U.S. DEPARTMENT OF ENERGY | OFFICE OF FOSSIL ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

CSN CARBON STORAGE NEWSLETTER

MAY 2020

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

DOE Announces Funding for CCUS Projects.

The U.S. Department of Energy's (DOE) Office of Fossil Energy (FE) announced funding for carbon capture, utilization, and storage (CCUS) projects. The Funding Opportunity Announcement (FOA), titled "*Engineering-Scale Testing from Coal- and Natural-Gas-Based Flue Gas and Initial Engineering Design for Industrial Sources*," will support cost-shared research and development (R&D) projects that capture and store carbon dioxide (CO_2) emissions from industrial sources. Responses are due by June 5, 2020. In addition, DOE/FE also announced the *selection of five projects* under the "Carbon Storage Assurance Facility Enterprise (CarbonSAFE): Site Characterization and CO_2 Capture Assessment" FOA. The projects selected under this FOA will (1) assess and verify safe and cost-effective commercial-scale geologic storage sites for anthropogenic CO_2 emissions, and (2) assess the technical and economic viability of carbon capture or purification technologies for sources that will supply CO_2 to the storage sites. From *energy.gov*. April 2020.

Document Highlights DOE's CCS R&D.

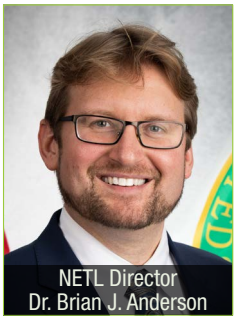
A document released by DOE's National Energy Technology Laboratory (NETL) highlights 20 years of DOE/NETL carbon capture and storage (CCS) R&D. The document, titled "*Safe Geologic Storage of Captured Carbon Dioxide: Two Decades of DOE's Carbon Storage R&D Program in Review*," details the role played by DOE's *Regional Carbon Sequestration Partnership (RCSPs) Initiative*, as well as the CarbonSAFE Initiative. An excerpt from the Executive Summary can be found in the Publications section of this newsletter. From *energy.gov*. April 2020.

Petra Nova site, located near Houston, Texas (USA).

ANNOUNCEMENTS

NETL's Decarbonization Work Highlighted at Meeting.

NETL Director Brian Anderson shared information on NETL's decarbonization work *while speaking at a Massachusetts Institute of Technology (MIT) Energy Initiative meeting*. NETL's advancements in cost-effective implementation of CCUS technologies were highlighted, as was DOE/NETL's Carbon Storage Program.



NETL Director
Dr. Brian J. Anderson

DOE Announces Funding for CO_2 Capture Research.

DOE announced funding for research aimed at advancing CO_2 capture technology. The initiative encompasses two concurrent FOAs: one by DOE's Office of Science (SC) and another by DOE's FE. *The SC FOA* invites DOE's national laboratories to submit proposals for research in materials and chemical sciences. *The FE FOA* focuses on applied development of new materials and the field testing of prototypes.

Get to Know NETL.

NETL *released a series of "Get to Know NETL" videos* highlighting work being conducted at NETL facilities. The series includes an overview of NETL as well as videos about NETL sites in *Albany, Oregon*; *Morgantown, West Virginia*; and *Pittsburgh, Pennsylvania*.

NETL research site in Albany, Oregon (USA).

ANNOUNCEMENTS *(cont.)*

Global CCS Institute Hosts CCS Webinar.

The Global CCS Institute conducted a webinar explaining how CO_2 storage works and addressing myths and misconceptions. *Presentation slides* and *video* of the webinar, titled "CCS Talks: All you need to know about CO_2 storage," are available.

Pandemic's Impact on CO_2 Emissions.

According to *data released by the U.S. Energy Information Administration (EIA)*, energy-related CO_2 emissions in the United States could potentially decline by 7.5% in 2020 as a result of stay-at-home restrictions due to the coronavirus. Similar measures enacted by European Union (EU) member states have led to the EU experiencing a 58% reduction in daily CO_2 emissions, according to consultants.

