also be produced using fossil and/or waste resources with carbon capture and storage (CCS) at lower costs, although many individual processes will need to lower their CO_2e emissions to meet DOE's Clean Hydrogen Production Standard. Achieving the Hydrogen Shot's cost goal for producing clean hydrogen through diverse technology options best-suited to different regionally-specific resources across the nation can unlock new and expanded domestic markets for hydrogen, including steel manufacturing, clean ammonia, energy storage, and heavy-duty transportation. This would create more clean energy jobs, reduce greenhouse gas emissions when powered by low-carbon electricity, and position America to compete in the clean energy market on a global scale.

DOE has published, or is the process of publishing, comprehensive technology assessments covering a portfolio of technology pathways that have the potential to meet the Hydrogen Shot goal. These technology pathways are organized into three broad categories: thermal conversion, water electrolysis, and advanced pathways. These assessments track status, identify key challenges and opportunities for cost reduction and technology advancement, and provide promising scenarios for meeting the Hydrogen Shot goal through each of the covered technologies.

Analyzing Progress Toward the Target

Thermal Conversion

Hydrogen Shot Technology Assessment: Thermal Conversion Approaches, a comprehensive technology assessment including cost analyses of different pathways producing clean hydrogen from thermal conversion of fossil and waste feedstocks with carbon capture was published in December 2023, serving as a baseline for future analyses and progress tracking (McNaul et al. 2023). Three commercial processes covered in the assessment were analyzed with rigorous detail by the National Energy Technology Laboratory (NETL): steam methane reforming, autothermal reforming of natural gas, and co-gasification of fossil and waste feedstocks, all with CCS. NETL used their various Quality Guidelines for Energy System Studies to model these processes to determine costs and life cycle greenhouse gas emissions. Two of these pathways, steam methane reforming and autothermal reforming, both with CCS, have modeled costs that nearly achieve the cost target of Hydrogen Shot goal, with costs around $1.60 per kg, but with life cycle CO_2e emissions typically greater than 4 kg of CO_2e per kg of hydrogen produced. In these approaches, additional RD&D is necessary to further reduce the emissions while still bringing down costs. Gasification with CCS was modeled to be $3.75 per kg, requiring significantly more research to bring costs down from current values. The assessment highlights pathway-specific needs for meeting the Hydrogen Shot cost goal, including technology advancement needs (with quantitative targets) as well as non-technical factors (such as feedstock pricing, siting, etc.). DOE continues to support ongoing analyses and stakeholder engagements aimed at refining the current assessment.

Water Electrolysis

For the water electrolysis pathways, DOE published *Hydrogen Shot: Water Electrolysis Technology Assessment*, outlining the status, RD&D needs, and potential scenarios for cost reductions for five different electrolyzer technologies (Hydrogen Fuel Cell Technologies Office 2024). The current cost of hydrogen produced using electrolyzers in grid connected scenarios is typically above $6 per kg, although, with limited renewable penetration on the grid, this hydrogen would not qualify as clean. Additional scenarios considering direct coupling with multiple sources of clean electricity, including from renewables, could achieve clean hydrogen costs near $5 per kg, based on current technologies. The assessment highlights needs for meeting the Hydrogen Shot cost goal in each of the electrolyzer technologies, including RD&D innovations addressing major cost drivers—both technical (e.g., performance and durability impacting capital and operating expenditures) as well as nontechnical (e.g., soft costs and supply chain bottlenecks). As with thermal conversion technologies, DOE continues to support ongoing analyses and stakeholder engagements of the water electrolysis pathways aimed at refining the current assessment (e.g., Acevedo et al. 2023; Prosser et al. 2023; Badgett et al. 2024).

Advanced Pathways

Advanced pathways include emerging approaches that have the potential to achieve highly efficient utilization of renewable resources for affordable carbon neutral hydrogen production. The three categories within the advanced pathways include: solar photoelectrochemical water-splitting, thermochemical water-splitting (including direct solar-driven processes), and biological conversion of bio and waste streams, such as fermentation and microbial electrolysis cells. These pathways are at relatively early stages of development but could have significant regional impacts on decarbonization as they mature. Research in these pathways also provides valuable fundamental insights relevant to the optimization of the thermal conversion and water electrolysis pathways, addressing priority research opportunities identified by the DOE Office of Basic Energy Sciences in its 2021 report *Foundational Science for Carbon-Neutral Hydrogen Technologies* (Office of Science 2021). The DOE recently convened a technical experts meeting on advanced pathways. As a result, a summary document is being prepared for publication in a high-impact peer-reviewed journal. This document, intended as a technology assessment of the advanced pathways, focuses on identifying key fundamental knowledge gaps and addressing the most important applied science and engineering needs to accelerate commercialization of the most promising emerging approaches.

Tracking Action and Accomplishments

DOE has made significant progress across RDD&D, including the aforementioned reports and analyses, contributing toward meeting the Hydrogen Shot goals. In March 2024, DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) announced 36 new projects for electrolyzer RD&D and manufacturing with total project costs of $1.1 billion through BIL funding for the Clean Hydrogen Electrolysis Program (Section 816) (U.S. Congress 2021a). In addition to advancing the technology and the domestic supply chain, these projects will enable 10 gigawatts per year of domestic electrolyzer stack manufacturing capacity assisting with achieving economies of scale and, thereby, significantly decreasing electrolyzer capital costs.

In addition, the Office of Fossil Energy and Carbon Management (FECM) announced $4 million to advance reversible fuel cell technologies that can enable low-cost hydrogen (H_2). FECM additionally announced a $15 million funding opportunity for projects that convert feedstock, such as coal, biomass, petcoke, household waste, industrial wastes, and waste plastics into syngas, to enable low-cost hydrogen production that can be coupled with CCS.

DOE is also exploring the emerging opportunity to tap into recoverable reserves of subsurface hydrogen from natural geologic processes, including through $20 million funding to 16 projects from Advanced Research Projects Agency-Energy.

Since Hydrogen Shot was launched in 2021, there has been a 25-fold increase in electrolyzer installations (planned and installed) across the United States—from 0.17 gigawatts in 2021 to 4.5 in 2024 (HFTO 2024).

As part of the BIL, in October 2023, the DOE Regional Clean Hydrogen Hub Program, led by the Office of Clean Energy Demonstrations, announced seven selections for hydrogen hubs to receive $7 billion along with over $40 billion in private sector cost share. These hydrogen hubs have planned hydrogen production facilities encompassing various technologies, including thermal conversion with CCS and electrolysis using renewables, nuclear, and grid electricity.

Finally, to spur innovation, DOE launched the Hydrogen Shot Incubator Prize to identify, develop, and test disruptive technologies. Similarly, to facilitate greater linkages between basic science and applied RD&D, DOE HFTO launched the H2LinkSC initiative in 2023 and selected four national lab projects linking fundamental science work to accelerate electrolysis applied R&D.

Roadmapping: The Path Ahead

Progressing Along Technology Pathways

Thermal Conversion

Several pathways mentioned within the *Hydrogen Shot Technology Assessment: Thermal Conversion Approaches* report did not have sufficient published data to conduct a rigorous analysis on their baseline costs and pathways to the Hydrogen Shot cost goal (McNaul et al. 2023). The National Energy Technology Laboratory is in the process of preparing a comprehensive analysis covering the costs and life cycle emissions of these pathways, expected to be published in Fiscal Year 2025. The Office of Fossil Energy and Carbon Management will fund $9 million in pre-front-end engineering design (pre-FEED) studies in Fiscal Year 2025 for carbon capture systems at hydrogen production facilities using coal, mixed waste/biomass, or natural gas feedstocks. These pre-FEED studies aim to advance commercial-scale carbon capture systems that separate CO_2 with at least 95% capture efficiency at new or existing hydrogen production facilities, addressing the important priority of improved emissions reductions within the thermal conversion approaches. The studies will also provide more up to date data to enable cost estimation for new carbon capture techniques for future clean hydrogen plants.

Water Electrolysis

As part of the BIL, the DOE Clean Hydrogen Electrolysis Program, led by HFTO, is required to validate progress towards $2 per kg for electrolytic hydrogen by 2026 (BIL Section 816) (U.S. Congress 2021a).. This is a key checkpoint on the way to

realizing the Hydrogen Shot goal. HFTO will continue to leverage national laboratory and industrial expertise in technoeconomic and lifecycle analyses to track current costs and potential future scenarios that would enable $1 per kg for clean hydrogen by 2031 for each electrolyzer technology (HFTO 2024).

As part of the Clean Hydrogen Electrolysis Program, DOE announced $750 million in funding that includes projects to dramatically accelerate cost reductions of clean hydrogen through electrolysis. Some of these new projects will develop next-generation electrolyzer materials and components specifically aimed at enabling the Hydrogen Shot goal. RD&D advances from this work will be tracked including evaluating their impact on hydrogen production cost reduction through, for example, improvements in performance, efficiency, durability, cost, and/or manufacturing. HFTO also funds the national labs to support advancement of electrolyzer technologies through RD&D consortia and megawatt-scale electrolyzer test beds that will come online in 2026, including the Hydrogen from Next-Generation Electrolyzers of Water consortium. These testbeds will enable testing of full electrolyzer systems on renewable energy profiles and help validate performance and durability under these conditions. The ability to load follow without significant electrolyzer degradation will be critical in such systems.

Supporting Next-Generation Innovation

Advanced Pathways

The advanced pathways are promising longer-term approaches that could potentially produce clean hydrogen at high conversion efficiencies with low cost, contingent on targeted technical advancements. In support of the solar photoelectrochemical water-splitting and thermochemical water-splitting advanced pathway technologies, DOE announced $20 million in funding for 11 projects working with HydroGEN, HFTO's advanced water-splitting consortium focused on accelerating RD&D of diverse early-stage water-splitting technologies for clean, sustainable hydrogen production. The benchmarking and protocols effort, supported by HydroGEN and led by Pacific Northwest National Laboratory and industry partners, aims to direct the RD&D resources in the most effective way to advance these technologies towards commercialization. RD&D efforts relevant to the advanced pathways based on biological processes are supported through the BioHydrogen consortium developing a carbon-neutral technology to convert waste biomass into H_2 via biological strain engineering, bioprocess design for scaling up, and integrating fermentation with microbial electrolysis cells (Chou 2024).

The Office of Science has recently made significant investments in the award of eleven national laboratory-led Energy Earthshots research centers, two of which target the Hydrogen Shot, and 18 university-led science foundations for Energy Earthshots projects. These awards were specifically designed to can provide foundational knowledge important for a wide range of different fields and technological areas. Activities related to the Hydrogen Shot are focused on improving and discovering new materials and materials chemistry, separations chemistry, electrolysis, and catalysis for hydrogen production.

Through ongoing analyses and funded projects, DOE will be able to track technical advancements that are critical to enable the Hydrogen Shot, and this progress will be incorporated into future assessments. The regional clean hydrogen hubs are a key part in demonstrating these technologies and documenting progress. In the long term, achieving the Hydrogen Shot is expected to unlock large-scale demand for clean hydrogen and support U.S. decarbonization goals.

Long Duration Storage Shot

90% Reduction | **10+ hours** | **1 decade**

The second of the Energy Earthshots—Long Duration Storage Shot™—was announced on July 14, 2021, and aims to achieve affordable grid storage for clean power anytime, anywhere by reducing the cost of grid-scale energy storage by 90% for systems that deliver over a duration of 10+ hours within the decade.

Defining the Goal

Long-duration energy storage (LDES) is essential to the flexibility, reliability, and decarbonization of the future electricity system. Launched in 2021, the Long Duration Storage Shot establishes the target to reduce by 90% the cost of grid-scale energy storage that can provide 10+ hours of energy by 2030.

Meeting the Mission

Variable renewable generation is critical to a decarbonized grid, but on its own, it cannot cost-effectively serve 100% of electricity demand at all periods. Therefore, the future decarbonized grid will need innovative solutions to ensure flexibility and reliability. Grid-scale LDES is a key option to provide vital grid services to enable renewable generation while also increasing local control of the power system and building resilience for communities that are frequently disconnected from or may not have access to the grid. Developing the technology and manufacturing processes to reach the Long Duration Storage Shot cost targets will also establish a new, U.S.-based manufacturing industry for storage products.

Measuring: Target Baseline and Assessment Approach

The Long Duration Storage Shot target is based on the 2020 cost of lithium-ion batteries. Reaching the goal of a 90% reduction in cost translates to grid-scale long-duration storage systems with pathways to reach a levelized cost of storage of $0.05 per kilowatt-hour by 2030.

The Long Duration Storage Shot takes a technology-agnostic approach and considers any electricity-in and electricity-out technology, including electrochemical, mechanical, thermal, or chemical storage, that can meet the cost goal. Since the initiation of the Long Duration Storage Shot in 2021, DOE has launched two efforts to examine current and projected costs for LDES technologies:

- Pacific Northwest National Laboratory's Cost and Performance Report: This biennial report, first published in 2022 and updated (online) in 2024, tracks the costs of grid-scale energy storage systems for a variety of power capacities and durations. This effort includes present-day costs and future business-as-usual (BAU) projections for 2030 costs. (Pacific Northwest National Laboratory 2022)
- Storage Innovations 2030: This multipronged effort identifies and funds interventions, such as precompetitive RD&D opportunities and high-impact RD&D pathways, that will lower the costs of LDES systems in 2030 faster than the BAU scenarios in the aforementioned report. (Office of Electricity 2023)

Analyzing Progress Toward the Target

In July 2023, through Storage Innovations 2030, DOE published 10 technology strategy assessments which evaluated the critical technical barriers, precompetitive RD&D opportunities, and RD&D pathways to result in the lowest costs of LDES. The findings of these assessments were synthesized and published in the August 2024 report, titled *Achieving the Promise of Low-Cost Long Duration Energy Storage* (Office of Electricity 2024a). Information provided in these assessments, such as is illustrated in Figure 2, feature the BAU 2030 cost values for 10 technologies, and the potential low levelized cost of storage after RD&D innovation portfolios are implemented. On average, the top 10% of these innovation portfolios can reduce levelized cost of storage by 12%–85% to $0.03–$0.26 per kilowatt-hour across all considered storage technologies. The report and the technology strategy assessments include detailed information about the high-impact RD&D opportunities to achieve these lost costs.

