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U.S. DEPARTMENT OF ENERGY

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SUBCOMMITTEE ON ENERGY

U.S. HOUSE OF REPRESENTATIVES

UNEARTHING INNOVATION: THE FUTURE OF SUBSURFACE SCIENCE AND TECHNOLOGY IN THE UNITED STATES

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Chairman Williams, Ranking Member Bowman, and honored members of the House Committee on Science, Space, and Technology, I am Dr. Alexandra Hakala, a senior research physical scientist and acting Senior Fellow for Geologic and Environmental Systems representing the National Energy Technology Laboratory (NETL) within the U.S. Department of Energy (DOE). Thank you for the opportunity to testify today on the crucial subject of subsurface science and its vital role in understanding and harnessing the vast resources beneath our feet.

Importance of Subsurface Science Research and Development (R&D)

The DOE plays a vital role in advancing subsurface science R&D in new application areas relating to the Nation's energy future. By bringing together experts from various scientific fields, DOE focuses on enhancing our understanding of subsurface systems and optimizing their utilization for geologic CO_2 storage, hydrogen storage, geothermal energy, and other applications. Collaboration between DOE and the National Laboratories is instrumental in driving progress in subsurface science. These partnerships foster knowledge exchange, leverage expertise, and facilitate the translation of research into tangible solutions.

In my testimony, I will highlight the vital research and achievements of DOE Offices and the National Laboratories in the field of subsurface science and technology development. I will also emphasize the importance of fundamental-to-applied R&D in subsurface science and technology and the significance of DOE offices working together to accelerate knowledge and technology advancement. These initiatives are integral to shedding light on the role subsurface science plays in mitigating climate change, exploring innovative energy production and storage solutions, ensuring the environmentally prudent development of subsurface resources, and addressing the nation's legacy of nuclear weapons development. By focusing on these areas of research, DOE can advance subsurface science to enable responsible energy development and minimize environmental impact.

Subsurface R&D at DOE

DOE Subsurface Energy Innovation (SEI) Crosscut

The DOE SEI Crosscut funds research, development, demonstration, and deployment (RDD&D) to improve the accuracy, precision, and speed with which subsurface resources can be assessed, accessed, and monitored. Such advancements will allow the technologies listed below to become market- competitive, scalable, and permanent clean energy solutions, and create tens of thousands of good-paying jobs:

- Geothermal energy, which requires dramatic cost reductions in Enhanced Geothermal System (EGS) capability to increase its footprint beyond 0.5 percent of U.S. electricity generation;
- Geologic carbon storage, currently happening at 0.1 percent of the rate necessary to meet climate goals;
- Geologic hydrogen storage, currently only feasible in unique and rare geologic features;
- Sustainable critical mineral (CM) extraction, necessary to reduce high American import reliance; and
- Geologic hydrogen sourcing, a new and potentially cost-effective, zero-emission source of hydrogen.

SEI Crosscut activities reduce the uncertainty and cost burden facing these technologies through the production and application of tools, data products, and workstreams that improves observational, decision-making, and operational capabilities. Such activities require advancements across fundamental science, and applied RDD&D, which is why the SEI Crosscut membership spans the Offices of Science, Fossil Energy and Carbon Management, Energy Efficiency and Renewable Energy, and Clean Energy Demonstrations, as well as ARPA-E. The SEI Crosscut leverages the integration of state-of-the-art High-Performance Computing (HPC) resources, Artificial Intelligence (AI), Machine Learning (ML), and simulation capabilities with applied technology workstreams necessary to build subsurface simulation and interpretation visualization, prediction, and decision-making tools.

Enhanced Geothermal Shot

A major focus in key crosscutting efforts is the execution of DOE's Energy Earthshots Initiative™. The Initiative sets cost and performance targets on a decadal timescale and drives forward breakthrough RD&D across the Department. Each ambitious, yet achievable, Energy Earthshot target represents a major innovation goal that we know we must achieve to solve the climate crisis, reach our 2050 net-zero emissions goals, and create the jobs of the new clean energy economy.