CCUS Project Launches Wiki Page.

The ALIGN-CCUS project *launched a Wiki page* to communicate the project's activities to non-experts. Integrated into the project's website, the Wiki provides user-friendly access to the project objectives and outputs. The web-based platform will be continually updated through the conclusion of the project.

PROJECT and BUSINESS DEVELOPMENTS

Partners Investigate Second Phase Under DOE's CarbonSAFE Initiative.

The Kansas Geological Survey, along with private and public partners, is characterizing a site as one of DOE's CarbonSAFE projects. The joint effort—the Integrated Midcontinent Stack Carbon Storage Hub—is the second phase of the effort, with the objective of investigating the subsurface geology at sites in southwest Kansas and southwest Nebraska (USA) to verify the viability of CO_2 storage. *The CarbonSAFE Initiative aims to reduce technical risk, uncertainty, and costs of commercial-scale storage projects*. From *Phys.org*. April 2020.

CCS Facility Provides Updated Capture Totals.

The CCS facility at SaskPower's Boundary Dam Power Station in Saskatchewan, Canada, reported a total of 61,801 metric tons of CO_2 captured in March 2020 (approximately 62% of capacity). The average for the previous 12 months at the CCS facility was 55,328 metric tons of CO_2 captured. The facility captured 178,520 metric tons of CO_2 in the first quarter of 2020 and has captured more than 3.2 million metric tons of CO_2 since it went online in October 2014. From *Pipeline News*. April 2020.

Agreement Signed to Study CCS in Malaysia.

JOGMEC, JX Nippon Oil & Gas Exploration, and PETRONAS signed a joint agreement to study the use of CCS technology to develop gas fields in Malaysia that produce a mixture of methane and CO_2. In the study, CO_2 produced from the fields will be separated, captured, and injected into suitable storage reservoirs. From *Carbon Capture Journal*. March 2020.

Large-Scale Capture, EOR Project Announced.

Agreements to develop a large-scale CO_2 capture facility that will include CO_2-enhanced oil recovery (EOR) operations in an existing oil field were finalized. Starwood Energy and Oil and Gas Climate nitiatives (OGCI) Climate Investments announced the agreements for the facility, which will be integrated with a natural gas power plant. Jointly developed by Starwood and Elysian Ventures, LLC, the project will use commercially available CO_2 capture technology and aims to capture 90% of the CO_2 emissions from an existing power facility for use in EOR operations. From *Starwood Energy Group Press Release*. April 2020.

CCUS Study Awarded.

The *Athos consortium*, which manages the *Athos CCUS* project in the Noordzeekanaal region of the Netherlands, awarded a concept select study to *io consulting* to support the review of options for CO_2 transportation and storage from the region's industrial CO_2 emitters. io consulting will support an evaluation of the transportation infrastructure required to capture CO_2 and transport it offshore to depleted hydrocarbon reservoirs in the Dutch sector of the North Sea. From *Carbon Capture Journal*. April 2020.

Multi-Year CCUS Collaboration Announced.

Cambridge Quantum Computing (CQC) and Total S.A. announced a partnership to develop algorithms and quantum computing solutions for advanced CCUS technologies. The collaboration will apply CQC's quantum computing and quantum chemistry experience to Total's CCUS R&D efforts. From *Cambridge Quantum Computing News Release*. April 2020.

CCUS Projects Awarded Funding in UK.

United Kingdom Research and Innovation (UKRI) announced funding for a range of decarbonization projects for the first phases of the UK government's Deployment and Roadmap Program strategies for decarbonization. The projects aim to help the UK achieve net-zero emissions by 2050 as part of the UK government's Clean Growth Strategy. From *Carbon Capture Journal.* April 2020.

LEGISLATION and POLICY

Virginia Governor Signs Clean Energy Legislation.

The governor of Virginia (USA) signed the Virginia Clean Economy Act into law, requiring Virginia state electricity providers to become carbon free by 2050. Under the new laws, Virginia plans to join the *Regional Greenhouse Gas Initiative (RGGI)*. From *Virginia Business*. April 2020.