Since 2021, the industry has made steady progress towards the Long Duration Storage Shot goal. According to Standard & Poor, a range of technologies—including sodium, flow, and lithium batteries—have seen 10%–30% cost reductions between 2021 and 2024 (Kim 2024). The analysis also aligns with the Storage Innovations 2030 finding that compressed air is near the shot's target and has relatively fewer opportunities for further cost reduction.

Other DOE publications and efforts have been influential to the development of the Long Duration Storage Shot strategy. In 2020, DOE launched the Energy Storage Grand Challenge, DOE's first comprehensive effort to coordinate energy storage strategy. This coordination mechanism is ongoing as of late 2024, and a planned roadmap is expected to be released in 2025.

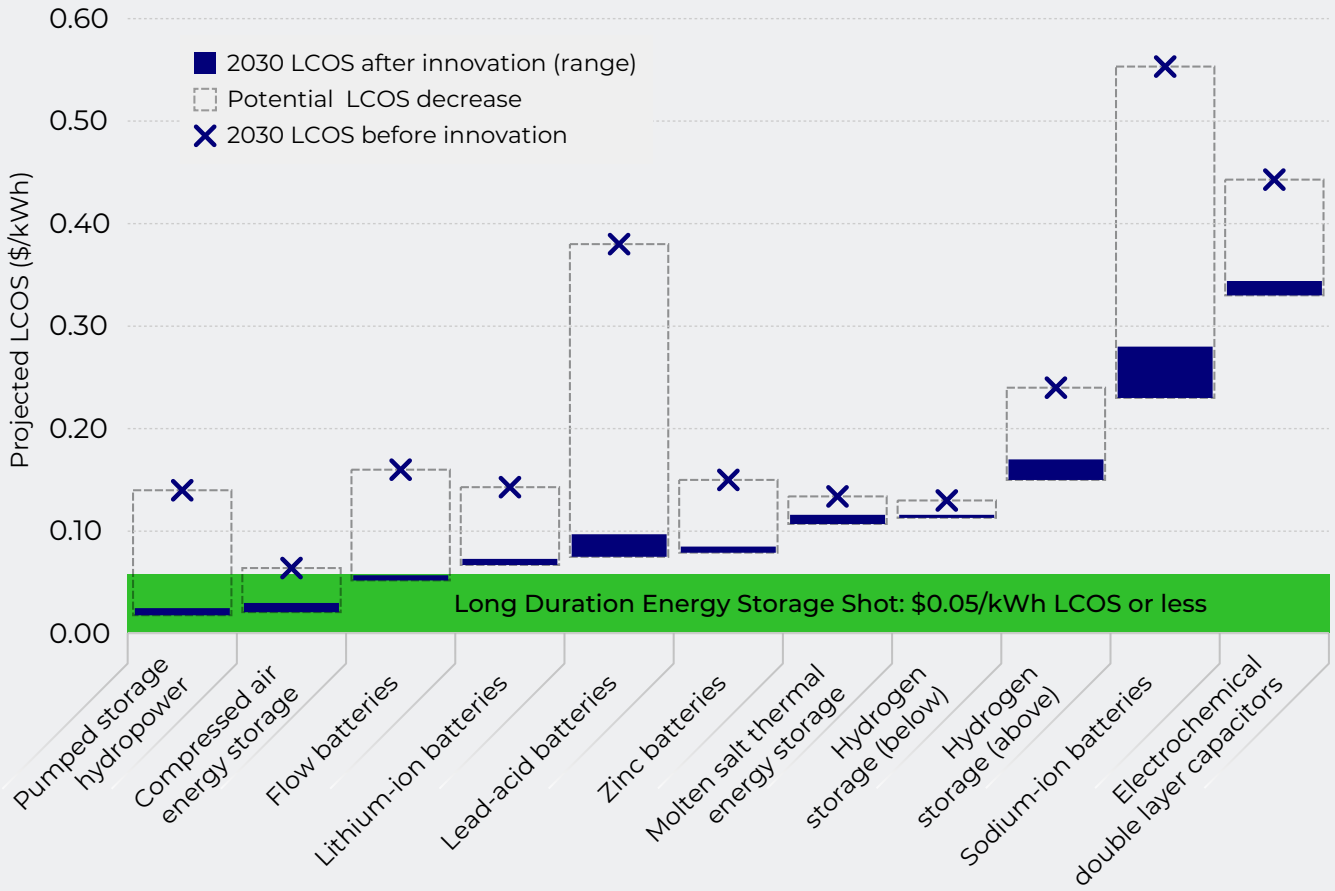


Figure 2. Potential impact of implementing top innovations on the projected 2030 levelized cost of storage (LCOS) as identified by Storage Innovations 2030. *Source: Office of Electricity 2024*

Tracking Action and Accomplishments

Many DOE initiatives and accomplishments have supported the Long Duration Storage Shot since it was launched in 2021. In addition to Storage Innovations 2030, DOE has developed a number of other impactful reports, including *Pathways to Commercial Liftoff: Long Duration Energy Storage*, which explores LDES technology needs and market barriers to widescale adoption (DOE 2023e). This report is expected to receive updates as market conditions evolve. Also, the Office of Electricity's *Energy Storage Safety Strategy* showcases over a decade of funded investments in safety research, the results from which are now encoded in more than 30 industry standards (Office of Electricity 2024b). As a result of the BIL, DOE's Office of Clean Energy Demonstrations has awarded over $340 million in demonstration and validation awards to show that new LDES technologies will work reliably and cost effectively in the field. Finally, on Aug. 13, 2024, the Office of Electricity joined the Pacific Northwest National Laboratory in opening the 93,000-square-foot Grid Storage Launchpad, which will revolutionize clean energy innovation and support efforts to develop grid-scale energy storage technology by enabling testing and validation of next-generation materials and systems under realistic grid operating conditions.

Roadmapping: The Path Ahead

Progressing Along Technology Pathways

Both the Pacific Northwest National Laboratory's cost and performance and the Storage Innovations 2030 efforts are planned to continue, with report updates planned every two years to examine revised costs and cost projections across a range of energy storage technologies and various power capacities and durations. The Storage Innovations 2030 team is also planning a larger effort to streamline the stakeholder engagement process. Their continued results will help DOE prioritize its RD&D activities and structure its research portfolios to target the highest-impact innovations. Stakeholder engagement will continue to be essential to tracking progress towards the goal.

DOE recognizes the importance of technology prioritization and strategic planning through the duration of the Long Duration Storage Shot, as documented in the forthcoming DOE Energy Storage Strategy and Roadmap (an in-development update to the Energy Storage Grand Challenge 2020 Roadmap [DOE 2020]). To the extent practical, DOE is taking a technology-open approach when optimizing the balance between selecting technology winners and targeting RD&D direction to have the highest impact. For example, in the past two years, both the Office of Clean Energy Demonstrations and Office of Electricity have selected over 20 LDES demonstration projects (totaling nearly $400 million in awards) that include thermal, mechanical, and electrochemical technologies. Cost metrics from these steel-in-ground projects will provide a critical milestone to understand progress towards the Long Duration Storage Shot. As part of an open competitive process in 2024, the Office of Electricity identified three industry consortia to further the shot's goals with various non-lithium electrochemistries. As documented in the Storage Innovations 2030 technology strategy assessments, these electrochemistries will benefit most from these precompetitive R&D activities.

Progress toward the Long Duration Storage Shot goals since 2021 has been substantial, and the thousands of stakeholders working to implement and deploy energy storage technologies are transforming an industry that had minimal presence in the power system only a few years ago. DOE has funded a range of mechanisms to not only track progress on LDES costs but also to accelerate their progress towards achieving the ambitious Long Duration Storage Shot target.

Supporting Next-Generation Innovation

The Storage Innovations 2030 technology strategy assessments identify some of the innovations with the greatest potential to lower the costs of each LDES technology. These lists of innovations are not prescriptive, and each comes with caveats explored in its report, but these results do capture some of the high-impact themes when considering how to lower the costs of specific LDES technologies and are described in Table 1 .

Table 1. Top Three Potential Innovations for Long-duration Energy Storage Technologies as Identified by Storage Innovations 2030

Technology Family	Top Three Potential Innovations To Drive Down Costs of Long-Duration Storage
Flow Batteries	• Novel active electrolytes • Manufacturing for scale • Accelerate the discovery of metrics/materials
Lead-Acid Batteries	• Re-design of standard current collectors • Advanced manufacturing • Demonstration projects
Lithium-Ion Batteries	• Rapid battery health assessment • Controls to improve cycle life • Impurities reduction technique
Sodium (Na) Batteries	• Cathode-electrolyte interface • In-operations materials science research • Electrolyte development
Supercapacitors	• Cell packaging • Hybrid components • Automated manufacturing
Zinc (Zn) Batteries	• Separator innovation • Pack/system-level design • Demonstration projects
Hydrogen Storage	• Liquid hydrogen carriers (above) • Hydrogen carrier advancements (above) • Demonstration (above/below)
Compressed Air Energy Storage	• Demonstration projects • System modeling and design/operation • Mechanical compression/expansion
Pumped Storage Hydropower	• Hybrid pumped storage hydropowers projects • Testing durability of new materials/structures • 3D printing technology at large scale
Thermal Energy Storage	• Single-tank storage • Heat-to-electricity conversion improvements • Large-scale demonstration

Carbon Negative Shot

The third of the Energy Earthshots—Carbon Negative Shot™—was announced on November 5, 2021, and is the all-hands-on-deck call for innovation in technologies and approaches that will remove CO_2 from the atmosphere and durably store it at meaningful scales for less than $100 per net metric ton of CO_2e.

Defining the Goal

The Carbon Negative Shot is the all-hands-on-deck call for innovation in technologies and approaches that will remove CO_2 from the atmosphere and store it at meaningful scales for less than $100 per net metric ton of CO_2-equivalent (net tCO_2e).

Meeting the Mission

Carbon dioxide removal (CDR) has a critical role in helping the United States address the climate crisis and achieve net-zero emissions by 2050. CDR refers to approaches that capture CO_2 directly from the atmosphere and store it in geological, biobased and ocean reservoirs or in value-added products to create negative emissions. To reach our global climate goals, gigatonnes of atmospheric CO_2 must be removed every year by mid-century, alongside aggressive decarbonization (Intergovernmental Panel on Climate Change 2018). To advance the development of this emerging and necessary industry, DOE launched the Carbon Negative Shot.

Measuring: Target Baseline and Assessment Approach

DOE's Carbon Negative Shot portfolio is composed of six CDR approaches, capable of removing CO_2 from the atmosphere at gigatonne scales, with robust measurement, reporting, and verification. These approaches are:

- Direct air capture with storage
- Soil carbon sequestration
- Biomass carbon removal with storage
- Enhanced mineralization
- Marine CDR (mCDR or ocean-based CDR)
- Afforestation, reforestation, and revegetation.

To reach the goal of the Carbon Negative Shot, DOE needs to advance the development of all major CDR pathways. The Carbon Negative Shot aligns expertise, capabilities, and cutting-edge science across DOE to deliver technology improvements that reduce the cost of CDR, facilitating rapid commercialization and scale-up. CDR is a nascent sector without robust, public baseline cost values that relies on voluntary markets to set the price for removing CO_2.

The metric used to measure the progress of the Carbon Negative Shot will be the average cost per net tCO_2e removed, inclusive of the cost of robust measurement, reporting and verification to support that removal for at least 100 years. Given that CDR is a nascent technology and spans methods that are nature-based, engineered or technological, and geochemical, there is no single standard to measure this value. Accurately measuring the progress of the Carbon Negative Shot will require robust analyses, as well as reliable measuring, monitoring, reporting, and verification.

The Carbon Negative Shot's progress will be measured based on analyses and quantitative evaluations of the costs of relevant CDR pathways. It will be updated as pathways and sub pathways progress from laboratory experiments to field tests and demonstrations at scale.

Analyzing Progress Toward the Target

The National Renewable Energy Laboratory-led *Technological Innovation Opportunities for CO_2 Removal* report describes one such quantitative evaluation of the cost reduction potential of technological innovation for a single example case, direct air capture coupled with *in situ* mineralization (Agbo et al. 2024). This example case is illustrated in Figure 4. This assesses the cost of net CO_2 removal, joining techno-economic analysis with life cycle assessment by presenting the cost of capturing and sequestering net atmospheric CO_2, with any energy related upstream emissions counting against net CO_2 removed. Comprehensive evaluations for other CDR pathways and subpathways will enable measuring progress of CDR costs.

In addition to quantitative analyses, DOE will also continually identify and aim to support technological innovation opportunities, both incremental and disruptive. *The Technological Innovation Opportunities for CO_2 Removal* report characterizes potential innovations through qualitative heat maps for each CDR pathway that help identify areas with the greatest potential for cost reduction (Agbo et al. 2024). Such characterizations will help inform DOE's RD&D priorities.

Tracking Action and Accomplishments

DOE has supported RD&D related to CDR well before the launch of the Carbon Negative Shot across its basic and applied programs. These activities have accelerated since the launch of the Carbon Negative Shot, and some important milestones related to funding opportunities and stakeholder engagement are show in Figure 3.

