CSN CARBON STORAGE NEWSLETTER

AUGUST 2017

This newsletter is compiled by the National Energy Technology Laboratory to provide information on recent activities and publications related to carbon storage. It covers domestic, international, public sector, and private sector news in the following areas:

CARBON STORAGE PROGRAM DOCUMENTS and REFERENCE MATERIALS

NATIONAL ENERGY TECHNOLOGY LABORATORY

DOE/NETL HIGHLIGHTS

NETL Releases Latest Best Practice Manuals for Geological Storage.

The U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) released three 2017 revised edition Best Practice Manuals (BPMs) for geologic storage projects ("*Public Outreach and Education for Geologic Storage Projects*"; "*Risk Management and Simulation for Geologic Storage Projects*"; and "*Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects*"). The BPMs provide a holistic approach to carrying out a geologic storage project from inception to completion. The revised BPMs were developed in conjunction with the *Regional Carbon Sequestration Partnerships (RCSPs)*, an initiative launched by DOE's Office of Fossil Energy (FE) and NETL in 2003 to develop and test the best technologies for safe and permanent storage of carbon dioxide (CO_2). RCSP experts worked with DOE on the latest updates by incorporating knowledge gained in their respective partnership projects. The 2017 revisions include new information learned as the RCSPs progressed to large-scale Development Phase field projects, as well as a variety of carbon storage scenarios at different geologic and geographic settings across the United States. From *DOE/NETL News Release* on July 17, 2017.

ANNOUNCEMENTS

NETL's Geologic Carbon Storage Risk Assessment Tools Recognized.

The Carbon Sequestration Leadership Forum (CSLF) recognized DOE's National Risk Assessment Partnership (NRAP) as a project that contributes to the advancement of carbon capture and storage (CCS) technology deployment. NRAP is one of approximately 50 such projects worldwide to be recognized over the past decade by CSLF, an international, ministerial-level organization focused on the development of CCS technology. For more information, visit the *NRAP website*.

CSLF 2017 Mid-Year Meeting Proceedings Available.

The proceedings from CSLF's 2017 Mid-Year Meeting, held April 30 through May 4, 2017, in Abu Dhabi, United Arab Emirates, are now available online. The documents and presentations cover the Projects Interaction and Review Team Meeting, Technical Group Meeting, and Policy Group Meeting.

Successful Demonstration of NETL-Supported Project.

An NETL-supported project successfully concluded a six-month testing campaign at the Technology Centre Mongstad (TCM) in western Norway, a facility for testing and improving CO_2 capture. Approximately 14,000 metric tons of CO_2 were captured during testing. DOE and the Royal Norwegian Ministry of Petroleum and Energy have a bilateral Memorandum of Understanding (MOU) covering fossil energy-related research to leverage each country's investments in carbon capture, utilization, and storage (CCUS).

NETL employees with hosts at Technology Centre Mongstad (February 2017).

Collaboration to Test CO_2 Reduction in Residential Houses.

Iida Group Holdings Co Ltd (Iida GHD) and Osaka City University will collaborate to test residential houses that store CO_2 by using artificial photosynthesis. The houses supplied for the test will not only reduce CO_2 emissions, but also "consume" it by using an artificial photosynthesis technology that uses solar energy to convert CO_2 into hydrogen.

PROJECT and BUSINESS DEVELOPMENTS

Husky Energy Investing in Pilot Plant.

Husky Energy Inc. is increasing investment in CCS technology by aiming to develop a plant larger than its current CCS plant at its Pikes Peak South operation. The new plant will be located at the same site as the smaller CCS plant, which was developed by clean energy company Inventys Inc. The CO_2 captured from the new project will be used alongside CO_2 recovered from other facilities for enhanced oil recovery (EOR) operations. Expected to be commissioned in late 2018, the plant will utilize Inventys' second-generation CCS technology that captures CO_2 in a solid material rather than a solvent. From *Saskatoon StarPhoenix* on July 14, 2017.

Power Plant Evaluation MOU Includes CCS.

Statoil, Vattenfall, and Gasunie signed an MOU to evaluate converting Vattenfall's gas-powered Magnum plant, located in the Netherlands, into a hydrogen-powered plant. The scope of the MOU also includes the exploration of designing a large-scale value chain where the production of hydrogen is combined with CO_2 capture, transport, and permanent storage. According to a *Statoil press release*, the conversion has a potential CO_2 emission reduction of 4 million tons of CO_2 per year. From *Carbon Capture Journal* on July 17, 2017.