Shell Aims to Be Net-Zero by 2050.

Officials from Royal Dutch Shell laid out a strategy to reduce the company's greenhouse gas emissions to net-zero by 2050. The company previously had long-term intensity-based targets rather than goals based on absolute emissions reductions. From *Reuters*. April 2020.

EMISSIONS TRADING

RGGI States Initiate Auction Process for Auction 48, Release CO_2 Budget Source Compliance Materials.

The states participating in RGGI's 2020 auctions initiated the auction process for their 48th quarterly CO_2 auction, scheduled for June 3, 2020. Auction 48 will offer 16,336,298 CO_2 allowances for sale at a minimum reserve price of $2.32. An 11.8 million CO_2 allowance cost containment reserve (CCR) will also be made available. (The CCR will be accessed if the interim clearing price exceeds the CCR trigger price of $10.77.) In addition, the RGGI states *released materials* for CO_2 budget source compliance for their fourth three-year control period, which is from January 1, 2018, through December 31, 2020. From *RGGI*. April 2020.

Canadian Government Releases Notice of Intent to Amend Pricing Regulations.

The Canadian government announced an intent to amend carbon pricing regulations amid the coronavirus pandemic. The Canadian Minister of Environment and Climate Change intends to develop regulations for the country's *Output-Based Pricing System* that would amend reporting requirements within Canadian provinces. From *JD Supra*. April 2020.

SCIENCE NEWS

Researchers Use 3D Printing to Predict Rock Fractures, Aid Carbon Storage.

Researchers are 3D-printing minerals to help better predict fracture formation, which could be used to improve understanding of carbon storage. Working with their university's Rock Physics Research Group, researchers from Purdue University (USA) used a 3D printer to create synthetic rock samples, enabling the team to use a computer program to control the quality of the synthetic rock. The research, which was supported by DOE's SC and Sandia National Laboratories, was *published in the journal Scientific Reports*. From *Purdue News*. April 2020.

Long-Living Tropical Trees Play Role in CO_2 Storage.

A team of scientists found that a group of fast-growing, long-lived, slow-to-reproduce trees in some tropical rainforests play a large role in CO_2 storage. The study of the trees, which are referred to as "long-lived pioneers," provides insight into the roles of different species of trees in CO_2 storage. The research, led by the German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, was *published in the journal Science*. From *ScienceDaily*. April 2020.

Conversion Test Facility Being Built.

A test facility to convert CO_2 from air into solid carbon is being built at Karlsruhe Institute of Technology (KIT) in Karlsruhe, Germany. The NEgative Carbon diOxide to Carbon (NECOC) research project's test facility will aim to actively reduce CO_2 emissions by capturing CO_2 from ambient air and, together with renewable hydrogen, convert it into methane, which will serve as a "carbon carrier." More information on the process can be found in KIT's *press release*. From *KIT Press Release*. March 2020.

Study Explores Oceans' Ability to Store CO_2.

A study found that the world's oceans have the potential to capture and store twice as much CO_2 from the atmosphere as previously thought. Scientists from the Woods Hole Oceanographic Institution (WHOI) came to their conclusions by recalculating the section of upper ocean layer that sunlight can penetrate, referred to as the euphotic zone. WHOI scientists then used data gathered from chlorophyll sensors to help reveal the true edges of the euphotic zone, finding that the depths of the boundary vary throughout the world. The study concluded that the world's oceans may have the potential to absorb approximately twice as much CO_2 each year than original data projected. From *New Atlas*. April 2020.

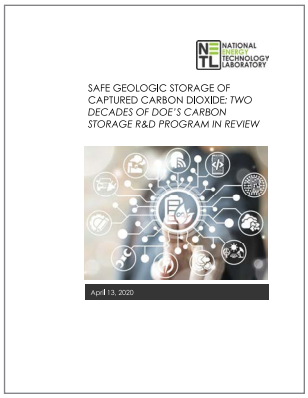
Research Examines Mature Forests' Ability to Store CO_2.