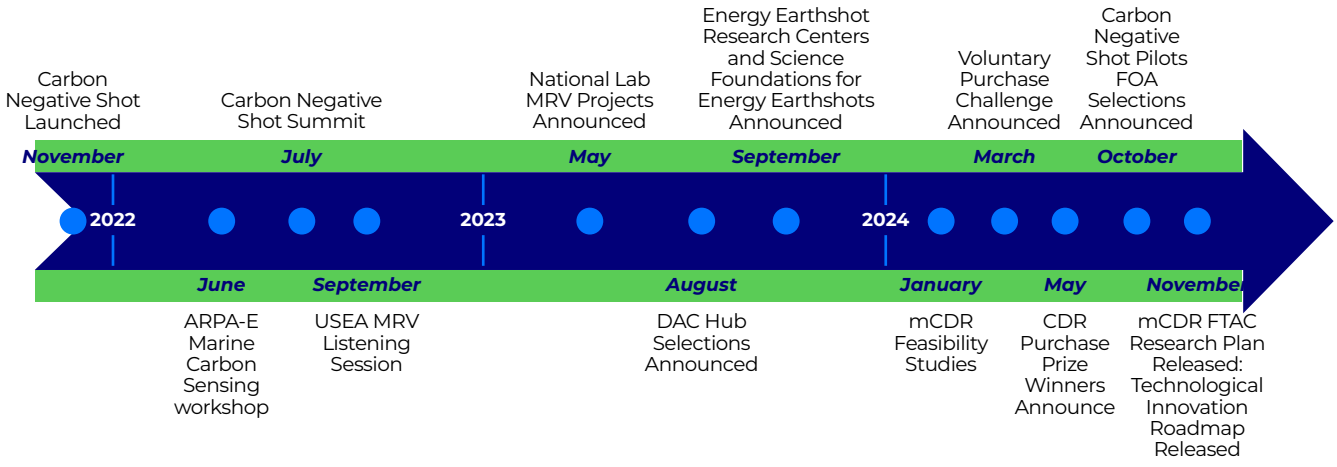


Figure 3. The Carbon Negative Shot has benefited from over 10 efforts since its launch in November 2022 through November 2024, including summits, workshops, listening sessions, project awards, research centers and foundations, studies, prize winners, and reports.

Roadmapping: The Path Ahead

Progressing Along Technology Pathways

Future assessments over the next decade of the costs of CDR and durable storage will involve potential updates of the technological innovation opportunities, the National Renewable Energy Laboratory's Annual Technology Baseline framework (National Renewable Energy Laboratory 2024) to identify technology-specific cost and performance framework and the National Energy Technology Laboratory's Baseline Case Studies (e.g., Valentine et al. 2024), combined with anonymized data submitted as part of the Carbon Dioxide Removal Purchase Pilot Prize and the Carbon Negative Shot Pilots removal projects, the Regional Resource Hubs for Purpose-Grown Energy Crops, and the Mixed Algae Conversion Research Opportunity.

As CDR tax credits, voluntary purchases, and CDR projects mature and operationalize, data from these initiatives will inform both the price and cost of CDR and DOE's future priorities as communicated through multiyear program plans, updates to the *Carbon Management - Pathways to Commercial Liftoff* report (DOE 2023a), DOE strategic documents, in additional to funding opportunities and requests for information.

Ultimately, these analyses, combined with RD&D projects will inform the cost curve of CDR and resource needs. This will, in turn, inform the eventual 2050 CDR portfolio and prime the private sector and market to work with the public sector to effectively remove gigatonnes of legacy CO_2 from the atmosphere.

Supporting Next-Generation Innovation

The *Report of the Basic Energy Sciences Roundtable on Foundational Science for Carbon Dioxide Removal Technologies* identifies priority research opportunities for CDR technologies (Office of Science 2022). The priority research opportunities are based on the virtual roundtable on foundational science for CO_2 removal technologies held by the Office of Science's Basic Energy Sciences program in March 2022 to determine the fundamental knowledge base to underpin the Carbon Negative Shot. This report identifies five priority research opportunities for foundational science advancements in CDR technologies that address key challenges in:

- Mastering interfacial physicochemical processes to improve CO_2 capture efficiency and prevent material passivation.
- Creating materials that simultaneously exhibit multiple properties for CO_2 capture and release or conversion.
- Discovering unconventional pathways and materials for energy-efficient CO_2 capture, release, and conversion.
- Controlling the multiphase interactions required for CO_2 conversion into molecules, minerals, and materials.
- Achieving predictive understanding of coupled processes in complex subsurface geologic systems for secure long-term carbon storage.

The report emphasizes the need for integrated experimental and computational approaches, including advanced in-situ characterization and machine learning, to bridge multiple length and time scales and accelerate the development of effective and scalable CDR technologies.

The *Technological Innovation Opportunities for CO_2 Removal* report identifies several opportunities for incremental and disruptive innovations for CDR, specifically for direct air capture, mineralization, biomass carbon removal with storage and marine CDR (Agbo et al. 2024). Incremental CDR improvements focus on cost reduction and efficiency gains within existing technologies. Examples include optimizing energy use and sorbent performance in direct air capture enhancing reactor design in ex-situ mineralization, improving monitoring and quantifying co-benefits in enhanced rock weathering, and optimizing

processes and supply chains in biomass carbon removal with storage and improving membrane performance and scalability in marine CDR. In contrast, disruptive innovations introduce novel approaches: integrating direct air capture with renewables or byproduct harvesting, employing biological enhancement or advanced sensing in mineralization, utilizing hyperaccumulators to expand enhanced rock weathering applications, developing advanced sensing and durable systems for marine CDR, and enhancing photosynthetic efficiency and feedstock pretreatment in biomass carbon removal with storage.

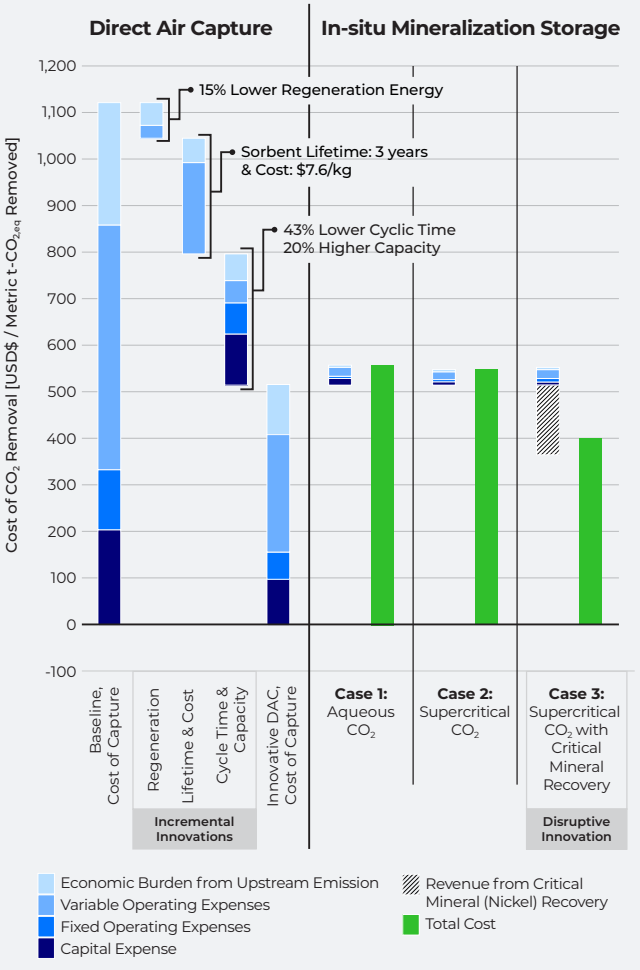


Figure 4. Waterfall chart of potential cost reduction impacts of technological innovation in from the *Technological Innovation Opportunities for CO_2 Removal* report. *Source: Agbo et al. 2024*

Table 2. Qualitative Assessment of the Impact Technological Innovation May Have on the Costs for Various Direct Air Capture Pathways

Direct Air Capture Technology Class	Sorbent Capital Expenditures and Lifetime	Nonsorbent Contactor Capital Expenditures	Regeneration Capital Expenditures	Contactor Energy Demand	Regeneration Energy Demand	Capture Capacity/ Kinetics	Today's Cost at 1 Megaton per Year (In 2023 U.S. Dollars per Ton of Net CO_2)
Amine/Alkali Solid Chemical Adsorbent	High[c]	Low[a]	Low	Low	High	Low	$300–$700
Metal-Organic Framework/Zeolite Solid Physical Adsorbent	Medium[b]	Medium	Medium	Low	Medium	Low	$650
Mineral Solid Adsorbent	Low	Medium	Medium	Low	Medium	Medium	$550
Moisture-Swing Solid Adsorbent	Low	High	Low	Low	Low	Medium	Insufficient data available
Electro-Swing Solid Adsorbent	Very High[d]	Medium	Not applicable	Low	Medium	Low	$700
Hydroxide Liquid Solvent	Low	Medium	Medium	Low	Medium	Low	$400–$700
Amino Acid salt Liquid Solvent	Medium	High	Medium	Low	Medium	Medium	Insufficient data available
Carbonate Liquid Solvent	Low	High	Low	Low	Medium	Medium	Insufficient data available
pH-Swing Liquid Solvent	Low	Medium	High	Low	High	Low	$650
Electro-Swing Liquid Solvent	High	Medium	Medium	Low	High	Medium	Insufficient data available
Membrane	Medium	Low	Medium	Low	Low	Low	Insufficient data available

[a] **Low**: Potential for technology innovation in this category to reduce the cost of direct air capture by <10%.

[b] **Medium**: Potential for technology innovation in this category to reduce cost of direct air capture by 10%–25%.

[c] **High**: Potential for technology innovation in this category to reduce cost of direct air capture by 25%–50%.

[d] **Very High**: Potential for technology

Enhanced Geothermal Shot

90% Reduction

$45/MWh

2035

The fourth of the Energy Earthshots—Enhanced Geothermal Shot™—was announced on September 8, 2022, and is a department-wide effort to dramatically reduce the cost of enhanced geothermal electricity by 90% to $45 per megawatt-hour by 2035.

Defining the Goal

The Enhanced Geothermal Shot is a DOE-wide effort to dramatically reduce the cost of enhanced geothermal systems (EGS)—by 90% to $45 per megawatt-hour by 2035.

Meeting the Mission

Reducing the costs of EGS will spur investments in the technology, in turn unlocking the nation's significant heat resources to provide secure, firm, flexible power for the equivalent of more than 65 million American homes. Increased use of EGS will bolster the robust domestic geothermal industry, provide U.S. jobs that leverage the skilled oil and gas workforce, and offer opportunities to expand geothermal direct use and heating and cooling nationwide.

Measuring: Target Baseline and Assessment Approach

The Enhanced Geothermal Shot target is based on assumptions in DOE's *GeoVision* study, with updates based on recent technology advances (Geothermal Technologies Office 2019). The study estimates the amount of geothermal energy that could be deployed by 2050 based on the Regional Energy Deployment System (ReEDS), a capacity expansion model for the continental U.S. power sector (National Renewable Energy Laboratory 2024). The analysis provides a basis for the Enhanced Geothermal Shot cost reduction target, which is necessary to reach the 90 gigawatts or more of EGS deployment calculated in the analysis.

Two major resources undergirding the Enhanced Geothermal Shot and its goals are the Geothermal Technologies Office's (GTO) multiyear program plan (Porse 2022), and the National Renewable Energy Laboratory Annual Technology Baseline (National Renewable Energy Laboratory 2024). The multiyear plan outlines the GTO's vision and mission, presenting a high-level technology structure for research starting in Fiscal Year 2022 and running through the end of Fiscal Year 2026, whereas the Annual Technology Baseline provides updated model-based values including levelized cost of electricity for various power sources. These values are based on ReEDs scenarios and are the primary metric for the Enhanced Geothermal Shot, providing a comparable cost comparison to other power sources. In the Enhanced Geothermal Shot analysis performed by the National Renewable Energy Laboratory, it is predicted that the capacity weighted average levelized cost of energy of all developed deep-EGS resources in 2035 is $45.6 per megawatt hour and $45.9 per megawatt-hour in 2050 (Augustine et al. 2023). The results were used to develop an Enhanced Geothermal Shot cost target of $45 per megawatt-hour for EGS.

Analyzing Progress Toward the Target

DOE is focused on learning while doing, emphasizing field tests and demonstrations to evaluate and refine technologies and techniques for creating EGS reservoirs. Some key ways of executing this approach include the Frontier Observatory for Research in Geothermal Energy (FORGE), DOE's flagship facility for EGS R&D, and EGS Pilot Demonstrations funded by the BIL. These investments provide measurable returns towards the Enhanced Geothermal Shot goals. DOE also has an extensive R&D portfolio for enabling technologies that are critical to help EGS reach the shot's goal.

Tracking Action and Accomplishments

Since the release of the Enhanced Geothermal Shot, DOE has supported and realized achievements in multiple EGS projects. The most notable of these are advancements in Utah at FORGE. For example, in August 2024, the team at Utah FORGE completed a successful full-scale 30-day circulation test. For the majority of this test, a consistent rate of 420 gallons of water per minute was injected with no drop in injectivity and a constant recovered fluid temperature of ~370°F. In addition to the stimulation success, the facility also realized a seven-fold increase in on-bottom drilling rates from about 14 to 100 feet per hour at an equivalent depth of 6,000 feet, accomplished by adoption of advanced polycrystalline diamond compact drill bits and physics-based workflows developed in the oil and gas industry. These combined results represent significant breakthroughs in creating EGS reservoirs, and the work is providing vast amounts of data that will continue to be made publicly available to support further EGS advances.