Subsurface innovation can advance progress for Carbon Negative Shot™, but perhaps most of all for the subsurface-focused Energy Earthshot is DOE's Enhanced Geothermal Shot™, which aims to bring geothermal energy – the vast energy resource beneath our feet – to Americans nationwide by driving down the cost of enhanced geothermal systems (EGS) by 90% to $45/MWH between now and 2035. These cost reductions would unlock 90 gigawatts-electric (GWe) of clean, firm, and flexible energy, enough to power 65 million American homes. Achieving the Energy Earthshot target could also create a geothermal industry that supports more than 250,000 jobs, including jobs that leverage existing skillsets from the oil and gas sector to ensure an equitable transition for those workers.

Office of Fossil Energy and Carbon Management (FECM)

Within the DOE's FECM, significant efforts have been devoted to advancing subsurface science R&D to address the pressing challenges of mitigating climate change, exploring innovative energy solutions, and ensuring responsible subsurface resource utilization. Through collaborative efforts, cutting-edge research, and systems analysis capabilities, NETL strengthens the ability of FECM to deliver innovative approaches for advanced energy systems. Subsurface science priorities include:

- **Foundational work for Carbon Transport and Storage Program (CTS)**: This program has supported R&D projects for over two decades, validating geologic carbon storage as a viable climate mitigation solution. It has leveraged the Regional Carbon Sequestration Partnerships (RCSP), which conducted field tests to safely store more than 11 million metric tons of CO_2. The RCSPs have transitioned to the Regional Initiative projects and now provide regional technical assistance to carbon storage stakeholders. This is a time of unprecedented development of carbon storage projects. Globally, projects in operation capture and store more than 40 million metric tons annually (MTpa) with more than 200 additional MTpa planned. The findings from the RCSP have laid the foundation for commercial-scale projects supported by the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) initiative.
- **Three interfacing initiatives to realize basin-scale deployment of commercial-scale storage:** The CTS program has developed an integrated approach with three interfacing initiatives to ensure safe and secure geologic storage of captured CO_2. The Bipartisan Infrastructure Law (BIL)-funded CarbonSAFE Initiative pairs with the new Carbon Basin Assessment and Storage Evaluation (CarbonBASE) and Carbon Storage Technology Operations & Research (CarbonSTORE) initiatives. These three efforts are designed to be executed in coordination to enable sustained and responsible stewardship of carbon storage resources and projects as the CCS industry is implemented over time.
  - → **Commercial-scale storage**: The BIL-funded CarbonSAFE initiative aims to develop commercial-scale geologic storage facilities and associated transport infrastructure. The goal is to provide future access to billions of metric tons of secure geologic storage capacity. These facilities, expected to range from 20 to 40 facilities, will enable the injection of up to 100 million metric tons of CO_2 per year by 2030. Future facilities developed post BIL will further enable decarbonization from point sources to meet the decarbonization goals of greater than one billion metric tons per year by midcentury.

- → **Basin-scale storage resource data gaps, efficiency, impacts, and management**: As individual and hub-scale storage projects come online, managing basin-wide storage resources becomes crucial for efficient, safe, and secure geologic storage of captured CO_2. To address this challenge, the CTS base program will invest in the CarbonBASE initiative. This initiative will collect geologic data, develop basin-scale management tools, and deploy basin-wide monitoring systems to assess the efficiency and security of storage resources.
- → **At-scale technology validation and performance testing**: The CarbonSTORE initiative funded by the CTS base program focuses on accelerating the development of enabling technologies for carbon storage. CarbonSTORE facilities are intended to belong-term field laboratories that will test, validate, and demonstrate emerging technologies in different geological settings. This includes monitoring and control systems, characterization tools, storage efficiency methods, and risk avoidance and mitigation technologies.

