Carbon Storage Newsletter

FEBRUARY 2015

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HIGHLIGHTS

"Department of Energy, Shell Canada to Collaborate on CO_2 Storage."

The U.S. Department of Energy (DOE) and Shell Canada announced intentions to collaborate in field tests to validate advanced monitoring, verification, accounting (MVA), and assessment technologies for underground carbon dioxide (CO_2) storage at Shell's Quest carbon capture and storage (CCS) project in Alberta, Canada. The technologies under consideration would be tested alongside the state-of-the-art, comprehensive monitoring program Shell has already put in place for the Quest project. The test results are expected to provide additional information that would benefit future large-scale CCS projects around the world. Details of the collaboration are expected to be finalized in early 2015. From *NETL News Release* on February 4, 2015.

"Energy Department Project Captures and Stores One Million Metric Tons of Carbon."

The U.S. Department of Energy (DOE) announced that the Midwest Geological Sequestration Consortium's (MGSC) Illinois Basin-Decatur Project successfully captured and stored 1 million metric tons of carbon dioxide (CO_2) in a saline formation. The CO_2 is captured from the Archer Daniels Midland Company ethanol-production facility in Decatur, Illinois. It is then compressed and transported by pipeline for injection approximately 7,000 feet below the surface into the Mount Simon Sandstone formation. Since initiation in November 2011, the injection has sustained pressure increases below regulatory limits. The injected CO_2 is expected to remain hundreds of feet below a 300-foot thick shale formation that acts as a seal. The project is part of DOE's Regional Carbon Sequestration Partnerships (RCSP) Initiative, which is developing and deploying carbon capture and storage (CCS) technologies across the United States. MGSC, led by the Illinois State Geological Survey (ISGS), is evaluating CCS options for the 60,000-square-mile Illinois Basin, which underlies most of Illinois, southwestern Indiana, and western Kentucky. From *NETL News Release* on January 8, 2015.

"Oil Operators Gain Powerful, User-Friendly Enhanced Oil Recovery Planning Software."

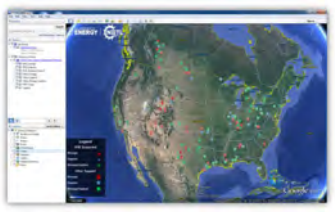
Under a cooperative agreement with DOE's National Energy Technology Laboratory (NETL), NITEC LLC developed new software, called COZView/COZSim, that enables quicker, more affordable technical studies of CO_2-enhanced oil recovery (CO_2-EOR) for small- to mid-sized U.S. oilfield operators. The software has the following features: (1) addresses the physical and chemical factors that impact the flow and recovery of reservoir fluids, such as solubility of CO_2 in water and oil or swelling of oil in the presence of CO_2; (2) allows an integrated feasibility study to be completed within one month, compared to the six or more months required for other approaches; and (3) integrates a friendly, interactive user interface (COZView) for pre- and post-processing of simulation results with a reservoir simulator (COZSim) that can model CO_2-EOR in oil reservoirs. The NETL-funded version of the software can be downloaded from the NITEC LLC website free of charge. The website also includes a comprehensive user manual and a number of tutorials. From *NETL News Release* on December 15, 2014.

Announcements

Technical Session on Engineering Geologic CO_2 Storage Systems.

The American Institute of Chemical Engineers (AIChE) Annual meeting scheduled for November 8-13, 2015, in Salt Lake City, Utah, USA, will include a technical session, titled, "Engineering Geologic Carbon Dioxide Storage Systems." Research presentations covering the science and technology of carbon storage, as well as field demonstrations of CO_2 injection, are encouraged. Conference details, abstract submission, and more information are available via the above link.

5th Version of NETL's CCS Database Now Available.



NETL's CCS Database includes active, proposed, and terminated CCS projects worldwide. The information is sourced from publically available information to provide the public with information regarding efforts by various industries, public groups, and governments towards development and eventual deployment of CCS technology. As of November 2014, the database contained 274 CCS projects worldwide. The 274 projects include 69 capture, 60 storage, and 145 for capture and storage in more than 30 countries across 6 continents. While several of the projects are still in the planning and development stage, 128 are actively capturing and injecting CO_2. NETL's CCS Database is available as a Microsoft Excel spreadsheet and also as a customizable layer in Google Earth.

Novel Carbon Capture Solvent Begins Pilot-Scale Testing for Emissions Control.

Pilot-scale testing of an advanced technology for capturing CO_2 from flue gas has begun at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama, USA. Under a cooperative agreement with the DOE/NETL, Linde LLC is operating a nominal 1-megawatt-electric pilot plant expected to capture 30 tons of CO_2 per day. The testing will validate performance of the Linde-BASF CO_2 capture technology on actual coal-derived flue gas. The test program consists of three phases: initial start-up and operation with flue gas and solvent recirculation, parametric testing, and long-duration testing for a minimum of 60 days. Following pilot testing, Linde and BASF will pursue opportunities for larger-scale testing.

$842.1 Million Requested for Fossil Energy Programs.

The President's FY 2016 budget seeks $842.1 million for the Office of Fossil Energy (FE), including $560 million for Fossil Energy Research and Development (R&D). In FY 2016, Fossil Energy R&D will continue to focus on CSS and activities that increase the performance, efficiency, and availability of systems integrated with CCS. The FY 2016 budget requests $108.8 million for carbon storage R&D. The overall goal of the Carbon Storage Program is to develop and validate technologies to ensure safe and permanent geologic storage of captured CO_2. The development and validation of these technologies is critical to (1) ensure stakeholders have the capability to assess, monitor, and mitigate storage risks for CO_2, and (2) ensure the viability of large-scale carbon storage.