LEGISLATION and POLICY

U.S. and Mexico Strengthen North American Energy Cooperation.

Representatives from the United States and Mexico have identified common goals for a trilateral agenda with Canada to accelerate the development of untapped resources, increase energy trade, and enhance the security of their energy systems. A potential point of emphasis could be furthering the three countries' mutual interest in CCS technology. From *Platts* on July 13, 2017.

Carbon Capture and Utilization Bill Introduced.

A bill supporting the CCS industry was introduced, in which tax credits would be extended and increased for power generators and industrial facilities that capture and store their own CO_2, as well as for carbon utilization. The *Carbon Capture and Utilization Act* would provide a $40 tax credit for every metric ton of CO_2 stored underground, and a $35 per ton credit for CO_2 utilized for purposes such as EOR. Credits of $20 and $10 per ton are currently offered for capture and utilization, respectively. From *Utility Dive* on July 13, 2017.

California Lawmakers Approve Policy Extension.

The California legislature passed a package of bills that extends the state's plan to address greenhouse gas (GHG) emissions by a decade. The legislation extends California's cap-and-trade program through 2030 and includes requirements for large industrial facilities to upgrade old equipment by 2023. In addition, the new package seeks to reform California's existing cap-and-trade market by reducing the number of free carbon allowances by 40 percent by 2030 and requiring offsets be sourced from within the state. From *Reuters* on July 17, 2017.

Renewable Energy Bill Introduced.

Legislation that would transition the United States to 100 percent clean and renewable energy by 2050 was introduced in the U.S. House of Representatives. The "*100 by '50 Act*" has seven core components, one of which includes investment in carbon storage. A *one-page summary of the bill* is available. From *U.S. Representative Jared Polis Press Release* on July 19, 2017.

EMISSIONS TRADING

Emissions Trading on South Korea's Climate Agenda.

According to the South Korean government, the country will rely on its cap-and-trade program to meet its goals for reducing GHGs. Established in 2015, South Korea's emissions trading system (ETS) covers approximately two-thirds of the country's national GHG emissions. The second phase of the systems implementation, which will take place from 2018 through 2020, will introduce foreign credits. The third phase launches in 2021. From *Bloomberg BNA* on July 20, 2017.

New Zealand Government to Reopen ETS.

The New Zealand government will reopen their ETS to international carbon credits, officials announced. In a range of ETS-related decisions, officials also announced the intention to control the number of New Zealand Units (NZUs) of carbon by putting up predetermined quantities for auction, removing the $25 per metric ton upper limit on the price of a metric ton of New Zealand carbon. New Zealand's ETS had been closed to international markets since 2015. From *The National Business Review* on July 26, 2017.

CLIMATE and SCIENCE NEWS

Carbon Storage Chemical Reaction Identified by Researchers.

Scientists from the California Institute of Technology (Caltech) and the University of Southern California (USC) discovered a way to speed up the slow part of a chemical reaction that allows CO_2 to be stored in the ocean, allowing the rate-limiting part of the process to go 500 times faster. The team of researchers collaborated by using isotopic labeling and two methods for measuring isotope ratios in solutions and solids to study calcite, a form of calcium carbonate. The group's findings were published in the online journal *Proceedings of the National Academy of Sciences*. From *ScienceDaily* on July 17, 2017.

Scientists Research 100-Year-Old Fluid Flow Law.

A 100-year-old scientific law used to describe how fluid flows through rocks has been challenged by Imperial College London engineers, which has the potential to lead to advances in CCS. Using 3-D videos to show how fluid moves through rock, the scientists discovered that the fluid flow is unstable, as opposed to the previously held premise in which gases move through rock via their own separate, stable pathways. The process, termed dynamic connectivity, shows that the pathways that fluids flow through last for a short period of time, wherein it then rearranges and forms into different ones. The discovery has the potential to allow engineers to more accurately model how fluids flow through rock. From *ScienceDaily* on July 17, 2017.

Researchers Discover New CO_2 Conversion Process.