- **Technical assistance**: The Regional Initiative program, now expanded to a more place-based technical assistance framework, provides specific assistance to support development of large-scale storage facilities and regional carbon management hubs. The objectives are to fill knowledge gaps, provide crucial information to operators, and develop community engagement strategies.
- **Risk assessment and management**: The CTS program has been focused on reducing uncertainty associated with geologic carbon sequestration through the National Risk Assessment Partnership (NRAP). NRAP, a multi-laboratory initiative led by NETL and including Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Pacific Northwest National Laboratory (PNNL), and Lawrence Berkeley National Laboratory (LBNL), has developed open-source tools for assessing and quantifying risks throughout the lifecycle of a storage project. NRAP is also expanding its scope to manage risks associated with the deployment of multiple commercial-scale storage projects in a region.
- **CO_2 mineralization storage resources**: The CTS program invests in small-scale CO_2 injection and research on storage via mineralization. It is currently assessing potential storage resources in subsurface and surface locations throughout the nation. Proof-of-concept studies are being conducted in volcanic basins and offshore basalts, exploring unconventional storage resources to support regional decarbonization goals.
- **AI/ML enabled technologies**: The CTS program is advancing storage technologies, such as sensors, telemetry, and power sources, to streamline characterization and monitoring capabilities. These technologies, integrated into the Science-informed Machine Learning for Accelerating Real-Time (SMART) Decisions initiative, aim to improve the efficiency and effectiveness of field-scale carbon storage through real-time visualization, forecasting, and virtual learning to revolutionize decision-making in subsurface applications. SMART focuses on developing ML-based tools that consolidate technical knowledge, optimize carbon storage reservoirs, and improve understanding of subsurface behavior during carbon storage operations.

- **Transport systems**: FECM is investing in multi-modal front-end engineering design (FEED) and Pre-FEED studies and the development of analysis tools for evaluating CO_2 transport systems. This includes pipeline, rail, truck, and marine modes. Applied research in CO_2 transport priority areas includes the impact of impurities on transport modes, leak detection protocols, repurposing existing infrastructure, and intermodal hubs.
- **Energy Data Xchange (EDX)**: The CTS program and the development of EDX as a data curation and collaboration platform includes both public and private data sharing capabilities, entire life cycle of data, data discovery, transformation, and integration. EDX maintains all data from the CTS program, including NRAP and SMART tools. A multi-cloud DisCO2very platform combines mapping, tools, models, machine learning, and advanced data discovery to enable users to find and apply relevant data for carbon storage analyses. EDX is federated with other agency databases, providing comprehensive access to subsurface data. These resources support site selection, risk analysis, and decision-making processes, democratizing access to models and data for improved resource management and decision support.
- **Terrestrial carbon sequestration**: DOE's terrestrial carbon sequestration work began with FECM investments in the early 2000s. It involved a coordinated approach across forest management, agriculture, and woody crops. The focus was on technology development, economic modeling, and stakeholder engagement. Collaborative efforts assessed carbon sequestration at various scales and deepened our understanding of capture mechanisms and carbon fluxes. FECM is currently partnering with DOE's Office of Technology Transitions to commercialize measurement, reporting, and verification technologies. Further efforts are needed to understand, assess, monitor, and implement commercial terrestrial carbon sequestration, including analytical work and technology development.
- **Offshore subsurface:** FECM's offshore subsurface research focuses on enhancing subsurface characterization, improving subsurface property prediction in data-scarce areas, and unlocking the energy extraction and storage potential of our Nation's subsurface. This research provides valuable insights into offshore infrastructure performance, identifies potential hazards, and explores opportunities to repurpose existing offshore energy infrastructure for accelerated offshore CCUS projects.
- **Critical minerals**: FECM has funded efforts to characterize the mineral deposits found in secondary and unconventional feedstocks, such as coal, under burden and overburden layers, recycled resources, and shale. These efforts include the assessment of different potential ore minerals (e.g., monazite for rare earth elements (REE)) that are found within the original subsurface formations and how that contributes to ease of extraction of the metals of interest. Data is being collected in a number of basins across the U.S. in the CORE-CM Initiative for the assessment of REE and other CM content and is curated via the Energy Data Xchange. Data analysis, including machine learning tools, have been developed and used to help better predict the locations of formations higher in critical minerals.
- **Underground hydrogen storage:** In 2021, FECM initiated the SHASTA (Subsurface Hydrogen Storage Assessment and Technology Acceleration) project, a collaborative effort between NETL, PNNL, LLNL, and Sandia National Laboratories (SNL). The project aims to assess the feasibility, safety, and reliability of storing pure hydrogen or hydrogen natural gas blends in subsurface environments. Key challenges addressed by the SHASTA team include evaluating the efficacy of different underground systems, such as depleted hydrocarbon

reservoirs, saline aquifers, and salt caverns, for hydrogen storage. Additionally, the project investigates hydrogen loss due to biogeochemical reactions, containment risks through caprock, faults, fractures, or leaky wells, and the development of real-time monitoring technologies for assessing gas migration, potential leakage, microbial activity, and well integrity.