New Membrane Technology for Post-Combustion Carbon Capture Begins Pilot-Scale Test.

A new, DOE-sponsored technology for capturing 90 percent of the CO_2 emitted from a coal-burning power plant has begun pilot-scale testing. The PolarisTM membrane system, developed by Membrane Technology and Research, Inc. (MTR) uses a specially designed CO_2-selective membrane (a microporous film that acts as a semi-permeable barrier) to separate CO_2 from other gases in a coal-burning plant's flue gas. The data from this pilot test will provide DOE, MTR, and project partners with insights into the next steps required for scale-up and field tests.

Carbon Storage in the News

"CCS Collaboration Launched in Teesside, UK."

A group of industrial plants in Teesside, United Kingdom (UK), known as the Teesside Collective, has launched a collaboration to set up a CCS-equipped industrial zone. The plan for the project is for industries in the region to capture emissions and transport them via a shared pipeline network for storage under the North Sea. BOC, Lotte Chemical, SSI, and GrowHow's Teesside facilities will form the four "anchor projects" of the Collective's work; the steering group also includes National Grid, Tees Valley Unlimited, and the North East Process Industry Cluster Tees Valley Unlimited was awarded $1.5 million in funding by the UK's Department of Energy and Climate Change (DECC) to develop a business case for the CCS cluster and recommend a funding mechanism. From *The Chemical Engineer* on January 22, 2015.

"Magellan Provides Update on Poplar CO_2-EOR Pilot."

According to Magellan Petroleum Corporation officials, downhole injection pressure has remained stable at above miscibility pressure at the CO_2-EOR pilot at Poplar Dome in Montana, USA. Magellan has been injecting CO_2 into the B-2 zone of the Charles formation through an injector well for approximately 150 days. In addition to the stable injection pressure, the data also shows that injected CO_2 has entered

Carbon Storage in the News (Continued)

into the target formation matrix. During January 2015, two of the four pilot producer wells exhibited oil production with small volumes of natural gas and injected CO_2 also being produced. From *Magellan Petroleum Press Release* on January 29, 2015.

"[Australian Government] Injects $25m into CCS Research."

Australia's Minister for Industry and Science announced that the Australian Government would provide $25 million over five years to the CO2CRC Otway Project and related activities. According to a CO2CRC official, a major focus of the research will be on high resolution monitoring and verification of stored CO_2 and continued research into CO_2 capture technologies. The funding will be provided to CO2CRC under the CCS Flagships Program. The funding will be matched by contributions from CO2CRC members, in particular $10 million from the Australian coal industry's Coal21 Fund and a $5 million Victorian Government grant announced in September 2014. From *CO2CRC News Release* on February 2, 2015.

Science

"NASA, NOAA Find 2014 Warmest Year in Modern Record."

According to two separate analyses conducted by NASA and the National Oceanic and Atmospheric Administration (NOAA), the Earth's 10 warmest years in the instrumental record (with the exception of 1998) have occurred since 2000, with 2014 ranking as the warmest since 1880. Scientists at NASA's Goddard Institute of Space Studies (GISS) analyzed surface temperature measurement data, which was also independently analyzed by NOAA scientists. The data showed that since 1880, the Earth's average surface temperature has warmed by approximately 1.4°F, with the majority of the increase occurring over the past three decades. The GISS analysis incorporated surface temperature measurements from 6,300 weather stations, observations of sea surface temperatures, and temperature measurements from Antarctic research stations, while the raw data analyzed by NOAA scientists was analyzed using an algorithm that took into account varied spacing of temperature stations and urban heating effects that could affect the calculations. From *ScienceDaily* on January 16, 2015

Policy

"UK Increases CFD Funding for [Low-Carbon] Projects."

The UK government increased funding available for low-carbon projects under the Contract for Difference (CfD) scheme, allocating approximately $38 million starting in 2017-2018 for "Pot 2" funding, which focuses on offshore wind and biomass projects. Total funding available for the CfD scheme has now increased to approximately $495 million, with the projects receiving 15-year contracts after winning the auction. Additional funding is expected to be made available for CfDs for renewables and CCS in future years, increasing to more than approximately $1.5 billion in 2020-2021. From *Clean Technology Business Review* on January 29, 2015.

"Transferring responsibility of CO_2 storage sites to the competent authority following site closure."

The following is the Abstract of this article: "The requirements for pre-qualifying a site for CO_2 storage are well developed. Less attention has been paid to rehearsing and preparing for the transfer of responsibility of the storage site from the operator to a governmental authority following closure of the site at the end of the injection period. This is not surprising because the industry is in its infancy and most effort has been focused on working towards the early stages of the various projects. A procedure for complying to the regulatory requirements for the transport of responsibility in the CCS Directive has been proposed, which consists of a chart with Site Closure Milestones and a traffic light system for treating irregularities in observed behavior of the storage site, and accompanying criteria. The procedure was successfully tested on the K12-B CO_2 injection pilot. Conclusions have been drawn on the basis of several dry runs for reporting the requirements for transfer of responsibility including feedback from operators and regulators." **Ton Wildenborg, Geert de Bruin, Alexander Kronimus, Filip Neele, Jens Wollenweber, and Andy Chadwick**, *Energy Procedia*. (Subscription may be required.)