Researchers discovered a new process that has the potential to create useful products from carbon emissions. Chemists from Yale and Oregon State University have found the framework for a new method of electrochemical CO_2 reduction (using electricity to change CO_2 into value-added products) by using a zinc-porphyrin electrocatalyst. The researchers discovered the zinc-porphyrin complex acts as a catalyst in that the zinc ion binds the reactant but does not change its oxidation state, while the porphyrin ion (or ligand) is reduced and delivers electrons to complete the reaction. The new finding was *published in the journal ACS Central Science*. From *Yale News* on July 27, 2017.

Mountain Forests Store Carbon Better than Flatland Forests.

Researchers from CyVerse, a project funded by the National Science Foundation and led by the *University of Arizona*, have found that mountain forests may be better at storing CO_2 than flatland forests. Researchers came to their hypothesis by collecting data from reflected light pulses off the surface of the Earth to map the height of trees and elevation. Looking through the cross sections of a 3-D map, the study showed the trees on the valley floors had more biomass than those on the mountaintops; the more biomass a tree has, the more CO_2 it has removed from the air. From *Tuscon.com* on July 29, 2017.

JOURNAL ARTICLES

Assessing the Risk of Carbon Dioxide Emissions from Blue Carbon Ecosystems.

The following is the Abstract of this article: "'Blue carbon' ecosystems, which include tidal marshes, mangrove forests, and seagrass meadows, have large stocks of organic carbon (Corg) in their soils. These carbon stocks are vulnerable to decomposition and – if degraded – can be released to the atmosphere in the form of CO_2. [The authors] present a framework to help assess the relative risk of CO_2 emissions from degraded soils, thereby supporting inclusion of soil Corg into blue carbon projects and establishing a means to prioritize management for their carbon values. Assessing the risk of CO_2 emissions after various kinds of disturbances can be accomplished through knowledge of both the size of the soil Corg stock at a site and the likelihood that the soil Corg will decompose to CO_2." **Lovelock, Catherine E.; Atwood, Trisha; Baldock, Jeff; Duarte, Carlos M.; Hickey, Sharyn; Lavery, Paul S.; Masqué, Pere; Macreadie, Peter I.; Ricart, Aurora M.; Serrano, Oscar; and Steven, Andy D. L.**, *Frontiers in Ecology and the Environment*. (Subscription may be required.)

CO_2 Trapping in the Context of Geological Carbon Sequestration.

The following is the Abstract of this article: "Geological sequestration of CO_2 has been identified as a mitigation option to the problem of climate change which the world is facing today. This review gives a comprehensive overview of carbon storage technology and focuses on the different methods that have been used for the sequestration of CO_2 in geological formation. [CCS] involves the capturing of [CO_2] from large commercial plant such as power plant, and transports them to geological storage site for long-term storage in geological formations such as basalt, depleted oil and gas field, coal seams, and saline aquifers. The principles of CO_2 sequestration and trapping mechanisms are presented in this work. CO_2 hydrate formation, which is a good trapping mechanism if it is thermodynamically stable, is also explained along with the important geological site selection characteristics. Finally, the monitoring techniques for detection of CO_2 plumes in the reservoir using geophysical and geochemical methods are explored." **Kazeem O. Rabiu, Lidong Han, and Diganta Bhusan Das**, *Reference Module in Earth Systems and Environmental Sciences*. (Subscription may be required.)

The Application of Supercritical Carbon Dioxide for the Recovery of Residual Hydrocarbon Reserves at the Late Stage of Reservoir Engineering.

The following is the Abstract of this article: "The unique experimental base which allows to investigation and model the processes of extraction, wipe hard-to-recover hydrocarbon resources from a variety of solid porous media in a wide range of state parameters including critical area, using a variety of solvents, including [CO_2], is created. The experiments on the displacement of various hydrocarbons from the reservoir model [CO_2] in the temperature range 20-200°C and pressures of 5 to 45 MPa, as well as qualitative experiments on the extraction of hydrocarbons from core samples are conducted. The experimental results obtained prove high efficiency of the supercritical [CO_2] for the displacement and extraction of hard to recovery hydrocarbon deposits." **Filenko DG, Dadashev MN, Grigoryev EB, and Vinokurov VA**, *Recent Advances in Petrochemical Science*. (Subscription may be required.)

Screening Test of Amino Acid Salts for CO_2 Absorption at Flue Gas Temperature in a Membrane Contactor.