Researchers from the State University of New York (SUNY) College of Environmental Science and Forestry (ESF) and Western Sydney University found evidence that mature forests have a limited ability to store CO_2. ESF's Department of Sustainable Resources Management (USA) collaborated with Western Sydney University's (Australia) *Eucalyptus Free Air CO_2 Enrichment* research facility to study a 90-year-old eucalyptus woodland in Western Sydney's Cumberland Plain exposed to elevated CO_2 levels. The study found that extra CO_2 absorbed by the trees was cycled through the soil and returned to the atmosphere. Previous models predicted that mature forests would store more CO_2 by acting as carbon sinks; the findings of this study, *published in the journal Nature*, suggest those sinks may be weaker or absent for mature forests. From *ScienceDaily*. April 2020.

PUBLICATIONS

Safe Geologic Storage of Captured Carbon Dioxide: Two Decades of DOE's Carbon Storage R&D Program in Review.

The following is from the Executive Summary of this DOE/NETL document: "Carbon capture, utilization, and storage (CCUS) is widely regarded as a necessary component in the global effort to reduce carbon dioxide (CO_2) emissions to the atmosphere in a cost-effective way. A key question about the viability of CCUS with respect to protection of human health and the environment is how to ensure that CO_2 injected in deep geologic reservoirs is securely stored. Geological storage of CO_2 has been a natural process in the Earth's upper crust for hundreds of millions of years. While this provides supporting evidence that CO_2 can be securely and safely contained in the deep subsurface, it is vitally important that the technical means exist to identify suitable sites and monitor stored CO_2 to verify secure containment. The U.S. Department of Energy (DOE) has invested more than $1 billion during the past two decades through its Carbon Storage Research and Development (R&D) Program to develop the technologies and capabilities for widespread commercial deployment of geologic storage. This investment has made DOE a leader in this worldwide effort. CCUS projects supported by DOE and other organizations around the world, which in 2019 injected more than 25 million metric tons of CO_2, have shown no adverse impacts to human health or the environment. And no DOE supported project has observed migration of CO_2 outside of the intended storage reservoir or confining cap rock. Increasing years of experience and a preponderance of successful projects will promote even further confidence in secure storage for operators, regulators, insurers, financial institutions, environmental groups, and the public."



Industrial Sources Carbon Capture Retrofit Database.

The following is a description of this DOE/NETL database: "This tool provides high-level analysis on the incremental costs for retrofitting point sources with carbon dioxide (CO_2) capture and/or compression systems applied to various high purity industrial CO_2 sources. Options are available to include costs of other technological improvements that would be required to comply with various regulations and New Source Performance Standards when installing CO_2 scrubbing technology."

Assessment of CO_2-enhanced oil recovery and associated geologic storage potential in the Michigan Northern Pinnacle Reef Trend.

The following is from the abstract of this article: "This paper provides an improved estimate of CO_2-EOR (where CO_2 is carbon dioxide and EOR is enhanced oil recovery) and CO_2 storage potential for depleted oil fields in Michigan's northern pinnacle reef trend (NPRT). [The authors'] methodology is based on capturing data on reservoir performance from reefs currently undergoing CO_2-EOR operations in the NPRT (referred to as 'monitored reefs'), and then applying them to other reefs within the NPRT (referred to as 'catalog reefs'). For each monitored reef, [the authors] calculate fractional primary recovery, fractional incremental EOR recovery, net utilization ratio, and storage efficiency factor. The corresponding incremental oil recovery from EOR, storage capacity until end of EOR, and total CO_2 injection needs are then estimated for each catalog reef and combined (over all monitored reefs) using a weighted averaging procedure. These weights are related to a statistical similarity measure that is calculated between each monitored reef and each catalog reef based on a number of variables related to production data, formation type, or descriptive geologic attributes. For the entire NPRT catalog of 383 reefs as used in this study, [the authors'] results indicate 118 million (MM) stock tank barrels (STB) (1.88×10^7 Sm^3) of incremental oil from EOR operations, corresponding to 49 MM metric tons (MT) of CO_2 storage and 266 MM MT of total CO_2 injection. However, approximately one-third of the reefs provide two-thirds of the potential for CO_2-EOR and geologic storage, assuming an economic threshold of 0.5 MM STB (80 000 Sm^3) of incremental oil from EOR." **Srikanta Mishra, Autumn Haagsma, Manoj Valluri, and Neeraj Gupta,** *Greenhouse Gases: Science and Technology.* (Subscription may be required.)