Geology

"Carbon dioxide storage in olivine basalts: Effect of ball milling process."

The following is the Abstract of this article: "The goal of this study is to propose a cost-effective method for the optimization of the ex situ carbonation of basaltic rocks. The ball milling process was applied to a sample of olivine basalt from the Troodos ophiolite complex (Cyprus) for the first time, in order to fabricate novel nanomaterials for CO_2 storage. The purpose was to accelerate the kinetics of rock–fluid reactions during the carbonation procedure. Various methodologies were used for the characterization of the starting rock material and the ball-milled samples. Preliminary results reveal that only a few hours of wet ball milling with ethanol as process control agent can induce significant changes to olivine basalt towards improvement of its performance for CO_2 storage. Specifically, CO_2 uptake measurements via the use of the temperature-programmed desorption (TPD) technique indicate that 4 h of ball milling with 50 wt.% ethanol can lead to an enhancement of the carbonation of olivine basalt by 295 [percent]. The experimental results strongly suggest that (i) olivine basalts have important CO_2-storage capacity and are very promising lithotypes for ex situ carbonation, and (ii) the ball milling process provides hopes for its use at an industrial scale as a preparation technique for the safe and permanent ex situ storage of CO_2." **Ioannis Rigopoulos, Klito C. Petallidou, Michalis A. Vasiliades, Andreas Delimitis, Ioannis Ioannou, Angelos M. Efstathiou, and Theodora Kyratsi**, *Powder Technology*. (Subscription may be required.)

Geology (Continued)

"Screening considerations for caprock properties in regards to commercial-scale carbon-sequestration operations."

The following is the Abstract of this article: "Risk management of commercial-scale [storage] operations involves comprehensive site characterization of reservoirs, especially with the long-term integrity of low-permeability seals. Even though storage costs are significantly less than those of carbon capture, the variable costs of pipeline transport can have a significant impact in the overall deployment budget for CCS technologies. This is especially valid with existing electrical generating units (EGUs) where CO_2 source–geologic sink matching may not have been considered in siting. It is therefore important to understand all options with source–sink matching, including storage reservoirs nearby EGUs with potentially sub-optimal confining zones. As such, a finely tuned comprehension of the effects of the most relevant caprock characteristics on its integrity during injection and storage will be paramount to ensuring the safety of future operations. This study supports an understanding toward this end first by summarizing the current regulatory framework and industry practices for assessing caprock integrity. After which it defines how pertinent caprock parameters, most notably the thickness of the primary seal layer, affect the principal sealing and [release] mechanisms involved in typical CO_2 injection and storage scenarios. Lastly, all of these analyses are synthesized into a back-of-the-envelope initial screening protocol." **Michael J. Hannon, Jr. and Richard A. Esposito**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

Technology

"Benchmark modeling of the Sleipner CO_2 plume: Calibration to seismic data for the uppermost layer and model sensitivity analysis."

The following is the Abstract of this article: "…The Sleipner project in the Norwegian North Sea provides more time-lapse seismic monitoring data than any other sites for tracking CO_2 plume development, but significant uncertainties still exist for some reservoir parameters. In order to simulate CO_2 plume migration and assess model uncertainties, [the authors] applied two multi-phase compositional simulators to the Sleipner Benchmark model for the uppermost layer (Layer 9) of the Utsira Sand and calibrated [the] model against the time-lapsed seismic monitoring data at the site from 1999 to 2010. Approximate match with the observed plume was achieved by introducing lateral permeability anisotropy, CH_4 in the CO_2 stream, and adjusting reservoir temperatures. Model-predicted gas saturation, thickness of the CO_2 accumulation, and CO_2 solubility in brine – none of them used as calibration metrics – were all comparable with interpretations of the seismic data in the literature. Hundreds of simulations of parameter sensitivity (pressure, temperature, feeders, spill rates, relative permeability curves, and CH_4) showed that simulated plume extents are sensitive to permeability anisotropy, temperature, and CH_4 but not sensitive to the other analyzed parameters. However, adjusting a single parameter within the reported range of values would not reproduce the north–south trending CO_2 plume. It took a combination of permeability, CH_4, and temperature adjustments to match simulated CO_2 plume with seismic monitoring data. On the other hand, even with a range of uncertain modeling parameters, the predicted fate of CO_2 fell within a narrow band, ~93 ± 2 [percent] structural/hydrodynamic trapping and ~7 ± 2 [percent] solubility trapping. The calibrated model is not unique. Other possibilities for reproducing the elongated plume such as a slight tilting of the caprock surface to the south and subtle geological features in the Layer 9 were not experimented with in this study, but are worthy of exploration for future studies. While it appears that [the authors] were able to reproduce the north–south elongated CO_2 plume, which is a modest improvement over previous models, the adjustments of parameters need to be verified with new observations." **Chen Zhu, Guanru Zhang, Peng Lu, Lifeng Meng, and Xiaoyan Ji**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

"Measurement and Modeling of CO_2 Solubility in Natural and Synthetic Formation Brines for CO_2 Sequestration."