The following is the Abstract of this article: "[Carbon dioxide] absorption at the temperature of flue gas inlet could reduce the costs related to flue gas cooling systems and improve the economic feasibility of the [post-combustion] carbon capture processes. Amino acid salts are considered as promising absorbents to absorb CO_2 in a membrane contactor at elevated temperatures because of their advantages of lower volatility, less degradation, and higher surface tension. In this study, 24 common amino acids have been screened for their potential to absorb CO_2 at the temperature of flue gas inlet in a membrane contactor. These screening processes involved examination of the water solubility of amino acids, measurement of surface tension and viscosity of their potassium salts, CO_2 capacity, and CO_2 membrane absorption test. Taurine, sarcosine, and glycine were identified as performing well in all the screening tests and were further investigated for CO_2 membrane absorption at high temperatures up to 80°C and various CO_2 loadings in a polypropylene hollow fiber membrane module. The results show that those amino acid salts are feasible to absorb CO_2 at high temperatures in a membrane contactor. Potassium sarcosinate is identified as the most promising absorbent for high-temperature CO_2 absorption with a better absorption performance than monoethanolamine and other amino acid salts." **Feijie He, Tao Wang, Mengxiang Fang, Zhen Wang, Hai Yu, and Qinhui Ma**, *Energy Fuels*. (Subscription may be required.)

JOURNAL ARTICLES *(cont.)*

Study on the ratio of pore-pressure/stress changes during fluid injection and its implications for CO_2 geologic storage.

The following is the Abstract of this article: "The success of fluid injection into geological formations, which is the main operation during both CO_2 geologic storage and wastewater injection, is contingent on the geomechanical integrity of the site. A key task that allows us to evaluate the risk of geomechanical failure is the precise prediction of pore-pressure buildup and subsequent change in the state of stresses during and after the fluid injection. Contrary to traditional approaches, where total stresses are assumed to remain constant, recent studies have ascertained that total stresses in fact change in every direction as fluid extraction/injection disturbs the pore-pressure field and causes deformations. In this study, [the authors] conduct an in-depth investigation of the ratio of change in total stress to that in pore-pressure, $\Delta\sigma/\Delta P$, which has been denoted in the literature as the pore-pressure/stress coupling. [The authors] employ a numerical simulation method that couples single-phase fluid flow in porous media with poroelasticity to explore the spatiotemporal evolution of the $\Delta\sigma/\Delta P$ ratio for various conditions. These numerical experiments allow us to examine how different material properties and structural geometries would influence the evolution of $\Delta\sigma/\Delta P$ in both vertical and horizontal directions. These ratios of pore-pressure/stress changes exhibit different spatiotemporal evolutions depending on key factors that include the hydraulic boundary condition, Biot's coefficient, Poisson's ratio, and the hydraulic diffusivity of both the injection zone and caprock. On the basis of observations, [the authors] suggest firsthand guidelines for analytically determining the ratio of pore-pressure/stress changes, $\Delta\sigma/\Delta P$. Finally, [the authors] use examples and case studies to illustrate how the $\Delta\sigma/\Delta P$ ratio can be incorporated into an analytic calculation for determining a maximum sustainable pressure limit." **Seunghee Kim and Seyyed Abolfazl Hosseini**, *Journal of Petroleum Science and Engineering*. (Subscription may be required.)

Liquidity, information, strategic trading in an electronic order book: New insights from the European carbon markets.

The following is the Abstract of this article: "The electronic limit order book (LOB hereafter) has rapidly become the primary way of trading European carbon assets over the 4 years of the EU ETS programme (2008–2012). In this first attempt of examining the informational content of an electronic order book, [the authors] evidence that order flow imbalances have a moderate capacity to predict short term price changes. However, [the authors] find that both LOB slope and immediacy costs help to forecast quote improvements and volatility in the next 30 min. Further, [the authors] explain why informed trading is highly influential and show that it consists in mixing order splitting strategies and posting fleeting orders once the asymmetric information is reduced. Overall, the consolidated status of the order book mirrors a high level of market uncertainty and a low degree of informational efficiency. In this way, strategic trading can in itself explain some of order book properties, independently of the degree of traders' sophistication and market competition." **Yves Rannou**, *Research in International Business and Finance*. (Subscription may be required.)

Mapping research on carbon emissions trading: a co-citation analysis.