In addition, DOE announced selections in the first-round opportunity for EGS Pilot Demonstrations funded by BIL Section 41007 (U.S. Congress 2021b). These projects will support field tests of EGS in differing geographic and geologic settings, including the superhot environment of Newberry Volcano in Oregon, helping increase understanding and prove out EGS in new settings. Findings from these field tests are crucial to help the industry derisk technologies and techniques and identify ways to reduce costs, moving toward the goals of the Enhanced Geothermal Shot. DOE realized numerous other successes across its R&D portfolio, from work to control fluid flow within EGS reservoir fracture networks to improvements in seismic sensors and monitoring techniques and kicked off the Geothermal Energy from Oil and Gas Demonstrated Engineering initiative in late 2024, which aims to leverage the skills and expertise of the oil and gas industry to expand use of geothermal energy.

Roadmapping: The Path Ahead

Progressing Along Technology Pathways

To help drive towards those cost goals, the multiyear plan outlines six primary research areas with associated performance goals and pathways for each: exploration and characterization; subsurface accessibility; subsurface enhancement and sustainability; resource maximization; data, modeling, and analysis; and geothermal integration and awareness. Each of these research areas encapsulates two to four performance goals with the current baseline for each goal and target technological advances. Each research area also includes multiple R&D pathways to achieve these targets. Similarly, DOE developed five pathways specific to achieving the Enhanced Geothermal Shot at the 2023 Enhanced Geothermal Shot Summit:

- Seeing with greater precision.
- Predicting with greater precision.
- Accessing the subsurface.
- Designing and building better wells.
- Manipulating and creating durable reservoirs.

These pathways provide a map for continued DOE R&D investments and engagement from multiple programs and offices, national laboratories, academia, and industry.

Supporting Next-Generation Innovation

DOE has a robust R&D portfolio that is advancing EGS and all geothermal technologies. In September 2024, DOE and the University of Utah reached an agreement to continue funding the Utah FORGE project through 2028 with $80 million in funding. That effort includes extensive infrastructure, robust instrumentation, and data collection and dissemination that can assist industry in understanding and replicating EGS activities. The site's cutting-edge research, coupled with an innovative collaboration and management platform, is helping scientists and engineers identify a replicable, commercial pathway to EGS. In addition, the initiative has selected 30 R&D performers through rigorous competitive solicitations, expanding the universe of research at the site and the knowledge base for EGS.

As noted previously, BIL Section 41007 authorized funding for EGS Pilot Demonstrations (U.S. Congress 2021b). DOE announced the first round of projects in February 2024 with $60 million in funding for three projects to explore innovative drilling, reservoir stimulation approaches, and operations in extreme heat environments. The second-round funding opportunity released in June 2024, targeting EGS demonstration in the eastern United States. These demonstrations, by learning while doing, will provide important information about the potential for and best approaches to EGS in a variety of geologic and geographic settings—including locations with no existing geothermal power development.

In addition to supporting pilot demonstrations and field tests, DOE will continue to invest in enabling technologies for EGS. The Geothermal Technologies Office recently selected five projects to improve wellbore integrity in high-temperature geothermal wells, through the development of tools needed to evaluate well cement and casing in severe geothermal environments. DOE is also funding the Geothermal Geophone Prize, supporting the nation's innovators and entrepreneurs to rapidly discover, develop, and deliver new high-temperature downhole seismic sensors, which could help researchers and industry professionals better understand and track changes in the subsurface during EGS stimulation. The prize is in its final round as of the end of 2024, with five innovators developing prototypes for field testing. Other current and planned future EGS research includes the development of active methods to control flow through created fractures, drilling demonstrations, and the capturing of geothermal energy from existing oil and gas assets, as well as leveraging the extensive knowledge, technologies, skill, and experience of the oil and gas sector to expand geothermal deployment. All data from funded projects are available through the Geothermal Data Repository on DOE's OpenEI website, helping to address the need for more and better-quality data to derisk technologies like EGS.

Through these efforts and others, DOE is advancing EGS toward the goals of the Enhanced Geothermal Shot through basic and applied research, interagency cooperation, community engagement, and collaboration with industry, academia, and national labs.

Recent technical progress, the depth and breadth of RD&D projects, industry partnerships, and a strong collaborative network all reflect steady progress toward the Enhanced Geothermal Shot, with the possibility that its goal may even be achievable ahead of schedule. Scaling demonstrations and field tests will be paramount to reaching this goal and realizing the extensive potential of EGS to contribute to the nation's clean energy future.

Floating Offshore Wind Shot

>70% Reduction

$45/MWh

2035

The fifth of the Energy Earthshots—Floating Offshore Wind Shot™—was announced on September 15, 2022 with the goal of driving down costs to $45 per megawatt hour by 2035 to spur U.S. leadership in floating offshore wind technology, accelerate decarbonization, and deliver benefits for coastal communities.

Defining the Goal

The Floating Offshore Wind Shot is an initiative to drive U.S. leadership in floating offshore wind design, development, and manufacturing. The Floating Offshore Wind Shot is an interagency initiative led by DOE, the U.S. Departments of the Interior, Commerce, and Transportation. The Floating Offshore Wind Shot seeks to reduce the cost of floating offshore wind energy by more than 70% by 2035 for deep-water sites far from shore.

Meeting the Mission

Researchers have estimated that U.S. offshore wind energy has a total resource potential of 4.2 terawatts, which is 3 times greater than the total electricity-generating capacity operating in the country in 2023 (Lopez et al. 2022; Energy Information Administration 2023). Approximately two-thirds of this offshore wind energy potential is located where the water is too deep for standard fixed-bottom offshore wind energy technologies, so floating technologies are needed. The National Renewable Energy Laboratory has conducted an initial analysis of the economic and deployment implications which suggested that reaching the Floating Offshore Wind Shot cost target could result in economic deployment of an estimated 96–121 gigawatts of floating offshore wind energy by 2050 (Mai et al. 2023). Floating offshore wind energy deployment at that scale would also spur economic, workforce, health, and environmental benefits.

Measuring: Target Baseline and Assessment Approach

The National Renewable Energy Laboratory estimated a levelized cost of energy for a precommercial, deep-water floating offshore wind power project in 2022. A projected global deployment of 31 gigawatts by 2035 resulted in a levelized cost of energy target of $45 per megawatt-hour by 2035, a 70% reduction from the 2022 estimate.

To support this initial cost target analyses, the lab is currently working on a project to characterize a framework structured around five mechanisms, each of which can result in cost reductions and be used to outline innovation pathways: materials, equipment, labor, energy yield, and risk.

Analyzing Progress Toward the Target

In addition, there are several pre-existing annual reports and analyses that support the Floating Offshore Wind Shot by tracking the deployment and levelized cost of energy trajectory of offshore wind. Although these are not specific to this Energy Earthshot, they characterize many aspects of the floating offshore wind energy industry that are relevant, including the levelized cost of energy, global and United States project pipelines, technology and supply chain development, and market readiness. These reports include the:

- *Offshore Wind Market Report*, which provides detailed information on the United States and global offshore wind energy industries, including project pipeline information, macroeconomic conditions, supply chain developments, deployment actions, and cost trends for both fixed bottom and floating offshore wind (Wind Energy Technologies Office 2023).
- *Offshore Wind Annual Technology Baseline*, which provides cost and performance projections across a range of RD&D advancements scenarios, resource characteristics, sites, prices, and financial assumptions. Projected parameters include capital expenditures, operation and maintenance expenditures, capacity factors, and levelized cost of energy (National Renewable Energy Laboratory 2023).
- *Cost of Wind Energy Review*, which provides a levelized cost of energy estimate for floating offshore wind, using a representative project off the Pacific Coast, and includes sensitivity analyses showing the range of effects that variables could have on the cost of wind energy (Stehly et al. 2022).

Since the original cost target was established in 2022, global macroeconomic conditions have shifted the likelihood of reaching the Energy Earthshot cost target. The inflationary pressures that negatively impacted fixed-bottom offshore wind prices and supply chains in the past two years also led to increased estimated levelized cost of floating offshore wind energy (Department of Energy 2024). The overall slowdown of the offshore wind energy industry will likely cause delays in deployment because of supply chain setbacks. Some developers have reduced their aspirations as costs rise and are instead focusing on lower-risk and nearer-term markets. This does not change the Energy Earthshot's overarching goal of achieving a dramatic, 70% reduction in the levelized cost of floating offshore wind energy by 2035; instead it shifts the absolute nominal value of the cost target and makes near-term deployment and infrastructure development even more important.

In May 2024, the Floating Offshore Wind Shot's federal partners published the *Floating Offshore Wind Shot Progress and Priorities Report*, which describes the significant investments and actions supporting the Energy Earthshot since it launched and the near-term priorities for future work (Wind Energy Technologies Office 2024). In addition to ongoing planning, leasing, and other supporting actions, these agencies have resulted in over $950 million in support for research, development, supply chain, demonstration, and deployment efforts associated with this Energy Earthshots since it was announced in September 2022. This support includes direct federal investments, associated cost share, and lease-related bidding credits. Highlighted accomplishments in this report include that:

- The U.S. Department of the Interior's Bureau of Ocean Energy Management held the first floating offshore wind lease auction off the coast of California in December 2022 and the second in the Gulf of Maine in October 2024. The also released the final wind energy lease areas off the coast of Oregon in February 2024.
- In January 2024, DOT announced a $426.7 million award to establish the first offshore wind terminal on the Pacific Coast funded by the Infrastructure For Rebuilding America program.
- DOE launched the three-phase, $6.85 million investment Floating Offshore Wind ReadINess Prize to develop the domestic supply chain for floating offshore wind energy.
- In April 2024, the Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control program from DOE's Advanced Research Projects Agency – Energy announced $38 million in additional funding to six projects to develop floating offshore wind designs.
- DOE invested over $18 million to support high-voltage, direct current voltage source converter systems and standards, controls, and curricula, announced September 2023.
- The Sea Grant Offshore Wind Liaison Program, supported by DOE and the U.S. Department of Commerce, was expanded to Washington, Oregon, and California to ensure continued discussion with communities related to floating offshore wind energy.

Roadmapping: The Path Ahead

Progressing Along Technology Pathways

The Floating Offshore Wind Shot represents an ambitious goal that requires an unprecedented effort across the federal government and the entire industry along with careful planning of priority activities and progress tracking. In addition to the annual reports listed above that track levelized cost of energy, future progress tracking could include national laboratory-led Floating Offshore Wind Shot-specific cost modeling, providing updates to the original analyses used to establish the cost target, taking major macroeconomic shifts into consideration. DOE is tracking other means of progress including engagement efforts, supply chain investments, the floating offshore wind energy project pipeline and installed capacity, and dollars dedicated to RDD&D efforts for Energy Earthshot-related activities. The strategic framework for the Floating Offshore Wind Shot was based on DOE's *Advancing Offshore Wind Energy in the United States* strategy report (Brown-Saracino et al. 2023). Working closely with our federal partners, we intend to use this strategy to guide priority actions under the Floating Offshore Wind Shot for the next several years.

Supporting Next-Generation Innovation

As described in the *Floating Offshore Wind Shot Progress and Priorities Report*, this shot's federal partners have identified a set of near-term priorities for each of its pillars (Wind Energy Technologies Office 2024). These priorities outline the major challenges still facing floating offshore wind deployment and highlight the importance of continuing innovation, such as:

- Cost reductions trough technology innovation to advance resource assessment research, floating system designs and modeling, manufacturing techniques, and operations and maintenance systems.
- Domestic supply chain development to identify gaps and solutions to inform decision making and develop robust, regional supply chains, while mobilizing critical investment through federal programs and lease bidding credits.
- Expanded, just, and sustainable deployment to advance siting and leasing of floating offshore wind, increase Tribal engagement, improve the understanding of impacts on the environment, fisheries, and communities, and develop the workforce.
- Transmission development to complete in-depth offshore wind transmission studies, improve planning tools and models to support the development of offshore transmission, and advance critical offshore high-voltage direct current transmission components.
- Cogeneration opportunities to conduct techno-economic analyses, technology R&D, and demonstration-scale deployments for floating offshore wind-to-X technologies (such as hydrogen production) and energy storage systems.

These priorities have the potential to significantly advance floating offshore wind deployment in the Unites States and drastically reduce costs. As this clean energy generation technology is at a nascent stage, cost modeling and analyses and deployment milestones can help demonstrate the impact of the Floating Offshore Wind Shot. Together with other federal offices, DOE will work to track the investments dedicated to the Floating Offshore Wind Shot and continue to engage with stakeholders to proactively plan future federal actions. The actions taken under this shot today will enable the future success of the technology, help achieve reduced costs, and provide clean energy to American communities along with economic, workforce, health, and environmental benefits.

Industrial Heat Shot

85% Reduction

2035

The sixth of the Energy Earthshots—Industrial Heat Shot™—was announced on September 21, 2022 and is a DOE-wide initiative to develop cost-competitive industrial heat decarbonization technologies with at least 85% lower greenhouse gas emissions by 2035.

Defining the Goal

The Industrial Heat Shot seeks to develop cost-competitive industrial heat decarbonization technologies with at least 85% lower greenhouse gas emissions by 2035.

Meeting the Mission

Developing these technologies will put the American industrial sector on course to reduce its carbon equivalent emissions by 575 million metric tons by 2050, roughly equal to the annual emissions generated by all passenger cars currently on the road (Industrial Efficiency and Decarbonization Office 2024). The Industrial Heat Shot will enable decarbonization of the industrial sector and help reach the goal of a net-zero emissions economy by 2050.