The following is the Abstract of this article: "[Carbon dioxide] solubility data in the natural formation brine, synthetic formation brine, and synthetic NaCl+$CaCl_2$ brine were collected at the pressures from 100 to 200 bar, temperatures from 323 to 423 K. Experimental results demonstrate that the CO_2 solubility in the synthetic formation brines can be reliably represented by that in the synthetic NaCl+$CaCl_2$ brines. [The authors] extended [their] previously developed model (PSUCO2) to calculate CO_2 solubility in aqueous mixed-salt solution by using the additivity rule of the Setschenow coefficients of the individual ions (Na^+, Ca^{2+}, Mg^{2+}, K+, Cl^-, and SO_4^{2-}). Comparisons with previously published models against the experimental data reveal a clear improvement of the proposed PSUCO2 model. Additionally, the path of the maximum gradient of the CO_2 solubility contours divides the *P-T* diagram into two distinct regions: in Region I, the CO_2 solubility in the aqueous phase decreases monotonically in response to increased temperature; in region II, the behavior of the CO_2 solubility is the opposite of that in Region I as the temperature increases." **Haining Zhao, Robert Dilmore, Douglas E. Allen, Sheila W. Hedges, Yee Soong, and Serguei N. Lvov**, *Environ. Sci. Technol*. (Subscription may be required.)

"Quantifying the Benefit of Wellbore Leakage Potential Estimated for Prioritizing Long-Term MVA Sampling at a CO_2 Storage Site."

The following is the Abstract of this article: "This work uses probabilistic methods to simulate a hypothetical geologic CO_2 storage site in a depleted oil and gas field, where the large number of legacy wells would make it cost-prohibitive to sample all wells for all measurements as part of the post injection site care. Deep well [release] potential scores were assigned to the wells using a random subsample of 100 wells from a detailed study of 826 legacy wells that penetrate the basal Cambrian formation on the U.S. side of the U.S./Canadian border. Analytical solutions and Monte Carlo simulations were used to quantify the statistical power of selecting a [release] well. Power curves were developed as a function of (1) the number of leaking wells within the Area of Review; (2) the sampling design (random or judgmental, choosing first the wells with the highest deep [release] potential scores); (3) the number of wells included in the monitoring sampling plan; and (4) the relationship between a well's [release] potential score and its relative probability of [release]. Cases where the deep well [release] potential scores are fully or partially informative of the relative [release] probability are compared to a non-informative base case in which

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[release] is equi-probable across all wells in the Area of Review. The results show that accurate prior knowledge about the probability of well [release] adds measurable value to the ability to detect a [releasing] well during the monitoring program, and that the loss in detection ability due to imperfect knowledge of the [release] probability can be quantified. This work underscores the importance of a data-driven, risk-based monitoring program that incorporates uncertainty quantification into long-term monitoring sampling plans at geologic CO_2 storage sites." **Nicholas A. Azzolina, Mitchell J. Small, David V. Nakles, Kyle A. Glazewski, Wesley D. Peck, Charles D. Gorecki, Grant S. Bromhal, and Robert M. Dilmore**, *Environ. Sci. Technol*. (Subscription may be required.)

"Design of foam-assisted carbon dioxide storage in a North Sea aquifer using streamline-based simulation."

The following is the Abstract of this article: "CCS – the collection of CO_2 from industrial sources and its injection underground – could potentially contribute to the reduction of atmospheric emissions of GHGs. In this paper, [the authors] investigate the [storage] of CO_2 in [formations] with the co-injection of surfactants for foam generation. This is equivalent to the use of foam for conformance control in [EOR] applications. To study foam-assisted [storage], [the authors] extend an in-house streamline-based simulator to model foam flow. [The authors] use two foam models that have been previously suggested in the literature. In both models foam hinders gas mobility through increasing its apparent viscosity. The modified simulator is validated by comparison to analytical solutions. [The authors] then investigate the performance of CO_2 [storage] with the co-injection of surfactants. [The authors] look at CO_2 [storage] in a North Sea [formation]. [The authors] study both simultaneous and alternating surfactant-gas injection at different fractional flows (i.e. water:gas ratios). For cases where a seal provides a reliable trapping mechanism, the simulation results suggest that the use of surfactants to generate foam significantly improves the storage efficiency at a marginal increase in water consumption. In this setting, CO_2/surfactant simultaneous injection at a 0.5 CO_2 fractional flow was found to be the optimum injection strategy for the case investigated. To the contrary, if the seal is unreliable or not present at the first place, CO_2/brine simultaneous injection at a 0.85 CO_2 fractional flow was found to be the optimum injection strategy. Although foam-assisted [storage] in this case further improves the storage efficiency, it does that at a significant increase in water consumption. This is since, although foam generation improves the sweep during the [storage] phase, it significantly hinders the sweep during the chase-brine injection phase. Based on that, having a design where the surfactant will degrade just before or during the chase-brine injection phase would provide the optimum [storage] strategy—without reliance on the presence or integrity of the seal." **Siriwat Vitoonkijvanich, Abdulkareem M. AlSofia, and Martin J. Blunt**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

"The microseismic response at the In Salah Carbon Capture and Storage (CCS) site."