The following is the Abstract of this article: "Carbon emissions trading (CET) is a market mechanism, aims to promote the control of globe [GHG] emissions. It is an important part of international environmental cooperation and it is also the important application research filed of environmental economics and institutional economics. There is a very obvious phenomenon that the publications about CET increasing year by year. This paper adopts the scientometric analysis method to assess the current state and explore the development trends of carbon emission trading domain based on the literature data retrieved from Web of Science. The research results of this paper could answer the following questions clearly. 1) Which subject category is the most popular in CET research area? Which journal published the most number of articles in this area? Which institution and country is the most productive in CET domain? 2) What are the major research areas and what documents are the most cited? Which journal are the most representative in CET research domain? 3) What are the new emerging trends and development in CET research area? On the whole, the research method in this paper provided a fresh research approach to assess the performance of CET research. The findings may help for the new researchers to pick out the most relevant articles, journals, institutions and seize the research frontier in CET field." **Dejian Yu and Chao Xu**, *Renewable and Sustainable Energy Reviews*. (Subscription may be required.)

Carbon dioxide storage schemes: Technology, assessment and deployment.

The following is the Abstract of this article: "[CCS] is the only technology available to mitigate large-scale [GHG] emissions from fossil fuel based power and industrial sectors in the near future. When technology to capture CO_2 is relatively mature and commercially available for power and industrial sectors, safe, reliable and long-term storage of captured CO_2 remains a key uncertainty affecting wide-spread deployment of [CCS] technology yet. In this paper, the authors assessed techno-economic aspects of geological CO_2 storage options, from CO_2 transportations, various geological storage approaches, to CO_2 leakage monitoring. Compared with depleted oil/gas reservoirs and coal seams, deep saline aquifers possess much larger storage capacities and may be possibly near many CO_2 emission sites due to widespread distributions. If CO_2 storage is combined with enhanced industrial production (e.g. oil, natural gas), it has a greater potential to reducing the overall cost of CO_2 storage. Potential CO_2 leakage may be the main barriers to the development of CO_2 geological storage. It is recommended to make full use of big data mining approach in selection and approval of CO_2 geological sites, estimation of storage capacities, assessment of potential leakage risks, awarding of carbon credits, as well as analysis of public acceptations. At the same time, as a leakage-free CO_2 storage option, CO_2 mineralization & industrial utilization is to trap CO_2 permanently in stable minerals by reactions with metal oxides and forming stable carbonates. These CO_2 mineralization & industrial utilization schemes need to guarantee sustainable or environmentally friendly processes and satisfy basic principles of industrial ecology if implemented on a large industrial scale. Currently, most of CO_2 storage schemes are still in the early stage of technological development and are still far from large-scale commercialization. The high cost, high energy penalty, safety and reliability, and policy uncertainties are main barriers for the implement of carbon storage schemes." **Zhihua Zhang and Donald Huisingh**, *Journal of Cleaner Production*. (Subscription may be required.)

REPORTS and OTHER PUBLICATIONS

A Reduced-Order Model for Wellbore Permeability Induced by Geomechanical Damage.

The following is the Executive Summary of this NRAP document: "This work is part of a broader effort to develop risk assessment models of potential leakage of CO_2 from existing and new wells at a CO_2 sequestration site. This report focuses on potential geomechanical damage to wells following injection of CO_2 into the storage reservoir and the resulting changes in reservoir and caprock stress. This report includes a description of the development of a geomechanical model of the wellbore, two different stress-permeability relations, the creation of a reduced-order model (ROM) providing a simple algebraic representation of the results of geomechanical stress on the wellbore, and the results of the application of the model to an example reservoir at 1,000 m depth. The model is preliminary in nature, and future work will include the development of a more complete representation of the stress relationships in the wellbore system. The preliminary work shows that relatively high injection pressures would be required to damage the wellbore."

Compressive and Tensile Strength of Class H Cement Exposed to High Pressure and Temperature Storage Conditions.