Measuring: Target Baseline and Assessment Approach

As part of the development of the Industrial Heat Shot, baselines for the current emissions intensity of process heating were developed using data, such as those in DOE's Industrial Efficiency and Decarbonization Office's Manufacturing Energy and Carbon Footprints (2021).The Industrial Heat Shot goal was designed to be inclusive of approaches like combustion of clean hydrogen and use of electricity from a decarbonizing grid.

Since its inception, the Industrial Heat Shot has focused on three pathways to decarbonize industrial heat: generating heat from clean electricity, integrating clean heat from alternative sources, and innovating low- or no-heat process technologies. Additionally, the Industrial Heat Shot recognizes the need for enabling cross-cutting technologies, like thermal energy storage and advanced materials.

These pathways are a key organizing principle for assessing progress. Techno-economic analysis and life cycle assessment, using, for example, the Techno-economic, Energy, & Carbon Heuristic Tool for Early-Stage Technologies Tool (TECHTEST Tool), will help track technical progress and relate it to quantifiable impacts at project and portfolio levels. Some identified candidate impact metrics include emissions intensity, levelized cost of heating, cost of abated carbon, and environmental impact factors. Some identified candidate impact metrics include emissions intensity, levelized cost of heating, cost of abated carbon, and environmental impact factors.

Analyzing Progress Toward the Target

Progress on the Energy Earthshot was highlighted throughout the first Industrial Heat Shot Summit in October 2023. In complement to the summit, DOE has published various analyses and strategic documents related to advancing technologies along these pathways, including the *DOE Industrial Decarbonization Roadmap* and *Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy* (DOE 2022; Cresko et al. 2022). As outlined in the *Pathways to U.S. Industrial Transformation: Unlocking American Innovation* report, DOE is pursuing analysis to identify and explore pathways to grow the U.S. industrial sector and sharpen the nation's competitive edge and national security while bending the sector's decreasing greenhouse gas emissions trend (Industrial Efficiency and Decarbonization Office 2024).

Tracking Action and Accomplishments

Since before its September 2022 announcement in Pittsburgh, Pennsylvania, program offices at DOE have been busy laying the foundations advancing the goal of the Industrial Heat Shot. In the last two years, the Industrial Efficiency and Decarbonization Office within the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy and Carbon Management, the Office of Nuclear Energy, the Office of Science and the Office of Clean Energy Demonstrations have accomplished an impressive list of milestones and deliverables related to the Industrial Heat Shot (Figure 5).

The Office of Science has recently made significant investments in the award of eleven national laboratory-led energy earthshots research centers, two of which target the Industrial Heat Shot, and 18 university-led science foundations for the Energy Earthshots projects. These awards were specifically designed to provide foundational knowledge important for a wide range of different fields and technological areas. Activities related to the Industrial Heat Shot are focused on understanding physio-chemical mediated processes to reduce energy inputs into industrial processes like steel manufacturing or oil and gas refining.

Additionally, DOE selected Arizona State University to lead the new institute, the Electrified Processes for Industry Without Carbon, to drive industrial decarbonization through electrification of process heat. This is the seventh Clean Energy Manufacturing Innovation institute and is a public-private

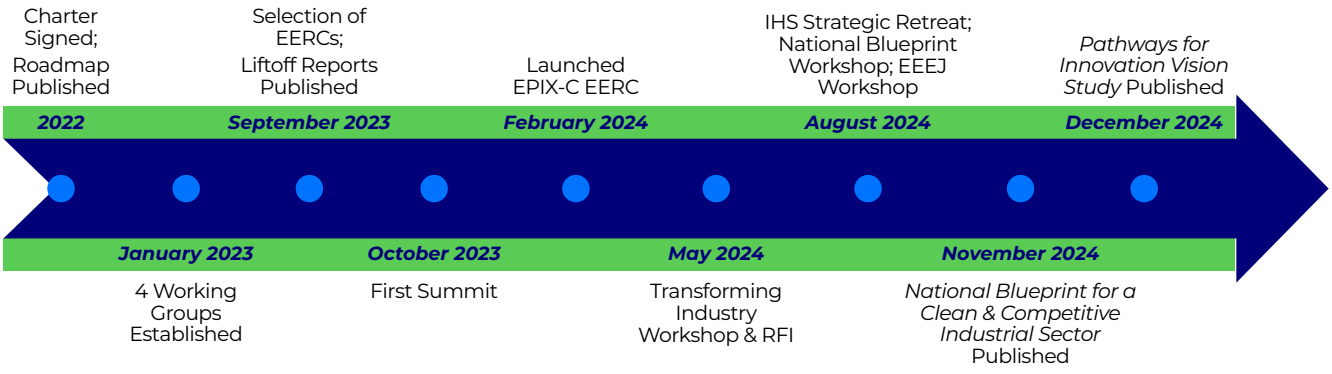


Figure 5: Since the Industrial Heat Shot's inception in 2022, many efforts across DOE have worked toward the shot's goal, including reports, roadmaps, summits, workshops, working groups, and opportunities to gather feedback.

partnership aimed at securing U.S. manufacturing competitiveness in a global economic environment that increasingly demands eliminating carbon emissions by developing the technologies and workforce required to transition fossil-fuel-based heating to electric heating.

In 2023, to coincide with the three identified pathways to decarbonization as well as the necessity of underpinning technologies, four working groups were established and presented at the first Industrial Heat Shot Summit, which focus on

- Heat from clean electricity
- Heat from alternative sources
- Innovative low- or no-heat solutions
- Thermal energy storage.

Roadmapping: The Path Ahead

Progressing Along Technology Pathways

Quantitatively tracking progress in the development of industrial heat decarbonization technologies is a significant challenge. Thermal processes are pervasive in industry, but there is wide diversity in temperature demands, equipment, processes, and applications (Cresko et al. 2022). Furthermore, the scope of the Industrial Heat Shot includes a wide range of technologies with different technology readiness levels, techno-economics, applications, and stakeholders (Cresko et al. 2022). DOE will coordinate across program offices and conduct careful, rigorous analysis to develop a consistent methodology to evaluate the emissions impact, the cost, and the level of development of these technologies.

For each Industrial Heat Shot pathway, DOE will identify a collection of representative technologies and track investments to advance those technologies. Over time, additional supporting analysis will allow us to layer on dimensions and complexity. For example, DOE will:

- **Track projects' technology readiness levels and adoption readiness levels** across pathways and representative technologies to demonstrate how DOE investments are advancing decarbonization of industrial heat. DOE can leverage this data to make more impactful funding decisions and to accelerate market adoption.
- **Map technologies to industrial processes** to determine how much heat demand is addressable by technologies in development. This analysis will also support effective resource allocation and highlight disparate needs between industries.
- **Assess technology cost and impact** to demonstrate declining costs and environmental impacts. Because of industrial process heterogeneities, each pathway requires unique modeling approaches to assess long-term impacts.

Collecting data from across the participating offices, the number of investments for each pathway and technology area can be tracked through the innovation pipeline (Table 3).

Table 3. Example of Tracking Investments for the Industrial Heat Shot

Projects Related to Integrating Clean Heat from Alternative Sources	Representative Technology 1	Representative Technology 2	Representative Technology 3
Foundational Science	1	0	2
Applied R&D	2	2	3
Demonstration	1	2	0

To conduct these assessments, DOE will leverage national laboratory teams and expertise, draw on existing publications, and pursue new analysis. New analysis may be conducted by a national-laboratory-based strategic analysis team, which maintains expertise in the industrial sector and thermal processes, through open solicitation or through other methods. To support the analytical efforts undertaken by the labs, DOE is building a library of relevant industrial emissions analyses and technology assessments.

Decarbonizing and assessing industrial heat are both significant challenges. The Industrial Heat Shot will lead DOE's efforts, leveraging the world-class analytical resources within our organization and national labs to spearhead a rapid, global decarbonization of industrial heat.

Supporting Next-Generation Innovation

Developing cost-competitive industrial heat decarbonization technologies with at least 85% lower greenhouse gas emissions is an ambitious and challenging goal that will require continued investment along the innovation pipeline. Thermal processes are essential and pervasive across industry, every industrial subsector uses heat in different ways to make products, and innovations in fundamental advancements to improve thermal technologies must also include innovations for application specific uses. As a result, advancement is needed across a portfolio of technologies spanning all pathways of the Industrial Heat Shot, which are:

- **Generating heat from clean electricity.** Technology areas include high-temperature heat pumps and electromagnetic heating. Innovations are needed to increase the operating temperature of heat pumps to expand use for medium-temperature processing, and scaling electromagnetic heating equipment (e.g., microwaves) to commercially relevant industrial scale.
- **Integrating clean heat from alternative sources.** Technology areas include solar thermal, small modular nuclear reactors, geothermal, hydrogen, and sustainable fuels. Innovations are needed to enable integration of co-located clean heat sources into industrial unit operation and facilities.
- **Innovating low- or no-heat process technologies.** Technology areas include bio-based manufacturing, electrochemical processes, ultraviolet curing, and advanced membrane separations. Materials and engineering science RD&D is needed to enable innovations in production routes that allow for materials transformations with substantially lower thermal inputs.
- **Enabling technologies and systems.** Technology areas include thermal energy storage, novel materials, modeling and simulation, controls systems, and data analytics. Application of machine learning and artificial intelligence could allow for faster innovation and uptake systems with optimized operations.

Developing these technologies will reduce the energy and emissions intensity of industrial processes, increase the global competitiveness of U.S. industry, and provide a pathway for companies to fulfill their sustainability commitments. Beyond energy and emissions impacts, innovative process heating technologies can provide benefits, such as reduced heating time, improved temperature uniformity, reduced manufacturing cost, improved product quality, higher product yield, reduced waste byproducts, and other cobenefits.

Across this portfolio, investment is needed to develop new and improved technologies, to ensure new technologies meet or exceed operational demands, to quantify nonenergy co-benefits and address cost competitiveness, and to scale up toward commercialization. RD&D pathways for many of these technologies are described in DOE's report Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy (Cresko et al. 2022). Going forward, DOE offices advancing these technologies will continue to coordinate investments to achieve the ambitious goals of the Industrial Heat Shot.

Clean Fuels and Products Shot

85% Reduction

2035

The seventh of the Energy Earthshots—Clean Fuels & Products Shot™—was announced on May 24, 2023, and is a Department-wide initiative focused on decarbonizing the fuel and chemical industry through alternative sources of carbon to advance cost-effective technologies with a minimum of 85% lower greenhouse gas emissions by 2035.

Defining the Goal

The overall objective of the Clean Fuels and Products Shot is to decarbonize the fuel and chemical industries through alternative sources of carbon with a goal that by 2035, developing cost-effective technologies from alternative feedstocks with a minimum of 85% lower greenhouse gas emissions compared to a 2019 baseline of petroleum-based products.

This goal will advance the vision of using sustainable carbon resources to meet a significant portion of projected 2050 demands for 100% of aviation fuel; 50% of maritime, rail, and off-road fuels; and 50% of carbon-based chemicals.

Meeting the Mission

Carbon-based fuels and chemical intermediates play pivotal roles in modern daily life and society, helping to meet transportation and consumer product needs. Given that fuels, chemicals, and other products are overwhelmingly produced from fossil-based feedstocks that result in significant net greenhouse gas emissions during processing and consumption, alternative feedstocks from renewable resources and more efficient processing routes are necessary to achieve the U.S. goals towards a net-zero greenhouse gas emissions economy. The scale of decarbonization effort needed requires a multifaceted approach, which targets diverse sets of feedstock resources that can be transformed by a range of conversion technologies to produce the fuels, chemicals and other products needed to maintain our society.

Measuring: Baselines and Assessment Approach

Numerous studies and reports help to define the current status of the Clean Fuels and Products Shot and direct strategic efforts toward the goal. A subset of these reports, which highlight the breadth of DOE efforts relevant to the Clean Fuels and Product Shot, include:

- *SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel Report* (DOE, U.S. Department of Transportation, U.S. Department of Agriculture 2022)
- *Industrial Decarbonization Roadmap* (Industrial Efficiency and Decarbonization Office 2022)
- *Bioenergy Technologies Office Multi-Year Program Plan 2023* (Bioenergy Technologies Office 2023)
- *Pathways to Commercial Liftoff: Decarbonizing Chemicals & Refining* (DOE 2023d)
- *2023 Billion-Ton Report* (Langholtz 2024)
- *Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process* (Rosales-Calderon et al. 2024a)
- *Sustainable Aviation Fuel State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway* (Rosales-Calderon 2024b)
- *Carbon Utilization Infrastructure, Markets, and Research and Development: A Final Report* (National Academies of Sciences, Engineering, and Medicine 2024)
- *Pathways to Commercial Liftoff: Sustainable Aviation Fuel* (DOE 2024c)

- *Sustainable Aviation Fuel Grand Challenge Roadmap Implementation Framework* (DOE, U.S. Department of Transportation, U.S. Department of Agriculture, U.S. Environmental Protection Agency 2024)
- *Pathways for U.S. Industrial Transformation: Unlocking American Innovation*, full report in preparation.

To reach the goals of the Clean Fuels and Products Shot, a multitude of technologies will need to be developed across the life cycles of diverse renewable resources, conversion technologies, and final products. Therefore, assessing progress in this Energy Earthshot is incredibly complex and a multidimensional approach is required.