- **Sustainable mining:** Even with unconventional and recycled sources, many new mines will be required to meet clean energy and climate change goals. The IEA[1] estimates that 4-6 times the current amount of critical minerals and metals will be needed by 2040 compared to what is used today to meet stated clean energy goals. The subsurface of the Nation holds significant reserves of critical minerals, often inaccessible due to depth or mining limitations. These "unmineable" mineral resources may be unlocked by leveraging advanced subsurface imaging, detection, drilling, and fluid handling technologies. The mines of the future will harness these advanced technologies, allowing for the extraction of mineral wealth with minimal environmental impact. By employing closed systems for leaching, extracting, and processing, these future mines will ensure minimal surface impacts while tapping into vast untapped mineral resources. As FECM's national laboratory, NETL R&D efforts align with the vision of a sustainable and environmentally responsible mineral extraction industry, strengthening America's position in critical minerals production.
- **Orphaned wells R&D:** The number of orphaned wells across the U.S. is estimated to approach 1 million[2,4]. Of these wells, between 90,000 and 130,000[3] are referred to as documented orphaned wells that have known locations and ownership. A second category of orphaned wells, referred to as "undocumented" orphaned wells, are wells for which no permits, records, location, nor ownership exist, and range between 210,000 and 746,000[3]. FECM initiated the Undocumented Orphaned Wells Program (UOWP) in 2022. This program is focused on developing technology, methodologies, and guidelines for identifying and characterizing undocumented orphaned wells. UOWP leverages the expertise of several national labs to support active stakeholders, such as the Interstate Oil and Gas Compact Commission, States, Tribes, and the Department of the Interior. NETL is working to bridge the knowledge gap and develop cost-effective methods for locating undocumented orphaned oil and gas wells, quantifying their emissions in order to prioritize their management for plugging. For example, since 2005, NETL has developed rapid airborne methods for locating undocumented orphaned wells through the development and field validation of advanced electromagnetic hardware and machine learning software.
- **Unconventional Field Laboratories:** The DOE has established a suite of 17 Field Laboratories across various basins in collaboration with industry, academia, and national laboratories. These Field Laboratories serve as platforms for collaborative research and aim to accelerate the development and application of new technologies, tools, and processes in unconventional field-based settings. The overarching objectives of these laboratories are to optimize operational efficiency, improve reservoir characterization, enhance recovery

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[1] IEA World Energy Outlook Special Report. 2021. "The Role of Critical Minerals in Clean Energy Transitions. The Role of Critical Minerals in Clean Energy Transitions (windows.net)

[2] Management of Abandoned and Orphaned Oil and Gas Wells, The American Association for the Advancement of Science

[3] Idle and orphan oil and gas wells—State and provincial regulatory strategies 2021, IOGCC, December 2021, https://iogcc.ok.gov/idle-and-orphan-oil-and-gas-wells-2021

[4] Wright, B., Hide and Seek: The Orphan Well Problem in America, Journal of Petroleum Technology, August 2021

efficiency, promote environmental sustainability by improving water use and preserving air/water quality, and explore future energy storage opportunities such as expanded CO_2 enhanced oil recovery (EOR), carbon storage, and hydrogen storage. The knowledge gained from these Field Laboratories will not only contribute to the understanding of subsurface dynamics in producing basins but also have practical applications in geologic CO_2 storage, hydrogen storage, and the development of mines of the future. Furthermore, future Field Laboratories are planned to expand the research scope, focusing on simultaneous CO_2-EOR with CO_2 storage, leveraging the knowledge gained from existing projects to support the deployment of commercially viable CO_2 injection for EOR and geologically storing CO_2.