Carbon dioxide storage resource assessment of Cretaceous- and Jurassic-age sandstones in the Atlantic offshore region of the northeastern United States.

The following is from the abstract of this article: "Carbon capture and storage is a critical technology for ensuring a range of clean energy options are available to meet future energy demand in the United States and abroad. A total of 1079 industrial CO_2 emission sources are located in the northeastern United States, where challenging surface and subsurface conditions limit onshore CO_2 storage potential. A systematic resource assessment was conducted using industry-standard resource classification methods established by the Society of Petroleum Engineers' Storage Resources Management System to characterize CO_2 storage resources in the middle–northern Atlantic offshore region along the eastern United States. Storable CO_2 quantities and storage efficiencies were estimated for Cretaceous- and Jurassic-age sandstone sequences. Regional data integration and analysis were conducted to estimate storable quantities and storage efficiencies using probabilistic methods with static volumetric calculations and dynamic simulations. Offshore storage efficiencies range from 1% to 13%, with regional-scale estimates of 37–403 billion t (Gt) of CO_2 classified as prospective storage resources. Dynamic CO_2 injection simulation in a middle Cretaceous sequence on the eastern flank of the Great Stone Dome suggests 30–51 million t of CO_2 can be stored and contained within the time and pressure constraints assumed for a commercial storage project. The regional Cretaceous and Jurassic plays identified in the offshore study region have prospective storage resources sufficient for long-term storage of CO_2 from nearby industrial sources onshore. Continued resource discovery efforts are recommended to assess the development and commerciality of the potential storage identified near the Great Stone Dome." **Isis Fukai, Laura Keister, Priya Ravi Ganesh, Lydia Cumming, Will Fortin, and Neeraj Gupta,** *Environmental Geosciences.* (Subscription may be required.)

An analysis of research hotspots and modeling techniques on carbon capture and storage.

The following is from the abstract of this article: "With the significant role that carbon capture and storage (CCS) could play in limiting the future temperature increase to below 2°C higher than pre-industrialization levels, a growing research interest of CCS is attracted to the environmental, economic, and social field. However, a bibliometric analysis-based comprehensive review of CCS which covers mainly all industry sectors and all regions of the globe has not been made yet. To provide deeper insight into the research trends, this study employs a bibliometric analysis to examine the basic features of the literature from 1997 to 2017 and identifies the key research hotspots and modeling techniques by reviewing the current status and new efforts. Based on the analysis of the temporal and spatial trends, disciplines and journals distribution, institutions, authors, and citations, the publications relating to the environmental, economic and social aspects of CCS are assessed. The results indicate that the total number of publications has rapidly increased since 2006 and entered a stable stage. The most productive country, journal, institute, and author are the USA, International Journal of Greenhouse Gas Control, United State Department of Energy, and Rubin E S, respectively. Based on the co-occurrence analysis of keywords, five hot research topics in CCS are recognized, including tackling climate change, CCS technology prospects, cost estimates, sectoral applications, and social attitudes. In addition, three main methodologies including life cycle analysis, optimization methods, and real options methods used in quantifying the social, economic, and environmental impacts of CCS are thoroughly refined based on selection, limitation, and improvement. Finally, the recommendations for CCS future work concerning environmental, economic, and social aspects are proposed." **Hui Li, Hong-Dian Jiang, Bo Yang, and Hua Liao,** *Science of the Total Environment.* (Subscription may be required.)