The following is the Abstract of this article: "In 2004, injection of CO_2 to be stored at depth began at the In Salah CCS site and a pilot microseismic monitoring array was installed in 2009. The In Salah project presents an unusual dataset since it is the first major non-EOR CCS project to be monitored for microseismicity. This paper outlines an extensive seismological study using a range of techniques, relying mainly on data from a single three-component geophone. Important information is derived from the data, such as event locations, event magnitudes, and fracture characteristics, which could be used in real-time to regulate the geomechanical response of a site to CO_2 injection. The event rate closely follows the CO_2 injection rate, with a total of 9506 seismic events detected. The locations for a carefully selected subset of events are estimated to occur at or below the injection interval, thereby ruling out fault or fracture activation caused by CO_2 migration at shallow depths. A very small number of events (11) with less well-constrained locations may have occurred above the injection interval. However, there is no microseismic evidence that these events are correlated with CO_2 injection and [the authors] suggest they are caused by stress transfer rather than CO_2 migration into the caprock. The observed maximum moment magnitude, Mw=1.7, is consistent with estimated fracture dimensions at the injection depth. Fracture orientation estimated using shear-wave splitting analysis is approximately NW-SE, in agreement with fracture orientations inferred from logging data. During periods of high injection rates the degree of anisotropy increases slightly and then falls back to original values when injection rates fall. This implies the CO_2 is opening pre-existing fractures which then close as pressure decreases. This an important proof-of-concept study that proves the value of microseismic monitoring of CCS projects, even with a limited array. [The authors] thus recommend that microseismic monitoring arrays are installed prior to CO_2 injection at future CCS sites to enhance understanding by making baseline and comparative studies possible. This would also provide real-time monitoring of the geomechanical response to injection, allowing operators to modify injection parameters and to help ensure the safe operation of a project." **Anna L. Stork, James P. Verdon, and J.-Michael Kendall**, *International Journal of Greenhouse Gas Control*. (Subscription may be required.)

"CO_2 EOR and storage in Jilin oilfield China: Monitoring program and preliminary results."

The following is the Abstract of this article: "Jilin oilfield is conducting the first large scale demonstration project on CO_2 EOR and storage in the northeast China. [Carbon dioxide] with high purity is produced from a nearby natural gas reservoir and injected into the tight oil reservoir of H-59 block. Up to early in 2012, more than 20×104 tons of CO_2 has been injected into the reservoir through a miscible flooding scheme. In order to track the migration of CO_2 in the reservoir and ensure a long-term storage safety, a monitoring program has been deployed in the field. The used monitoring techniques include wellbore integrity detecting, produced fluid sampling, CO_2 gas tracer, electric spontaneous potential measurement, micro-seismic and cross-well seismic. An environmental monitoring program is also implemented for verifying CO_2 [release]. Preliminary results indicate that it is effective to detect the movement of CO_2 in the oil reservoir by jointly applying various monitoring techniques based on wellbores. After more than four years of operation since 2008, nearly 80 [percent] of injected CO_2 has been stored in the reservoir with the rest of injected CO_2 breakthrough in the production wells. [Carbon dioxide] storage safety needs more detailed and comprehensive monitoring data for further verification. The obtained preliminary monitoring experience can provide valuable guidance for

Technology (Continued)

the future enlarged Jilin project and other CO_2 EOR and storage operations." **Liang Zhang, Bo Ren, Haidong Huang, Yongzhao Li, Shaoran Ren, Guoli Chen, and Hua Zhang**, *Journal of Petroleum Science and Engineering*. (Subscription may be required.)

"CO_2 sequestration by indirect carbonation of artificial gypsum generated in the manufacture of titanium dioxide pigments."

The following is the Abstract of this article: "In this paper, the use of red gypsum (RG), waste from the naturally occurring radioactive materials industry that is devoted to the production of the TiO_2 pigment, was evaluated as a source of calcium for CO_2 [storage] by an indirect carbonation process. The main objective was to valorise this waste and, at the same time, [analyze] the reduction of [GHG] emissions (CO_2) emitted by industrial sources that use this process. In order to induce the carbonation process, the extraction of calcium from the sample was required beforehand. For this, two different extraction routes were applied (the NaOH and NH_4OH pathways). The obtained results demonstrate that RG has high carbonation reactivity, depending on the extraction agent used at room temperature and pressure. The conversion of RG to calcium carbonate was 92 [percent] when using sodium hydroxide, whereas 64 [percent] was obtained with ammonium hydroxide extracting. The [behavior] and fluxes of the radionuclides and trace elements, initially contained in the RG, were also evaluated during the full carbonation process. In general, the levels of pollutants in the final calcite (calcium carbonate) were comparable to the ones found for typical unperturbed soils." **S.M. Perez-Moreno, M.J. Gazquez, and J.P. Bolivar**, *Chemical Engineering Journal*. (Subscription may be required.)

"Thin-film versus slurry-phase carbonation of steel slag: CO_2 uptake and effects on mineralogy."

The following is the Abstract of this article: "The results of direct aqueous accelerated carbonation of three types of steel manufacturing residues, including an electric arc furnace (EAF) slag and two basic oxygen furnace (BOF) slags, are reported. Batch accelerated carbonation tests were conducted at different temperatures and CO_2 pressures applying the thin-film route (liquid to solid, *L/S*, ratio = 0.3 L/kg) or the slurry-phase route (*L/S* ratio = 5 L/kg). The CO_2 uptake strongly depended on both the slag characteristics and the process route; maximum yields of 280 (EAF), 325 (BOF1) and 403 (BOF2) g CO_2/kg slag were achieved in slurry phase at T = 100°C and p_{CO_2} = 10 bar. Differently from previous studies, additional carbonates (other than Ca-based phases) were retrieved in the carbonated BOF slags, indicating that also Mg-, Fe- and Mn-containing phases partially reacted with CO_2 under the tested conditions. The results hence show that the effects of accelerated carbonation in terms of CO_2 uptake capacity, yield of mineral conversion into carbonates and mineralogy of the treated product, strongly rely on several factors. These include, above all, the mineralogy of the original material and the operating conditions adopted, which thus need specific case-by-case optimization to maximize the CO_2 [storage] yield." **R. Baciocchi, G. Costa, M. Di Gianfilippo, A. Polettini, R. Pomi, and A. Stramazzo**, *Journal of Hazardous Materials*. (Subscription may be required.)