With a goal to align and accelerate research across offices and industry, DOE will track technology development from basic science to applied R&D to pilot/demonstration stages in three key areas: fuel production pathways, chemical production pathways, and resource mobilization. The approach encompasses projects funded at universities, national labs, small and large businesses, nonprofit organizations, and consortia. Importantly, life cycle analysis and societal considerations are considered on a project- and technology-specific basis. DOE has conducted an initial analysis using this approach for this report, collecting information for projects associated with the Clean Fuels and Products Shot from offices including the Bioenergy Technologies Office, Industrial Efficiency and Decarbonization Office, FECM, Office of Science, Office of Clean Energy Demonstrations, Advanced Materials and Manufacturing Technologies Office, HFTO, and Advanced Research Projects Agency-Energy. The results of this initial analysis, summarized in Figure 6, help to visualize progress across the breadth of the fuels and chemicals industries, align research efforts, and identify research gaps.

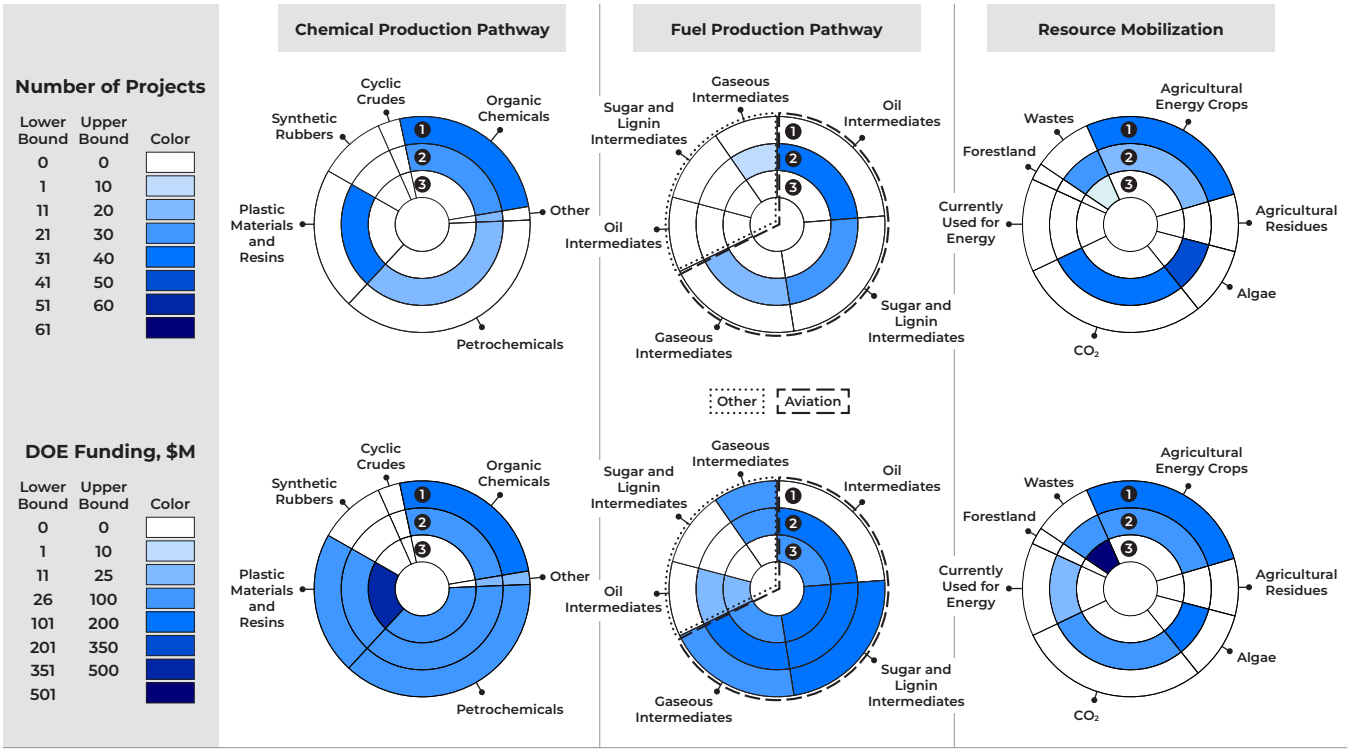


Figure 6. Technology development status for the Clean Fuels and Products Shot is shown in this figure. Color indicates that a sustainable feedstock pathway has reached specified technology development. 10.9% of the funding captured in this dashboard is duplicated between Production Pathway and Resource Mobilization charts and that duplication is intended to capture the full impact of funded work. Projects reported by DOE offices associated with this Energy Earthshot, documenting 445 relevant investments totaling over $4 billion. Offices providing data include: Bioenergy Technology Office, Industrial Efficiency and Decarbonization Office, FECM, Office of Science, Office of Clean Energy Deployment, Advanced Materials and Manufacturing Technologies Office, HFTO, Advanced Research Projects Agency-Energy.

Analyzing Progress Toward the Target

To analyze progress toward the goal of the Clean Fuels and Products Shot, DOE plans to track technology development stage annually using the approach described in the previous section. Energy Earthshots are ambitious decadal innovation efforts and to realize the benefits, the portfolio of projects must continue to rise above business as usual. It is important to front load the innovation pipeline and maintain support to ensure that diverse concepts are evaluated. Only then will innovations be ready for pilot and demonstration testing to support successful commercial liftoff. A healthy pipeline narrows in these later stages based on technological and commercial viability determined through by experimentation, analysis, and diverse stakeholder input.

Each major resource mobilization feedstock category in the Clean Fuels and Products Shot (e.g., energy crops, agricultural residues, wet waste, CO_2, etc.) will require successful resource supply chains and demonstrations of different technology pathways for utilization. Representative fuel and chemical pathways will require multiple piloting and demonstration projects for advancing catalytic and biocatalytic pathways. In particular, the U.S. chemicals subsector is diverse, producing over 70,000 different products (CISA 2022). Given the complexity and breadth of the chemicals sector, it would be expected that the pipeline of projects for chemicals is more numerous than that for fuels at all stages. Achieving the Clean Fuels and Product Shot goal and commercializing new clean fuels and products is possible. To underpin that, a healthy pipeline of projects across the RD&D spectrum must continuously build knowledge by tacking the challenges inherent in innovation and first-of-a-kind product development. An indicator of future success is simultaneously seeing the project count of pilots and demonstrations increase for a full range for feedstocks, fuels, and chemicals.

Tracking Action and Accomplishments

Figure 7 highlights important events and significant investments that occurred over the course of the eighteen months since the Clean Fuels and Products Shot was announced. These key actions and accomplishments stand alongside the key reports highlighted above and align with the four pillars of high-priority research areas for this shot, defined below.

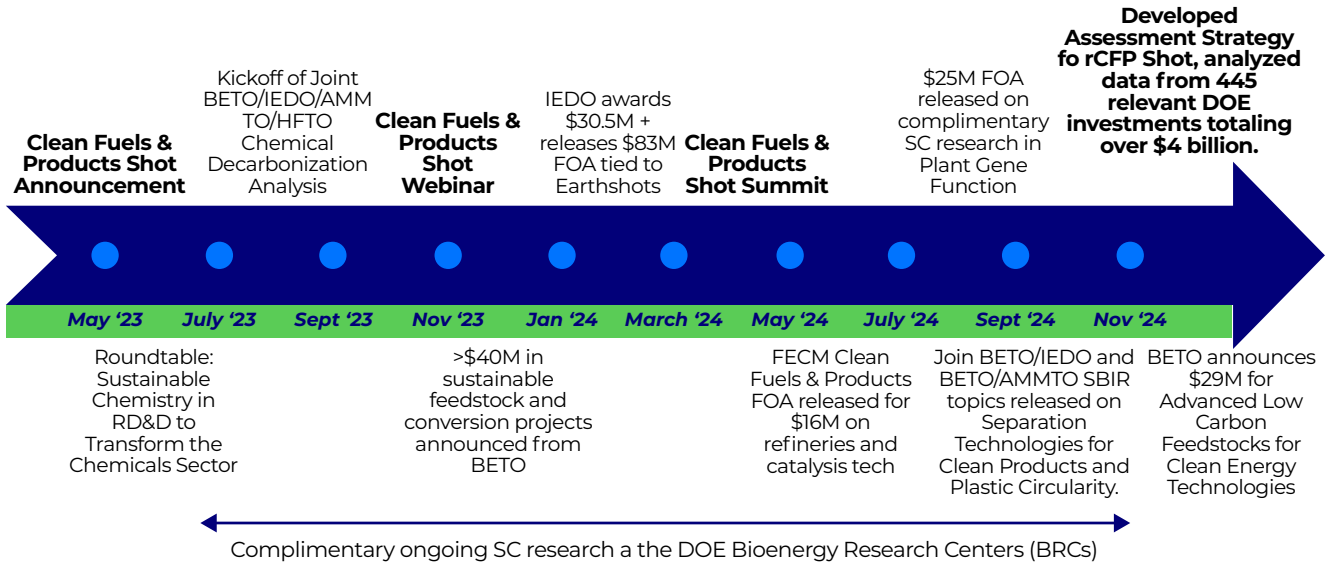


Figure 7. Significant events and investments that have been publicly announced over the 18 months since the Clean Fuels and Products Shot was announced in May 2023 include roundtable discussions, analyses, funding awards and projects, webinars, summits, and reports.

Roadmapping: The Path Ahead

Progressing Along Technology Pathways

Four key pillars have been defined as high-priority research areas to develop clean fuels and products. DOE is coordinating across offices to strategize, collaborate, and advance the state of technology in these areas, which are:

- **Resource and feedstock mobilization** to foster low-cost and resilient resource production and supply systems that are sustainable, increase resource circularity, and address challenges at resource-feedstock-conversion interfaces.
- **Carbon-efficient conversion processes** to advance catalytic and biocatalytic pathways that further develop and improve feedstock conversion, separations, and process design.
- **Technology scaling and demonstration** to test next-generation technologies and processes at scale, address commercial adoption barriers, and inform future innovation from deployment data. This will also de-risk technologies and integrate diverse sources of clean energy (electricity, wind, solar, modular nuclear, etc.) and clean hydrogen, leading to rapid adoption while providing end-use market solutions.
- **Consideration of broader societal impacts beyond technology** to create cradle-to-grave life cycle assessment and sustainability modelling to prioritize R&D efforts. This will also couple the monitoring of economywide resource impacts with purposeful integration of tailored, regionalized strategies.

Ongoing analysis within DOE offices and national labs will continue to inform Clean Fuels and Products Shot priorities. Further, each program office is continuously engaged with industry and other stakeholders through research project portfolios, workshops, and requests for information. When envisioning the path forward, DOE plans to use the assessment approach described to communicate and engage with stakeholders.

Transitioning to clean fuels and products will also lead to various community impacts. These impacts could be both positive (e.g., job creation) or negative (e.g., increased local air pollution or truck traffic). Therefore, additional key priorities for this Energy Earthshot include better elucidating the community impacts of biofuel, bioproduct, and other alternative feedstock-related infrastructure as well as determining best practices for engaging communities and equitably siting of clean fuel and product-related infrastructure to minimize any negative impacts. In line with these priorities, DOE's Bioenergy Technologies Office in coordination with DOE's Energy Justice and Equity Office is hosting regional listening sessions to discuss bioenergy infrastructure siting.

Supporting Next-Generation Innovation

The goal to develop fuel and chemical production pathways with at least 85% lower greenhouse gas emissions is highly ambitious. Certain promising technologies are progressing towards reaching this goal. For example, hydrotreated esters and fatty acids technology has advanced to a stage where it is expected to produce a large proportion of the sustainable aviation fuel in the next five years as reported in multiple recent reports, including those highlighted previously (e.g., Rosales-Calderon et al. 2024). Based on the National Renewable Energy Laboratory's *Sustainable Aviation Fuel State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway* report, producing aviation fuel with yellow grease (a used cooking oil) has the potential to reduce greenhouse gas emissions by 80% (Rosales-Calderon et al. 2024). However, the projected supply of yellow grease could only meet a small proportion of projected aviation fuel demand as reported in the *2023 Billion-Ton Report* (Langholtz, 2024). This example highlights the need for parallel development of low-carbon-intensity feedstocks and advanced technologies that can meet the projected volumetric needs for aviation fuel. This concept can be extended to many categories of clean fuels and products, where no single feedstock or conversion technology is likely to alone replace the fossil-based fuel or product. Further, 96% of U.S. goods are manufactured using chemical sector products (Cybersecurity and Infrastructure Security Agency 2022). Significant innovation is needed for cost-effective and sustainable technological growth.

Altogether, a substantial, coordinated effort across DOE offices and interagency partners will be necessary to drive these technologies forward and integrate them into complete fuel and chemical production pathways that can fully realize the Clean Fuels and Product Shot's vision. DOE technology offices driving the Clean Fuels and Products Shot will continue to communicate regularly to strategize and incorporate lessons learned to move promising technologies forward in development stage.

Affordable Home Energy Shot

>50% technology cost reduction

20% lower energy bills

1 decade

The eighth of the Energy Earthshots—Affordable Home Energy Shot™—was announced on October 12, 2023, and is a departmentwide initiative focused on accelerating breakthroughs to reduce the cost of energy-efficient retrofits in affordable homes by at least 50% and decrease residents' energy costs by at least 20% within a decade.

Defining the Goal

DOE launched the eighth of the Energy Earthshots—the Affordable Home Energy Shot—in October 2023 to reduce the upfront cost of upgrading a home by at least 50% while reducing energy bills by 20% within a decade.

Meeting the Mission

The Affordable Home Energy Shot aims to enable upgrades to American homes and improve energy affordability. Nearly one in four households nationwide experiences high energy burdens; as a result, more than 20% fell behind on their energy bills in 2023 (U.S. Census Bureau 2024). These trends disproportionately impact lower-income residents who live in older homes that often lack adequate insulation and energy-efficient appliances. This is based on 80% of area median income definition is based on U.S. Department of Housing and Urban Development's definition of "low-income" used for several of their affordable housing programs (Office of Community Planning and Development 2024).