Office of Science

The Office of Science (SC) provides fundamental knowledge and state-of-the-art capabilities, supporting discovery science and energy-use-inspired research to establish the foundations for the advancement of energy technologies. SC supports theoretical, computational, and experimental science across various topics to enhance our understanding of nature and promote national security. Research supported by SC is conducted at DOE's National Laboratories and institutions of higher education, including underrepresented and emerging research institutions, located across the U.S. SC operates user facilities such as x-ray and neutron sources, nanoscience facilities, genome sequencing facilities, and high-performance computing and network facilities that contribute to research in subsurface science and related areas like geothermal energy, carbon sequestration, energy storage, and environmental management.

- **Subsurface/Geothermal**: SC conducts computational, theoretical, and experimental research to advance subsurface energy technologies by understanding geo-mechanical/chemical, hydrological, and interfacial chemistry, and materials behavior. Predicting the coupled effects of rock stresses, fluid pressure, and reactive fluid transport is crucial for implementing subsurface technology. Basic research is needed to improve predictability and enable heat mining for geothermal energy, subsurface storage of carbon and hydrogen, and underground storage for environmental remediation. Challenges include developing theoretical models to understand fracture system behavior and connecting signals to subsurface processes using data science and machine learning methods.

  Two SC program offices, Advanced Scientific Computing Research (ASCR) and Basic Energy Sciences (BES), actively participate in the multi-office DOE SEI Crosscut. Other participating offices are EERE-GTO, FECM, ARPA-E, and NNSA. ASCR supports fundamental research to enable higher precision in subsurface characterization and monitoring by exascale simulation, data analysis, and basic research in AI/ML through ASCR's exascale computing project, core research program, and SC Energy Earthshots Initiative. ASCR also invested in basic research in edge computing, novel computational tools for data collection at various scales, verification and validation of field data, uncertainty quantification, and integration of massive heterogenous data using AI/ML techniques. BES also supports fundamental geosciences research through experimental and computational user facilities, single principal investigator and small team science through the BES Geosciences core program and SC Energy Earthshots Initiative, and larger multi-disciplinary, multi-institutional centers such as Energy Frontier and Energy Earthshot Research Centers.

The core program is distinct in its support for research combining geochemistry and geophysics, and its coordination with other research efforts across the BES portfolio and scientific user facilities. Taken together, this research contributes crosscutting knowledge to enable control of processes in extreme geological environments, large-scale subsurface storage of CO_2 via mineralization, and understanding geochemical and geophysical processes at larger scales.

- **Carbon Management**: SC supports theoretical and experimental research relevant to carbon capture, utilization, and storage. BES conducts fundamental research in materials and chemistry to advance carbon management technologies, including CO_2 removal and direct air capture. Workshops and roundtables have identified priority research opportunities to address scientific barriers in CO_2 removal technologies and carbon capture. ASCR funds exascale simulation projects to provide higher resolution characterization of geological sequestration and design and optimization of large-scale commercial systems. Research areas include energy transfer mechanisms, novel materials and chemical systems for efficient carbon capture, functionality of 2D materials, control of mineral dissolution and formation rates, and catalytic and enzymatic approaches for carbon concentration or conversion.
- **Critical Materials**: SC, primarily through BES, supports fundamental experimental and theoretical research to understand the basic properties of critical materials. This research is enabling the development of enhanced extraction, separation, processing methods, as well as the discovery of substitutes for critical materials that maintain or improve technology performance. Fundamental research in critical materials, including both rare earth and platinum group elements that play critical roles in clean energy technologies, is advancing our understanding of the physics and chemistry of critical materials and the dynamic geochemistry and properties of fracture systems and hydrothermal fluids. These advances are necessary for realizing innovations that reduce or eliminate critical mineral use and advancing new approaches for extraction and recovery from complex and dilute mixtures, respectively.
- **Biological and Environmental Research (BER) Environmental Studies**: The BER program invests in experimental and modeling research on the transformation of organic and inorganic compounds in the environment. Long-term studies in various watersheds, including those near Oak Ridge National Laboratory (ORNL), PNNL, and the East River of the upper Colorado River, focus on surface and groundwater interactions and the influence of physical and biogeochemical processes on environmental predictions.
- **Research related to Radiation and Environmental Management**: BES supports research that advances understanding of the effects of radiation on materials and chemical processes for heavy elements and ionizing radiation. This includes understanding defect evolution in irradiated materials and radiation chemistry in nuclear reactors and waste processing. Through support for research on the molecular-level chemistry of ores and legacy waste contaminants, BES is contributing to the development of new strategies for mining and remediation. Multiple SC programs, including BES, have collaborated with EM to define priority research directions that will advance the scientific foundations for future

environmental management technologies and support cleanup efforts at sites like the Hanford Site.