Terrestrial

"Optimizing carbon sequestration in arid and semiarid rangelands."

The following is the Abstract of this article: "Destocking degraded rangeland can potentially help climate change mitigation by re-[storing] emitted carbon. Broad-scale implementation has been limited by uncertainties in the magnitude, duration and location of [storage] and the profitability relative to the existing grazing land use. This paper employs a novel methodology to assess potential rangeland [storage] and its profitability, using 31 Mha of rangeland in New South Wales, Australia as a case-study. This approach combines remotely sensed data and modelled estimates of various components. Remotely sensed, synthetic aperture radar data were used to determine woody biomass of minimally degraded forest (benchmarks) and [neighboring] more-degraded forest, followed by [storage] modelling using non-linear growth rates based on woody thickening and slow-growing plantations, scaled to the benchmarks. Livestock concentration and livestock-based farm profits were modelled. [The authors] compared [storage] and grazing net profits, for a carbon price of AUD$10 Mg^{-1} CO_2-e, at different growth stages for different levels of forest attrition. [The authors] found that broad-scale destocking with subsequent C re-[storage] was initially unprofitable compared with grazing. However, after 50 years, with full costing of C emissions, the returns were similar for the two alternatives of continued grazing or re-[storage], for areas with biomass below benchmark levels. Reforestation of recently deforested land represents the most profitable option with profitability increasing with growth rate. Emissions of soil organic carbon, set in motion by climate change over the next century, were calculated to be the largest of all sources. Emissions from biomass, induced by climate change, will be higher where vegetation cannot adapt. The secondary effects of climate change will reduce re-[storage] and grazing profits, possibly limiting the carbon stored by re-[storage] projects." **Christopher Dean, Jamie B. Kirkpatrick, Richard J. Harper and David J. Eldridge**, *Ecological Engineering*. (Subscription may be required.)

"Long term carbon storage potential and CO_2 sink strength of a restores salt marsh in New Jersey."

The following is the Abstract of this article: "The study compares the amounts of carbon fixed via photosynthesis of a restored tidal marsh to the total organic carbon remaining in sediments of a natural tidal marsh and arrives at preliminary baselines for [carbon… storage] over time. The Eddy-covariance method (indirect method) was used to estimate marsh canopy net ecosystem exchange (NEE) and measured an annual gross primary production of 979 g C m^{-2}, while the loss through respiration was 766 g C m^{-2}, resulting in a net uptake of 213 g C m^{-2} yr^{-1}. Time of the day, solar irradiation, air temperature, humidity and wind direction all together explained 66 [percent] of the variation in NEE. The high marsh community of Spartina patens showed NEE to be significantly higher than the low marsh community. The net ecosystem carbon balance (NECB) over long time scales was estimated by measuring the actual amount of total organic carbon contained in dated sediment cores from a natural marsh (direct method), which resulted in a carbon accumulation rate of 192.2 g m^{-2} yr^{-1}. Changes in total organic carbon content over time in the core sample showed that 78 [percent] of organic carbon remained stored in the sediments after 130 years and only the most recalcitrant carbon (50

Terrestrial (Continued)

[percent]) remained under storage beyond 645 years. Overall the study showed that temperate macrotidal salt marshes are net [releases] of carbon with potential for long term carbon storage. The marsh turned into a carbon [release] at the beginning of May and switched back to being a source in late November. The average sedimentation rate estimated from the 137 CS dating (1950s to present) was 1.4 mm yr^{-1} which is similar to accretion rates of comparable S. patens patches in the east coast. Accretion rates derived from [the authors'] study are slightly lower than the 60+ year rate of sea level rise (2.6 mm yr^{-1}) recorded by tide gauge measurements in the Northeast." **Francisco Artigas, Jin Young Shin, Christine Hobble, Alejandro Marti-Donati, Karina V.R. Schäfer, and Ildiko Pechmann**, *Agricultural and Forest Meteorology*. (Subscription may be required.)

Trading

"China Opens National Registry for Carbon Offsets, Doubles Supply."

China has opened a national register for carbon offsets, known as Chinese Certified Emissions Reductions (CCERs), enabling carbon emission credits to be transferred from the national scheme to regional exchanges. In addition, the National Development and Reform Commission (NDRC) issued 7 million CCERs from 16 projects, adding to the 6.5 million CCERs approved in December 2014. Emitters are permitted to use CCERS to cover a percentage of their annual emissions. Participants in China's seven pilot emissions trading schemes can use a total of approximately 110 million CCERs annually, with demand expected to rise as new regions and sectors are included. From *The Business Times* on January 14, 2015.

"Carbon prices and incentives for technological development."