Although the Affordable Home Energy Shot is dedicated to affordable housing, the innovations that are achieved will benefit everyone everywhere.

Measuring: Target Baseline and Assessment Approach

The Affordable Home Energy Shot is dedicated to addressing the needs of affordable housing, which DOE defines as single-family, multifamily, and manufactured homes occupied by households earning less than 80% of the area median income. This is based on 80% of area median income definition is based on U.S. Department of Housing and Urban Development's definition of "low-income" used for several of their affordable housing programs (Office of Community Planning and Development 2024).

DOE estimates that 45% of affordable homes already can be upgraded cost-effectively today without any new R&D or technology—even when assuming that electrical infrastructure and ductwork upgrades are necessary in many homes. At the same time, there is a large fraction of affordable homes where upgrade packages are not currently cost-effective, even with incentives. These homes are the focus of the shot's innovation strategy.

Technology Mix

To achieve the Affordable Home Energy Shot target, DOE is focused on innovations in three pivotal areas which form the pillars of the Affordable Home Energy Shot:

- **Upgrading the building envelope**—the windows, walls, foundations, and roofs—to address the livability and comfort of indoor environments, making for healthier and more resilient homes.
- **Efficient electrification**, which will improve the affordability and comfort of low- to moderate-income homes, expanding community access to air conditioning.
- **Smart controls**, which are digital controls that can lower electric bills by managing home energy use through communication with the electric utility.

However, no single technology—or group of technologies—can achieve the target alone. To achieve customer-focused, affordable decarbonization, all three pillars of innovation must work together to build a foundation of deep energy-efficiency retrofits layered with efficient electrification and grid-enabling controls.

Setting the Baseline

DOE intends releasing a report in early 2025 to document the process used to set the numeric targets for the Affordable Home Energy Shot. The authors conducted a literature review and analysis to select an upfront cost reduction target that, if applied to the benchmark packages, would result in upgrades being cost-effective in most affordable housing units, including the application of modest incentives necessary in some situations. The target of 50% reduction in the upfront installed cost was selected as a balance between aggressiveness and achievability. This target includes the hard and soft costs of installation, including the cost of electrical upgrades.

The authors additionally determined an energy cost savings target that corresponds to the approximate level of energy cost savings resulting from the benchmark package. A target 20% reduction in energy bills was selected based on the median energy cost reduction resulting from benchmark upgrade packages in the most challenging climate and housing stock segment.

Together, these target selections result in most affordable homes in all states (85% of affordable homes nationally) achieving economically viable decarbonization. Most of the remaining 15% of homes lack whole-home central air conditioning and could still benefit from Affordable Home Energy Shot innovations through programs, like the DOE Weatherization Assistance Program, that may cover the upfront costs of eligible weatherization measures.

Analyzing Progress Toward the Target

Several DOE offices are working together to leverage new field data and tools to increase the robustness of analysis for affordable housing. Going forward, energy efficiency costs—and their possible future cost trajectories—will be tracked in the Buildings Annual Technology Baseline, a new cost assessment dataset supported by DOE, with the initial release expected in 2025.

Tracking Action and Accomplishments

On Oct. 12, 2024, the Affordable Home Energy Shot celebrated its one-year anniversary. During its inaugural year, DOE made significant strides toward achieving the ambitious targets outlined in this Energy Earthshot.

One highlight of these collaborative efforts was the Affordable Home Energy Shot Summit, held on June 5, 2024, which brought together over 900 stakeholders virtually to discuss crucial topics surrounding the future of affordable and equitable home-energy solutions. This summit was instrumental in aligning strategies to better meet the needs of communities nationwide.

Throughout the Affordable Home Energy Shot's first year, DOE has advanced funding opportunities to promote RD&D of cutting-edge energy technologies that will be instrumental in reaching this Energy Earthshot's goals. These investments are designed to drive down costs and enhance accessibility, particularly for underserved communities.

Roadmapping the Path Ahead

Progressing Along Technology Pathways

Potential cost reductions are possible through innovations in each of the technology pathways, with:

- The building envelope pillar supporting improved livability and comfort for more resilient homes. Innovation opportunities include advanced leakage detection, low-impact retrofit techniques, and panelized exterior insulation.
- The efficient electrification pillar supporting smaller, more efficient equipment that enables affordable and adaptable installation. Innovation opportunities include lower-voltage equipment, compact heat pump units, and integrated ventilation packages.
- The smart controls pillar enabling flexible energy loads that transform homes into energy resources. Innovation opportunities include grid-interactive technologies, smart electric panels, and shared circuit control between loads.

Additionally, substantial savings opportunities from innovations in business practice are possible. Many soft costs are associated with system sizing and design, risk mitigation, customer acquisition and project management. Innovations like remote assessments and automatic quote generation have the potential to significantly reduce the cost of home upgrades and make contractors more profitable.

Supporting Next-Generation Innovation

Additional research can help accelerate the path to achieving the Affordable Home Energy targets.

We have identified several opportunities where fundamental science can support next-generation building technologies, including materials innovations that can improve insulation for occupant comfort and reduce renovation timelines.

Enlisting the Full Innovation Ecosystem

Energy Earthshots drive fearless innovation, with DOE leading the way but recognizing the importance of enlisting the full innovation ecosystem with shared ambition. Energy Earthshots efforts engage key stakeholders and contributors from universities, DOE's national laboratories, industry and others, at every stage, through innovative funding, partnerships, engagement events (such as summits), and other mechanisms. Shared ambition with external actors, both within the U.S. private sector and internationally, strengthens the effort.

Engaging the Private Sector: Connections to Commercial Liftoff

Energy Earthshots are part of DOE's overall effort across the department to accelerate technologies from lab to market to spur the energy transition. DOE's Pathways to Commercial Liftoff Initiative ensures that the RD&D investments, including the Energy Earthshots, to accelerate clean energy technologies are clearly and effectively connected to commercialization efforts. They provide a common fact base on key challenges and a mechanism for the department to collaborate, coordinate, and align with the private sector on what it will take to commercialize key technologies, including clean hydrogen, long-duration energy storage, next-generation geothermal power, floating offshore wind energy, sustainable aviation fuels, and others. The cost and performance targets of the Energy Earthshots and the RD&D investments, analysis, and progress are critical pieces of this fact base to inform and spur investment in the private sector.

International Collaborations

Energy Earthshots international collaborations rise to U.S. ambition to drive fearless innovation, enhance existing multilateral engagements, and reinforce economywide breakthroughs at global scale. As a part of each technical collaboration, countries aim to share best practices, strategies, and progress toward mutual net-zero greenhouse gas goals.

DOE has active collaborations on Energy Earthshots with Australia, India, and Japan across three separate Earthshots.

The first official international collaboration for the Energy Earthshots was initiated with Japan for the Floating Offshore Wind Shot at the highest level through the U.S.-Japan Joint Leaders' Statement in April 2024. Both countries committed to work together toward global ambition in line with the Energy Earthshot, taking into consideration national circumstances, through the Clean Energy and Energy Security Initiative to pursue innovative breakthroughs that drive down technology costs, accelerate decarbonization, and deliver benefits for coastal communities. Japan's recently launched industry platform, the Floating Offshore Wind Technology Research Association, will play an intrinsic role in this aligned effort through its activities to reduce costs and achieve mass production of floating offshore wind energy through collaboration with academia.

DOE welcomed India as an international collaborator to the Hydrogen Shot in June 2023. Through the U.S.-India Joint Leaders' Statement, both countries agreed to collaborate to achieve their respective national goals to reduce the cost of green or clean hydrogen under India's National Green Hydrogen Mission and the United States' Hydrogen Shot. The U.S.-India Strategic Clean Energy Partnership will provide a powerful platform to implement these joint activities to accelerate cooperation in green hydrogen and other emerging technologies. In November 2024, India reconfirmed itself as an international collaborator for the Hydrogen Shot as both countries pursue ambitious goals through their respective national programs.

DOE welcomed Australia as an international collaborator on the Long Duration Energy Storage Shot through a ministerial joint statement on the occasion of the second U.S.-Australia Ministerial Dialogue on Energy in October 2024. Australia and the United States intend to work together towards global ambition in line with the Long Duration Storage Shot, taking into consideration national circumstances, to pursue innovative breakthroughs that drive down technology costs for long-duration energy storage, accelerate decarbonization of the electric grid, and ensure that a clean energy future is accessible and affordable for all communities.

The Energy Earthshots are tackling some of the most challenging technical obstacles to addressing climate change. Energy Earthshots will drive innovation to modernize our domestic energy infrastructure and place the United States at the center of leadership on the global clean energy trajectory. These challenges are truly global and will require international cooperation on a scale that has not yet been seen before. The Energy Earthshots international collaborations will enhance U.S. domestic efforts through the sharing of data, best practices, and lessons learned to accelerate progress on these ambitious goals while providing similar value to some of our most trusted and valued allies. These collaborations will further demonstrate U.S. technological and diplomatic leadership, as it is anticipated that these collaborations will continue to enhance multilateral as well as bilateral efforts on our way to achieving a net-zero economy.

Conclusions

In just over three years, since the Energy Earthshots Initiative was announced, DOE has extensively scoped, developed, and launched the portfolio of eight Energy Earthshots. The information in this report underscores that the Energy Earthshots portfolio is diverse and inclusive of many different technologies, pathways, and assessment methods with a common goal of improving lives through American innovation.

Through this initiative, DOE set highly ambitious technical and cost-reduction targets to pave the way for a revolutionary surge in decarbonization and clean energy production. The United States has seen historic energy transformations made possible through the BIL and IRA. It is critical to continue accelerating RD&D breakthroughs that will support an infrastructural boom in the coming decades. With billions of dollars at work in support of the goals, the Energy Earthshots Initiative is ensuring that scientific discoveries and R&D advancements lead to industry-ready technologies and tools that drive climate and economic progress. Through this initiative DOE has opened new facilities where entrepreneurs and engineers can test products, solve commercially relevant R&D challenges, and collaborate with world-class scientists on publicly funded infrastructure. Scores of new teams of scientists, engineers, entrepreneurs, utilities, and community partners have initiated new projects aligned with the strategies of the Energy Earthshots Initiative that will create the solutions of tomorrow.

The portfolio of activities supporting the Energy Earthshots will continue to expand, incorporating initiatives such as summits, additional analyses, and progress reports. Furthermore, progress toward these Energy Earthshots will continue through DOE's fundamental mission in supporting groundbreaking scientific discoveries, technical advancements through RD&D investments, and tangible impacts on economic growth and job creation.

References

Acevedo, Y.M., J.H. Prosser, J.M. Huya-Kouadio, K.R. McNamara, and B.D. James. 2023. *Hydrogen Production Cost with Alkaline Electrolysis*. U.S. Department of Energy. https://doi.org/10.2172/2203367.

Agbo, P., K. An, S. E. Baker, J. Cross, L. Kreibe, W. Li, C. Myers, S. H. Pang, H. T. Schaef, J. A. Schaidle, Corinne D. Scown, Evan D. Sherwin, Chinmayee Subban, Matt Villante, and Geetanjali Yadav. 2024. *Technological Innovation Opportunities for CO_2 Removal*. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2024-11/Carbon%20Negative%20Shot_Technological%20Innovation%20Opportunities%20for%20CO2%20Removal_November2024.pdf

Augustine, C., S. Fisher, J. Ho, I. Warren, and E. Witter. 2023. *Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office*. National Renewable Energy Laboratory. NREL/TP-5700-84822. https://www.nrel.gov/docs/fy23osti/84822.pdf

Badgett, A., J. Brauch, A. Thatte, R. Rubin, C. Skangos, X. Wang, R. Ahluwalia, B. Pivovar, and M. Ruth. 2024. *Updated Manufactured Cost Analysis for Proton Exchange Membrane Water Electrolyzers*. https://www.nrel.gov/docs/fy24osti/87625.pdf

Bioenergy Technologies Office. 2023. *Bioenergy Technologies Office Multi-Year Program Plan*. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2024-11/BETO Multi-Year Program Plan FY23_0.pdf

Chou., K. 2024. *BioHydrogen (BioH2) Consortium to Advance Fermentative H2 Production*. Hydrogen and Fuel Cell Technologies Annual Merit Review and Peer Evaluation Meeting. U.S. Department of Energy. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review24/p179_chou_2024_o.pdf?sfvrsn=afd65dd4_3

Cresko, J., et al. 2022. *Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy*. U.S. Department of Energy Workshop Report. www.osti.gov/biblio/1871912

Geothermal Technologies Office. 2019. *GeoVision: Harnessing the Heat Beneath Our Feet.* U.S. Department of Energy. https://doi.org/10.2172/1879171

Hill, Alice. 2022. "What the Historic U.S. Climate Bill Gets Right and Gets Wrong." Council on Foreign Relations. Updated Aug. 17, 2022. https://www.cfr.org/in-brief/us-climate-bill-inflation-reduction-act-gets-right-wrong-emissions.