Office of Energy Efficiency and Renewable Energy

Geothermal energy is a clean, renewable resource that can play a significant role in electricity generation, heating, and cooling. By harnessing geothermal power, the United States can create jobs, support impacted communities, and leverage the expertise of the oil and gas sector. Furthermore, geothermal energy offers opportunities for extracting critical materials from geothermal brines, developing a domestic supply of minerals like lithium, and enabling efficient processes such as direct-air capture and hydrogen production. Promising cutting-edge geothermal technologies include:

- **Enhanced geothermal systems (EGS):** Injecting water into hot rock underground to create reservoirs for electricity generation.
- **Supercritical geothermal energy**: Producing energy by heating water to a temperature and pressure that causes it to become a supercritical fluid.
- **Closed-loop geothermal**: Injecting fluid into interconnected wells in the subsurface, preventing fluid from contacting the rock.

The United States is home to vast heat subsurface resources, but a substantial amount of that heat is not accessible with current technology. Research and innovation to advance EGS and other cutting-edge geothermal technologies can unlock those resources and put new, clean, firm, and flexible electricity on the grid and open the possibility for geothermal energy nationwide.

Office of Environmental Management (EM)

The achievements and ongoing efforts within the DOE's EM deserve recognition as they exemplify the government's commitment to addressing the environmental legacy of national defense programs. EM has successfully completed cleanup operations at 92 out of 107 sites, showcasing significant progress over its 34-year tenure. Some notable accomplishments include:

- Safe demolition of the Hanford Site's Plutonium Finishing Plant, responsible for two-thirds of the nation's Cold War-era plutonium production.
- Construction and operation initiation of depleted uranium hexafluoride conversion plants at the Portsmouth and Paducah sites.
- Management of one of the world's largest groundwater and soil remediation efforts, treating billions of gallons of contaminated groundwater at sites like Hanford, Los Alamos, Moab, and Savannah River.
- Completion of waste vitrification activities and subsequent demolition of the Vitrification Facility at the West Valley Demonstration Project in New York.
- Full demolition of all Department of Energy-owned buildings at the Energy Technology Engineering Center in California.
- Establishment of the world's only deep geological repository, the Waste Isolation Pilot Project in New Mexico, dedicated to transuranic waste from atomic energy defense activities.

- Completion of the entire tank waste treatment system at the Savannah River Site, addressing one of the Department's significant environmental and financial liabilities.
- Commencement of large-scale treatment of radioactive liquid waste from underground tanks using the Tank-Side Cesium Removal System at the Hanford Site and the Integrated Waste Treatment Unit at the Idaho National Lab Site.

Conclusion

The DOE offices and the National Laboratories collaborate closely to develop crosscutting technologies for the subsurface. By combining expertise and capabilities, they drive innovation and advancements in subsurface science and technology. These crosscut collaborations allow the DOE to tackle complex challenges, such as carbon capture and storage, hydrogen storage, geothermal energy extraction, critical materials exploration, environmental management, and more. Through joint efforts, the DOE is at the forefront of developing sustainable and efficient solutions for subsurface resource utilization, contributing to the nation's energy security, environmental stewardship, and technological leadership.

In conclusion, my testimony has highlighted DOE's extensive expertise in subsurface science and the collaborative approach taken in R&D. The examples presented illustrate the DOE's commitment to advancing subsurface technologies and responsible resource management. Thank you for the opportunity to discuss some of these cutting-edge innovations, which have applications within – and beyond – the energy sector. I look forward to the opportunity to further discuss these crucial topics and respond to any questions you may have.