The following is the Abstract of this article: "There is concern that the carbon prices generated through climate policies are too low to create the incentives necessary to stimulate technological development. This paper empirically analyzes how the Swedish CO_2 tax and the European Union emission trading system (EU ETS) have affected productivity development in the Swedish pulp and paper industry 1998–2008. A Luenberger total factor productivity indicator is computed using data envelopment analysis. The results show that climate policy had a modest impact on technological development in the pulp and paper industry, and if significant it was negative. The price of fossil fuels, on the contrary, seems to have created important incentives for technological development. Hence, the results suggest that the carbon prices faced by the industry through EU ETS and the CO_2 tax have been too low. Even though the data for this study is specific for Sweden, the models and results are applicable internationally. When designing policy to mitigate CO_2 emissions, it is vital that the policy creates a carbon price that is high enough – otherwise the pressure on technological development will not be sufficiently strong." **Tommy Lundgren, Per-Olov Marklund, Eva Samakovlis, and Wenchao Zhou**, *Journal of Environmental Management*. (Subscription may be required.)

"Carbon emissions in a multi-echelon production-inventory model with lead time constraints."

The following is the Abstract of this article: "[The authors] develop a deterministic optimization model that incorporates carbon emissions in a multi-echelon production-inventory model with lead time constraints. [The authors] impose that each customer order must be delivered within the due date fixed by the customer. The quantity that cannot be delivered on time is a lost sale. [The authors] consider a multi-echelon supply chain with different external suppliers, different manufacturing facilities, and different distribution centers. [The authors] adopt a general inventory policy. Indeed, [the authors] do not impose any constraints on the stock level that must be kept for each product in each facility in each period and on the procurement order quantities in the different facilities. Carbon emissions are associated with the decisions of manufacturing of intermediate and final products, ordering (transportation) from external and internal suppliers, and inventory positioning of the different products in the different stages of the supply chain. [The authors] first deal with the case of carbon emissions tax and then turn to the case of carbon emissions cap. [The authors] use the model to provide a series of insights that would be of interest for firms and policy makers. Such insights would be difficult to obtain with classical production-inventory models. For instance, the integration of lead times permits to show how the amount of carbon emissions is non-monotone with the variation of customer lead time and orders frequency. Also, the consideration of a general inventory policy permits to show how some particular policies (such as the base stock and the fixed order quantity) leads to increasing emissions. In addition, [the authors] capitalize on the multi-echelon aspect of [their] model in order to study the effect of individual emissions caps on each facility with comparison to a global cap on the entire supply chain. For instance, [the authors] demonstrate that individual caps can achieve significant lower emissions but can paradoxically lead to increasing the per unit emissions. [The authors] also show how a share of emissions can improve per unit emissions without deteriorating total emissions." **Ramzi Hammami, Imen Nouira, and Yannick Frein**, *International Journal of Production Economics*. (Subscription may be required.)

"Tactical supply chain planning under a carbon tax policy scheme: A case study."

The following is the Abstract of this article: "[GHG] emissions are receiving greater scrutiny in many countries due to international forces to reduce anthropogenic global climate change. Industry and their supply chains represent a major source of these emissions. This paper presents a tactical supply chain planning model that integrates economic and carbon emission objectives under a carbon tax policy scheme. A modified Cross-Entropy solution method is adopted to solve the proposed nonlinear supply chain planning model. Numerical experiments are completed utilizing data from an actual organization in Australia where a carbon tax is in operation. The analyses of the numerical results provide important organizational and policy insights on (1) the financial and emissions reduction impacts of a carbon tax at the tactical planning level, (2) the use of cost/emission tradeoff analysis for making informed decisions on investments, (3) the way to price carbon for maximum environmental returns per dollar increase in supply chain cost." **Behnam Fahimnia, Joseph Sarkis, Alok Choudhary, and Ali Eshragh**, *International Journal of Production Economics*. (Subscription may be required.)

Trading (Continued)

"Market-Driven Emissions from Recovery of Carbon Dioxide Gas."

The following is the Abstract of this article: "This article uses a market-based allocation method in a consequential life cycle assessment (LCA) framework to estimate the environmental emissions created by recovering CO_2. [The authors] find that 1 ton of CO_2 recovered as a coproduct of chemicals manufacturing leads to additional greenhouse gas [GHG] emissions of 147–210 kg CO_2 eq, while consuming 160–248 kWh of electricity, 254–480 MJ of heat, and 1836–4027 kg of water. The ranges depend on the initial and final purity of the CO_2, particularly because higher purity grades require additional processing steps such as distillation, as well as higher temperature and flow rate of regeneration as needed for activated carbon treatment and desiccant beds. Higher purity also reduces process efficiency due to increased yield losses from regeneration gas and distillation reflux. Mass- and revenue-based allocation methods used in attributional LCA estimate that recovering CO_2 leads to 19 and 11 times the global warming impact estimated from a market-based allocation used in consequential LCA." **Sarang D. Supekar and Steven J. Skerlos**, *Environ. Sci. Technol*. (Subscription may be required.)

Recent Publications

"Electricity from Natural Gas with CO_2 Capture for Enhanced Oil Recovery: Emission accounting under Cap-&-Trade and LCFS."