PUBLICATIONS *(cont.)*

Time-lapse gravity monitoring of CO_2 migration based on numerical modeling of a faulted storage complex.

The following is from the abstract of this article: "In this study, the performance of both surface and borehole time-lapse gravity monitoring to detect CO_2 leakage from a carbon storage site is evaluated. Several hypothetical scenarios of CO_2 migration in a leaky fault, and thief zones at different depths at the Kimberlina site (California, USA) constitute the basis of the approach. The CO_2 displacement is simulated using the TOUGH$_2$ simulator applied to a detailed geological model of the site. The gravity responses to these CO_2 plumes are simulated using forward modeling with sensors at ground surface and in vertical boreholes. Results of inversion on one scenario are also presented. The surface-based gravity responses obtained for the different leakage scenarios demonstrate that leakage can be detected at the surface in all the scenarios but the time to detection is highly variable (10–40 years) and dependent on the detection threshold considered. Borehole measurements of the vertical component of gravity provide excellent constraints in depth when they are located in proximity of the density anomaly associated with the presence of CO_2, thus discriminating multiple leaks in different thief zones. Joint inversion of surface and borehole data can bring valuable information of the occurrence of leakages and their importance by providing a reasonable estimate of mass of displaced fluids. This study demonstrates the importance of combining multiphase flow simulations with gravity modeling in order to define if and when gravity monitoring would be applicable at a given storage site." **Delphine Appriou, Alain Bonneville, Quanlin Zhou, and Erika Gasperikova,** *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

Possibilities for CCUS in medium temperature geothermal reservoir.

The following is from the abstract of this article: "Based on the hypothetical structure, a 3D numerical simulation model was created to examine the flow characteristics of a geothermal field. According to the known dimensions, assumption of existing fault and petrophysical properties, the model can relate to the properties of Velika Ciglena geothermal reservoir, and thus the simulation results of heat flow (reservoir cooling due to reinjection of cooled water), wellbore injectivity and productivity are comparable with previously published data related to the same field. This simulation model for a geothermal reservoir of such structure has been made for the first time and was complemented by an analysis of possible CO_2 injection. It has been established that the effect of CO_2 storage is significant until CO_2 reaches the production well (first two years). The effect of pressure relief on the CO_2 injection well has been achieved because of simultaneous injection and production and due to an increase in CO_2 saturation which had consequently induced an increase of the effective permeability for CO_2. The effect of reservoir cooling is shown, which is significant only when the water is injected, while in the case of injection and production of CO_2, this effect does not reflect on the temperature of the produced fluid." **Domagoj Vulin, Lejla Muhasilović, and Maja Arnaut**, *Energy*. (Subscription may be required.)

A study on the thermal-hydrodynamical-coupled CO_2 flow process in the Ordos CCS-geological-formation.

The following is from the abstract of this article: "Non-isothermal flow in wellbores and geological formations is an important process associated with geologic storage of CO_2. Technically, simulation of it is a highly challenging task as it often encounters phase transition problems for the fluids involved, which may greatly influence the profiles of pressure, temperature, and flowrate along the wellbore and consequently changes the injectivity of the relevant gas injection. In this paper [the authors] present a coupled non-isothermal wellbore/reservoir model for simulating the relevant flow behaviors, in which the non-isothermal wellbore flow model CO_2Well and the reservoir simulator TOUGH$_2$/ECO$_2$N are combined to form a novel coupled flow model. The model developed is compared and verified by the existing wellbore-reservoir simulator T2Well with two CO_2 injection examples. These examples demonstrate that the present method has considerable computational advantages in simulating wellbore flows when phase transition occurs. [The authors] then apply this model to the Ordos CCS demonstration project in China, and investigate the sophisticated, thermal-hydrodynamically-coupled flow processes observed there owning to injection of the condensed, cold CO_2 that was directly captured from a nearby coal liquefaction plant. The results obtained by the simulation, along with the relevant field observations, provide in-depth insights into the CO_2 flow behaviors in both the wellbore and the geological formation. For example, the simulation revealed that, in the wellbore, the heat exchange between the injected CO_2 and the surrounding rock plays a critical role for the temperature distribution. It was also observed that phase transition occurred in the transferred period between the injection time and the shut-in time. In addition, both the simulation and field observation showed that most CO_2 injected entered the topmost layer due to the high transmissivity of the rock. The simulation also showed that the temperature-change zone travelled slower than the CO_2 plume. For example, the CO_2 plume extended to 430 m away from the injection site after 31 months of CO_2 injection, while the temperature-change zone extended merely about 90 m away, much smaller than that of the CO_2 plume. The simulation suggests that the injectivity at this site is about 0.83 kg/(MPa·s). The simulation also suggests that the injection temperature should be relatively high (e.g., above –3°C if the injection rate is more than 9.45 kg/s) to avoid formation of CO_2 hydrate in the subsurface." **Hongwu Lei, Yuna Cai, Meng Lu, Xiaochun Li, and Luke Daulton Connell,** *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