The following is the Abstract of this NRAP document: "In the United States, the implementation of [co]-storage (CO_2-O_2-SO_2 mixtures) from oxy-fueled combustion, coal gasification and sour gas is currently being considered in saline geologic formations. DOE NETL, as part of NRAP, was tasked to determine the risk related to geologic carbon storage. This report addresses the potential impacts on wellbore cement integrity following exposure to storage conditions. When plumes of injected CO_2 (or co-stored) gas come in contact with existing wells, the cement lining in the well is vulnerable to geochemical alteration, and impact the well's effectiveness as a barrier for unwanted fluid migration. In this study, cured Class H cement paste, used in well construction, was exposed to co-storage conditions, and the tensile and compressive strength were measured to understand the effects of co-stored gas on the geomechanical properties of cement. In addition, co-storage settings at higher formation temperatures may result in loss of cement strength under acidic conditions, though cement integrity has not been tested under fully in situ conditions. These observed effects have implications for the long-term effectiveness of wells using Class H cement paste in co-storage scenarios."

UK decarbonisation and carbon capture and storage.

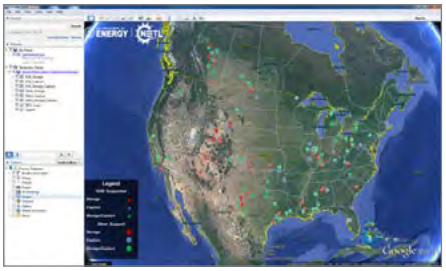
The following is the Summary of this document: "CCS is a way of 'decarbonising' fossil fuel power generation, through capturing and storing the CO_2 produced. CCS involves three steps; [1] Capturing CO_2 from power plants or industry, band compressing it to a liquid state [2] Transporting the CO_2 (usually via pipelines) to deep geological storage points such as depleted oil and gas fields or deep saline aquifers; and [3] Storing the CO_2 in these sites. [Carbon dioxide] can be captured pre- or post-combustion; [1] Post-combustion removes CO_2 from flue gases. This can be retro-fitted. [2] Pre-combustion reacts the fuel with oxygen, air, or steam, and after a further catalytic process removes the CO_2 and uses the hydrogen left over as fuel in a combined cycle gas turbine generating station. Only new fossil fuel power plants can be equipped with this. [3] Oxyfuel technology burns fossil fuels with nearly pure oxygen producing a flue gas of CO_2 and steam; the water condenses leaving flue gas of almost pure CO_2. This can be applied to new and existing fossil fuel stations. The ideal site for CCS generation is therefore close to a storage reservoir like depleted oil and gas fields and saline aquifers. A network of onshore and offshore pipelines to transport the captured CO_2 is also required. This could perhaps even be on a scale equivalent to the North Sea oil and gas industry. CCS is regulated through a licensing regime laid out in the Energy Act 2008. The Secretary of State for Business, Energy and Industrial Strategy (BEIS) is the licensing authority for offshore storage except within the territorial sea adjacent to Scotland."

ABOUT DOE'S CARBON STORAGE PROGRAM

The **Carbon Storage Program** advances the development and validation of technologies that enable safe, cost-effective, permanent geologic storage of CO_2. The Carbon Storage Program also supports the development of best practices for CCS that will benefit projects implementing CCS at a commercial scale, such as those being performed under NETL's Clean Coal Power Initiative and Industrial Carbon Capture and Storage Programs. The technologies being developed and the small- and large-scale injection projects conducted through this program will be used to benefit the existing and future fleet of fossil fuel power-generating facilities by developing tools to increase our understanding of the behavior of CO_2 in the subsurface and identifying the geologic reservoirs appropriate for CO_2 storage.

The *Carbon Storage Program Overview* webpage provides detailed information of the program's structure, as well as links to the webpages that summarize the program's key elements.

Carbon Storage Program Resources



The *National Energy Technology Laboratory's CCS Database* includes active, proposed, and terminated CCS projects worldwide. The information is taken from publically available sources to provide convenient access to information regarding efforts by various industries, public groups, and governments towards development and eventual deployment of CCS technology. NETL's CCS Database is available as a Microsoft Excel spreadsheet and also as a customizable layer in Google Earth.

Newsletters, program fact sheets, best practices manuals, roadmaps, educational resources, presentations, and more are available via the *Carbon Storage Program Publications webpage*.

Get answers to your carbon capture and storage questions at NETL's *Frequently Asked Questions webpage*.

ABOUT NETL'S CARBON STORAGE NEWSLETTER

Compiled by the National Energy Technology Laboratory, this newsletter is a monthly summary of public and private sector carbon storage news from around the world. The article titles are links to the full text for those who would like to read more.

National Energy Technology Laboratory

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