The following is from the Summary of this document: "This report evaluates emission accounting under California's existing climate policies for energy systems that integrate CCS with CO_2-EOR. CCS has been identified as potentially important for advancing California's 2050 goal of reducing [GHG] emissions by 90 [percent] below 1990 levels will be very difficult to achieve from a technical perspective alone. Moreover, nearly all technology portfolios identified in the study for achieving the 90 [percent] target require CCS, primarily as a way to overcome challenges from irreducible fuel requirements and limited supplies of low-carbon fuels. Near-term industrial experience is viewed by many to be important for ensuring availability of CCS technologies in time to meet California's 2050 emissions target. Systems that integrated CCS with CO_2-EOR ('CCS-EOR'), one of several approaches referred to as carbon capture utilization and storage ('CCUS'), have been identified as particularly important for early deployments due to their ability to reduce near-term emissions, accelerate development of CCS technologies and infrastructure that can enable deeper future reductions, attract commercial capital. As a result, proximate CCS deployments in California depend in part on resolving regulatory uncertainties regarding emission accounting for CCUS systems that integrate CO_2-EOR. Several companies have processed CCUS projects in California where the economics can be improved by using captured CO_2 for CO_2-EOR…"

"Enhanced Oil Recovery Market by Technology (Thermal, Gas, Chemical, Microbial and Seismic) and by Applications (Onshore and Offshore) – Global Trend & Forecast to 2019."

The following is a description of this document: "The increase in demand of [EOR] fluids for revitalization of aging brown fields for oil [and] gas production is expected to be a major driver for the [EOR] market. The [EOR] market is expected to grow at a healthy growth rate of 18.2 [percent] between 2014 and 2019. Chemical EOR is the fastest growing technology within [EOR] market across the globe and are suitable for all the application areas including onshore and offshore. The market was segmented on the basis of application areas, type, and regions in terms of value and volume. The market segments by application areas include onshore and offshore. The market segments for types include thermal EOR, chemical EOR, gas EOR, and other EOR. The geographic segmentation includes market size and market volume of North America, Asia-Pacific, Europe, South America, Africa, and Middle East. The overall market size of EOR has been presented in terms of excess production, that is, on the basis of the barrels of oil produced via EOR method…"

"A CCS future for Europe: Catalyzing North Sea action."

The following is from the Executive Summary of this document: "The 2014 SCCS Annual Conference, 'A CCS future for Europe,' brought together international CCS experts from industry, government, research, non-governmental organizations (NGOs), and finance to explore how Europe can regain momentum and deliver CCS. Plenary speakers gave perspectives on the problems and opportunities for CCS in Europe, and the measures needed to secure its future. These were set within the context of the European Council's energy and climate policy objectives for 2030. Delegates welcomed the agreement of a 40 percent emissions reduction target, the proposals to strengthen the [EU ETS], the recognition of the need for Member States to make appropriate decarbonization pathway and technology choices, continuation of Projects of Common Interest (PCIs), and the renewal of the New Entrants' Reserve funding mechanism (NER400) to support the demonstration of low-carbon technologies, including CCS. Following the plenary, detailed discussions were held in three priority areas: creating the right incentives for CCS, facilitating the development of CCS infrastructures through the 'cluster' approach, and catalyzing R&D activities to support CCS deployment. These discussions fed into the development of a set of recommendations aimed at guiding European policy makers. These are summarized here: the first section describes the broader approach for the European energy and climate policy community; the second describes more detailed actions for the European Commission, Member State governments, industry, and R&D actors."

Legislative Activity

"Guidance for states and provinces on operational and postoperational liability in the regulation of carbon geologic storage."

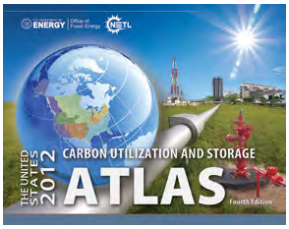
The following is the Abstract of this article: "The Interstate Oil and Gas Compact Commission (IOGCC) Task Force on Carbon Geologic Storage (CGS) has produced reports that constitute IOGCC guidance to U.S. states and Canadian provinces on the formation of legal and regulatory frameworks for the storage of CO_2 in non-hydrocarbon-bearing geologic formations. This paper describes the latest effort of the Task Force focused on issues of liability in all phases of a CGS project and discusses liability broadly under federal, state or provincial, and common law from the perspective of the state or provincial regulator." **Lisa S. Botnen, Kevin C. Connors, Kevin J. Bliss, Lawrence E. Bengal, John A. Harju**, *Energy Procedia*. (Subscription may be required.)

About DOE's Carbon Storage Program

The Carbon Storage Program is implemented by the U.S. Department of Energy's Office of Fossil Energy and managed by the National Energy Technology Laboratory. The program is developing technologies to capture, separate, and store CO_2 in order to reduce greenhouse gas emissions without adversely influencing energy use or hindering economic growth. NETL envisions having a technology portfolio of safe, cost-effective, carbon dioxide capture, transport, and storage technologies that will be available for commercial deployment.

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 U.S. Department of Energy's 2012 United States Carbon Utilization and Storage Atlas (Atlas IV) shows that the United States has at least 2,400 billion metric tons of potential carbon dioxide storage resource in saline formations, oil and gas reservoirs, and unmineable coal. Data from Atlas IV is available via the National Carbon Sequestration Database and Geographic Information System (NATCARB), which is a geographic information system-based tool developed to provide a view of carbon capture and storage potential.

Newsletters, program fact sheets, best practices manuals, roadmaps, educational resources, presentations, and more are available via the Carbon Storage Reference Shelf.

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

There are several ways to join the conversation and connect with NETL's Carbon Storage Program:

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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.

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