Materials and logistics for carbon dioxide capture, storage and utilization.

The following is from the abstract of this article: "The efforts to curtail carbon dioxide presence in the atmosphere are a strong function of the available technologies to capture, store and usefully utilize it. Materials with adequate CO_2 sorption kinetics that are both effective and economical are of prime importance for the whole capture system to be built around. This work identifies such materials that are currently used in CO_2 adsorption beds/columns at different global locations, along with their vital operational parameters, logistics and costs. Three main classes of materials currently in use to that end are discussed in detail here, namely solid sorbents, advanced solvents membrane systems. These materials are then compared in terms of their potential CO_2 uptake, operating parameters and ease of use and implementation of the respective technology. Tabular data are appended to each technology covered with the most relevant advantages and disadvantages. With such comprehensive survey of the recent state-of-the-art materials, recommendations are also made to facilitate the selection of systems based on their CO_2 yield, price and suitability to the geographical location." **Abdul Hai Alami, Abdullah Abu Hawili, Muhammad Tawalbeh, Rita Hasan, Lana Al Mahmoud, Sara Chibib, Anfal Mahmood, Kamilia Aokal, and Pawarin Rattanapanya,** *Science of The Total Environment*. (Subscription may be required.)

PUBLICATIONS *(cont.)*

The flow of embodied carbon through the economies of China, the European Union, and the United States.

The following is from the abstract of this article: "Indirect CO_2 emissions are gaining increasing interests in addition to direct CO_2 emissions, as policy makers become more aware of the possibilities for structural and technical change, sometimes resulting from policies, to move CO_2 emissions along supply chains. An analysis of the composition of emissions and carbon efficiency of production and their development over time may inform the formulation of demand-side and supply-side solutions for emission reduction over the entire life-cycle. In addition, understanding of emissions embodied in trade (EET) at intermediate and final stages is crucial for allocation of emission responsibilities in a fair manner. Hence, [the authors] account for global direct and indirect intermediate and final CO_2 emissions using the global, multiregional input-output model EXIOBASE 3.3. [The authors] present results for the flow of embodied carbon through the economies of 49 countries and regions using an interactive visualization and provide a comparative analysis of China, the US, and the EU. It shows that China has undergone rapid, continuous increase in both intermediate and final indirect CO_2 emissions compared to the other two economies from 1995 to 2015, to 26.1 Pg and 11.0 Pg respectively. Emission intensities in China are on average 3.7 times of the US and 2.4 times of the EU in the year 2015, implying the possibility of further reducing emission by efficiency improvement and fuel switching. CO_2 EETs of intermediate production by sectors in the three economies are also reported." **Kehan He and Edgar G. Hertwich,** *Resources, Conservation and Recycling.* (Subscription may be required.)

Inventory management in supply chains with consideration of Logistics, green investment and different carbon emissions policies.