Hydrogen and Fuel Cell Technologies Office. 2022a. *Advanced Liquid Alkaline Electrolysis Experts Meeting Report*. U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/advanced-liquid-alkaline-electrolysis-experts-meeting

Hydrogen and Fuel Cell Technologies Office. *2022b. Water Electrolyzer Technical Targets*. U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/hydrogen-production-related-links#targets

Hydrogen and Fuel Cell Technologies Office. 2023. *National Clean Hydrogen Strategy and Roadmap*. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf?sfvrsn=c425b44f_5

Hydrogen and Fuel Cell Technologies Office. 2024a. *DOE Hydrogen Program Record. Electrolyzer Installations in the United States*. U.S. Department of Energy. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24001-electrolyzer-installations-united-states.pdf?sfvrsn=43ae10f_1

Hydrogen and Fuel Cell Technologies Office. 2024b. *Hydrogen Shot: Water Electrolysis Technology Assessment*. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2024-12/hydrogen-shot-water-electrolysis-technology-assessment.pdf

Hydrogen and Fuel Cell Technologies Office. 2024c. *HFTO Hydrogen Production Overview*. U.S. Department of Energy. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/p000_peterson_2023_o.pdf?Status=Master

Industrial Efficiency and Decarbonization Office. 2021. *Manufacturing Energy and Carbon Footprints (MECS 2018*). U.S. Department of Energy. https://www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs

Industrial Efficiency and Decarbonization Office. 2022. *Industrial Decarbonization Roadmap*. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2022-09/Industrial Decarbonization Roadmap.pdf

Industrial Efficiency & Decarbonization Office. 2023. *Techno-economic, Energy, & Carbon Heuristic Tool for Early-Stage Technologies (TECHTEST) Tool*. U.S. Department of Energy. https://www.energy.gov/eere/iedo/techno-economic-energy-carbon-heuristic-tool-early-stage-technologies-techtest-tool

Industrial Efficiency & Decarbonization Office. 2024. *Pathways to U.S. Industrial Transformation: Unlocking American Innovation*. U.S. Department of Energy. https://www.energy.gov/eere/iedo/articles/pathways-us-industrial-transformation-unlocking-american-innovation

Intergovernmental Panel on Climate Change. 2018. *Global Warming of 1.5 °C*. https://www.ipcc.ch/sr15/

Kim, T., G. Hilton, S. Wilkinson. 2024. *Energy Storage Capex Continues to Fall In 2024 As Competition and Innovation Accelerate*. https://connect.ihsmarkit.com/documents/show/phoenix/5685540

Langholtz, M.H. 2024. *2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources*. Oak Ridge, TN: Oak Ridge National Laboratory. ORNL/SPR-2024/3103. doi: 10.23720/BT2023/2316165. https://www.energy.gov/sites/default/files/2024-03/beto-2023-billion-ton-report_2.pdf.

Larsen, John, Ben King, Hannah Kolus, Naveen Dasari, Galen Bower and Whitney Jones. 2022. *A Turning Point for US Climate Progress: Assessing the Climate and Clean Energy Provisions in the Inflation Reduction Act*. New York, NY: Rhodium Group. https://rhg.com/research/climate-clean-energy-inflation-reduction-act.

Londagin, S., R. Fourqurean, B. Haley, and G. Kwok. 2023. "DOE's Energy Earthshots: Innovation Unlocks Big Cost and Emissions Savings." Third Way. Sept. 23, 2023. https://thirdway.imgix.net/pdfs/does-energy-earthshots-innovation-unlocks-big-cost-and-emissions-savings.pdf.

Lopez, A., R. Green, T. Williams, E. Lantz, G. Buster, B. Roberts. 2022. *Offshore Wind Energy Technical Potential for the Contiguous United States*. https://www.nrel.gov/docs/fy22osti/83650.pdf

Mahajan, Megan, Olivia Ashmoore, Jeffrey Rissman, Robbie Orvis, and Anand Gopal. 2022. *Modeling the Infrastructure Bills Using the Energy Policy Simulator*. San Francisco, CA: Energy Innovation Policy & Technology, LLC. https://energyinnovation.org/wp-content/uploads/2022/08/Modeling-the-Inflation-Reduction-Act-with-the-US-Energy-Policy-Simulator_August.pdf.

Mai, T., P. Beiter, M. Mowers, M. Shields, P. Duffy. 2023. *Deployment Implications of Reaching the DOE Floating Offshore Wind Shot Goal*. Presentation (NREL/PR-5000-86020). https://www.nrel.gov/docs/fy23osti/86020.pdf

McCoy, A., W. Musial, R. Hammond, D.M. Hernando, P. Duffy, P. Beiter, P. Pérez, R. Baranowski, G. Reber, P. Spitsen. 2024. *Offshore Wind Market Report: 2024 Edition*. https://www.nrel.gov/docs/fy24osti/90525.pdf

McNaul, S., C. White, R. Wallace, T, Warner, H.S. Matthews, J.N. Ma, M. Ramezan, E. Lewis, D. Morgan, M. Henriksen, J. White, C. Munson, R. Stevens, T. Shultz. 2023. *Hydrogen Shot Technology Assessment: Thermal Conversion Approaches*. National Energy Technology Laboratory. https://doi.org/10.2172/2228279

National Academies of Sciences, Engineering, and Medicine. 2024. *Carbon Utilization Infrastructure, Markets, and Research and Development: A Final Report*. The National Academies Press. https://nap.nationalacademies.org/read/27732/chapter/1#ii.

National Renewable Energy Laboratory. 2024a. *Annual Technology Baseline*. Last updated July 19. https://atb.nrel.gov/

National Renewable Energy Laboratory. 2024b. *Regional Energy Deployment System*. https://www.nrel.gov/analysis/reeds/index.html

O.A. Marina, K. Ayers, E.B. Stechel, C.X. Xiang, K. Gross. 2024. *Benchmarking, Protocol Development and Community Engagement of Advanced Water Splitting Technologies*. Hydrogen and Fuel Cell Technologies Annual Merit Review and Peer Evaluation Meeting. U.S. Department of Energy. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review24/p170_marina_2024_o.pdf?sfvrsn=96514c31_5

Office of Clean Energy Demonstrations. 2024. *Regional Clean Hydrogen Hubs*. U.S. Department of Energy. https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0

Office of Community Planning and Development. 2024. "Uncapped" Income Limits for 2024. U.S. Department of Housing and Urban Development. "Uncapped" Income Limits for 2024

Office of Electricity. 2023. *Storage Innovations 2030-Accelerating Pathways towards the Long Duration Storage Shot*. U.S. Department of Energy. https://www.energy.gov/oe/storage-innovations-2030

Office of Electricity. 2023. Storage Innovations 2030. U.S. Department of Energy. Updated July 2023. https://www.energy.gov/oe/storage-innovations-2030.

Office of Electricity. 2024a. *Achieving the Promise of Low-Cost Long Duration Energy Storage*. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2024-08/Achieving%20the%20Promise%20of%20Low-Cost%20Long%20Duration%20Energy%20Storage_FINAL_08052024.pdf

Office of Electricity. 2024b. *Energy Storage Safety Strategic Plan*. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2024-05/EED_2827_FIG_SafetyStrategy%20240505v2.pdf

Office of Science. 2021. *Foundational Science for Carbon-Neutral Hydrogen Technologies*. U.S. Department of Energy. https://science.osti.gov/-/media/bes/pdf/brochures/2021/Hydrogen_Roundtable_Report.pdfuOffice of Science. 2022. Report of the Basic Energy Sciences Roundtable on Foundational Science for Carbon Dioxide Removal Technologies. Basic Energy Sciences Roundtable Report, U.S. Department of Energy. https://science.osti.gov/-/media/bes/pdf/reports/2024/CDR-full-report_0607224_2.pdf

Pacific Northwest National Laboratory. 2022. Energy Storage Cost and Performance Database. Pacific Northwest National Laboratory. Updated 2022. https://www.pnnl.gov/projects/esgc-cost-performance.

Pacific Northwest National Laboratory. 2024. *Grid Storage Launchpad Advancing the Next Generation of Grid Energy Storage Technologies*. https://www.pnnl.gov/grid-storage-launchpad-pnnl

Porse, S., D. Blankenship, C. Tasca, J. Winick. 2022. *Geothermal Technologies Office Fiscal Years 2022–2026 Multi-Year Program Plan*. U.S. Department of Energy. DOE/EE-2557. https://www.energy.gov/eere/geothermal/articles/geothermal-technologies-office-multi-year-program-plan-fy-2022-2026

Prosser, J.H, B.D. James, B.M. Murphy, D.S. Wendt, M.J. Casteel, T.L. Westover, and L.T. Knighton. 2023. *Cost Analysis of Hydrogen Production by High-Temperature Solid Oxide Electrolysis*. Int. J. Hydrog. Energy 4: 207-227.

Rosales-Calderon, O., L. Tao, Z. Abdullah, K. Moriarty, S. Smolinski, A. Milbrandt, M. Talmadge, A. Bhatt, Y. Zhang, V. Ravi, C. Skangos, E. Tan, C. Payne. 2024a. Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process. National Renewable Energy Laboratory. NREL/TP-5100-87802. https://www.nrel.gov/docs/fy24osti/87802.pdf

Rosales-Calderon, O., L. Tao, Z. Abdullah, K. Moriarty, S. Smolinski, A. Milbrandt, M. Talmadge, A. Bhatt, Y. Zhang, V. Ravi, C. Skangos, E. Tan, C. Payne. 2024b. *Sustainable Aviation Fuel (SAF) State-of-Industry Report: Hydroprocessed Esters and Fatty Acids Pathway*. National Renewable Energy Laboratory. NREL/TP-5100-87803. https://www.nrel.gov/docs/fy24osti/87803.pdf

Solar Energy Technologies Office. 2011. The SunShot Initiative. U.S. Department of Energy. https://www.energy.gov/eere/solar/sunshot-initiative.

Stehly, T., P. Duffy, D.M. Hernando. 2024. *2024 Cost of Wind Energy Review*. https://www.nrel.gov/docs/fy25osti/91775.pdf

U.S. Census Bureau. 2024. *Household Pulse Survey. Phase 4.0 Cycle 01: January 9 – February 5*. Accessed February 22, 2024. https://www.census.gov/data-tools/demo/hhp/#/?measures=ENERGYBILL&areaSelector=040

U.S. Congress. 2021a. Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 40314, §816 (codified as 42 U.S.C. 16161c (2021)). https://www.congress.gov/bill/117th-congress/house-bill/3684.

U.S. Congress. 2021b. Infrastructure Investment and Jobs Act, Pub. L. No. 117-28, sec. 41007, §a. https://www.congress.gov/bill/117th-congress/house-bill/3684.

U.S. Cybersecurity and Infrastructure Security Agency. 2022. *Chemical Sector Profile*. https://www.cisa.gov/resources-tools/resources/chemical-sector-profile

U.S. Department of Energy. 2020. *Energy Storage Grand Challenge Roadmap*. https://www.energy.gov/energy-storage-grand-challenge/articles/energy-storage-grand-challenge-roadmap

U.S. Department of Energy, U.S. Department of Transportation, U.S. Department of Agriculture, U.S. Environmental Protection Agency. 2022. *SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel.* https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

U.S. Department of Energy. 2023a. *Advancing Offshore Wind Energy in the United States; U.S. Strategic Contributions Toward 30 Gigawatts and Beyond*. https://www.energy.gov/sites/default/files/2023-03/advancing-offshore-wind-energy-full-report.pdf

U.S. Department of Energy. 2023b. *Pathways to Commercial Liftoff: Carbon Management*. https://liftoff.energy.gov/wp-content/uploads/2024/02/20230424-Liftoff-Carbon-Management-vPUB_update4.pdf

U.S. Department of Energy. 2023c. *Pathways to Commercial Liftoff: Clean Hydrogen*. https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf

U.S. Department of Energy. 2023d. *Pathways to Commercial Liftoff: Decarbonizing Chemicals & Refining*. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Chemicals-Refining.pdf

U.S. Department of Energy. 2023e. *Pathways to Commercial Liftoff: Long Duration Energy Storage*. https://liftoff.energy.gov/wp-content/uploads/2023/10/Pathways-to-Commercial-Liftoff-LDES-May-5_UPDATED-v10.pdf

U.S. Department of Energy. 2024a. *Floating Offshore Wind Shot Progress and Priorities Report*. DOE-Wind-Floating-Offshore-WindShot-Report-May2024.pdf

U.S. Department of Energy. 2024b. *Pathways to Commercial Liftoff: Offshore Wind*. https://liftoff.energy.gov/wp-content/uploads/2024/08/April-2024-LIFTOFF_DOE_Offshore-Wind-Liftoff-2.pdf

U.S. Department of Energy. 2024c. *Pathways to Commercial Liftoff: Sustainable Aviation Fuel*. https://liftoff.energy.gov/wp-content/uploads/2024/11/Pathways-to-Commercial-Liftoff_Sustainable-Aviation-Fuel.pdf

U.S. Department of Energy, U.S. Department of Transportation, U.S. Department of Agriculture, U.S. Environmental Protection Agency. 2024. *Sustainable Aviation Fuel Grand Challenge Roadmap Implementation Framework*. https://www.energy.gov/sites/default/files/2024-11/SAF-Implementation-Framework-Nov-2024.pdf

U.S. Energy Information Administration. 2023. *Annual Energy Outlook 2023*. https://www.eia.gov/outlooks/aeo/pdf/AEO2023_Narrative.pdf

Valentine, J., A. Zoelle, S. Homsy, H. Mantripragada, M. Woods, N. Roy, A. Kilstofte, M. Sturdivan, M. Steutermann, and T. Fout. 2022. *Direct Air Capture Case Studies: Sorbent System*. United States Department of Energy. https://doi.org/10.2172/1879535. https://www.osti.gov/servlets/purl/1879535.

Viswanathan, V., Mongird, K., Franks, R., Li, X., Sprenkle, V. 2022. 2022. *Grid Energy Storage Technology Cost and Performance Assessment.* Pacific Northwest National Laboratory Publication No. PNNL-33283. https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf

Wind Technologies Office. 2022. Floating Offshore Wind Shot Fact Sheet. U.S. Department of Energy. Floating Offshore Wind Shot Fact Sheet

Charting the Path: An Energy Earthshots Initiative Report

Measuring the Progress and Mapping the Future of the Energy Earthshots Portfolio

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U.S. DEPARTMENT OF ENERGY

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