The following is from the abstract of this article: "This study investigates the effects that carbon policies and green technologies may have on the integrated inventory of a two-echelon supply chain with consideration of carbon emissions during the processes of product production, transportation, and storage. The three carbon emissions policies: limited total carbon emissions, carbon taxation, and cap-and-trade, are considered in the study. The proposed model can assist firms in determining their corresponding optimal production quantity, delivery quantity, and green investment amount with an aim of minimizing the costs under different carbon emissions policies. Moreover, this study also provides practical implications for the government to make appropriate policies and regulations in balancing the trade-off between environmental protection and economic growth. Finally, the results indicate that firms adopting the carbon tax policy would prefer to invest in a relatively efficient green technology. With regard to the sources of carbon emissions, the effects of unit carbon emissions during production and unit distance of transportation are the most dramatic, and the cap limit has greater effects than the carbon emissions reduction factor of the green technology. Besides, the government should set the limit of carbon emissions within a reasonable range under the cap-and-trade policy to avoid suppliers overly trading their quotas of carbon emissions." **Yeu-Shiang Huang, Chih-Chiang Fang, and Ying-An Lin,** *Computers & Industrial Engineering.* (Subscription may be required.)

Proglacial freshwaters are significant and previously unrecognized sinks of atmospheric CO_2.

The following is from the abstract of this article: "Carbon dioxide (CO_2) emissions from freshwater ecosystems are almost universally predicted to increase with climate warming. Glacier-fed rivers and lakes, however, differ critically from those in nonglacierized catchments in that they receive little terrestrial input of organic matter for decomposition and CO_2 production, and transport large quantities of easily mobilized comminuted sediments available for carbonate and silicate weathering reactions that can consume atmospheric CO_2. [The authors] used a whole-watershed approach, integrating concepts from glaciology and limnology, to conclusively show that certain glacier-fed freshwater ecosystems are important and previously overlooked annual CO_2 sinks due to the overwhelming influence of these weathering reactions. Using the glacierized Lake Hazen watershed (Nunavut, Canada, 82°N) as a model system, [the authors] found that weathering reactions in the glacial rivers actively consumed CO_2 up to 42 km downstream of glaciers, and cumulatively transformed the High Arctic's most voluminous lake into an important CO_2 sink. In conjunction with data collected at other proglacial freshwater sites in Greenland and the Canadian Rockies, [the authors] suggest that CO_2 consumption in proglacial freshwaters due to glacial melt-enhanced weathering is likely a globally relevant phenomenon, with potentially important implications for regional annual carbon budgets in glacierized watershed." **Kyra A. St. Pierre, Vincent L. St. Louis, Sherry L. Schiff, Igor Lehnherr, Paul G. Dainard, Alex S. Gardner, Pieter J. K. Aukes, and Martin J. Sharp**, *Proceedings of the National Academy of Sciences of the United States of America.* (Subscription may be required.)

ABOUT DOE'S CARBON STORAGE PROGRAM

The **Carbon Storage Program** at the National Energy Technology Laboratory (NETL) is focused on developing and advancing technologies to enable safe, cost-effective, permanent geologic storage of CO_2, both onshore and offshore, in different depositional environments. The technologies being developed will benefit both industrial and power sector facilities that will need to mitigate future CO_2 emissions. The program also serves to increase the understanding of the effectiveness of advanced technologies in different geologic reservoirs appropriate for CO_2 storage—including saline formations, oil reservoirs, natural gas reservoirs, unmineable coal, basalt formations, and organic-rich shale basins—and to improve the understanding of how CO_2 behaves in the subsurface. These objectives are key to increasing confidence in safe, effective, and permanent geologic 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

Newsletters, program fact sheets, best practices manuals, roadmaps, educational resources, presentations, and more information related to the Carbon Storage Program is available on *DOE's Energy Data eXchange (EDX) website*.

Rig drilling a site characterization well at the Craig Power Station in Colorado, USA. *Photo Source: Schlumberger Carbon Services*

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 (note that all links were active at the time of publication).

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