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COLORADO SCHOOL OF MINES

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Transparency Through Technology: The Vital Link Between Monitoring and Public Perception in CCS Initiatives

By Anna Littlefield and Charlie Losche

The Inflation Reduction Act of 2022 has catalyzed significant growth in CCS, with projections indicating a substantial increase in capture capacity by 2035. With this expansion comes challenges, notably in securing Class VI permits for CO_2 injection, and most pressingly in maintaining public trust. Recent studies and news reports reflect the tenuous nature of CCS acceptance, especially in directly affected communities. In August of 2023, a CO_2 pipeline project was denied by North Dakota regulators, who stated that the operator, Summit had "failed to meet its burden of proof to show the (project) will produce minimal adverse effects on the environment and upon the welfare of the citizens of North Dakota". This, and other recent community push-back, is evidence that the permitting projects in the CCS industry may face unprecedented challenges from a stakeholder, landowner, and community standpoint.

The existential risk of permit rejections due to community push back and the inherent risk to environmental safety posed by CCS operations necessitates robust monitoring, reporting, and verification programs. However, in addition to being the operationally fastidious approach, effective monitoring is also imperative for community relations, as it is a means of conveying the safety status of a project to local stakeholders. Recognizing the criticality of monitoring, we outline the technologies that fulfill a dual purpose of allowing operators to meet monitoring standards while also providing the public with a means to interact with these projects in a timely and tangible way. The flexibility of Class VI monitoring guidance is a strength of the program, designed to allow unique monitoring schemes for highly diverse geologic settings. Rather than a regulatory box to check or a hurdle to overcome, monitoring on CO_2 injection projects is an opportunity for operators to practice transparency through technology, and rethink the usual stakeholder engagement.

Baseline Data Collection and Ongoing Monitoring

Baseline data collection and ongoing monitoring are key pieces of any monitoring, reporting, and verification (MRV) program. Understanding why the data is important for both regulatory reporting and community engagement is key in unlocking the value of the monitoring technologies. As the agency that oversees both federal Class VI injection applications and the Greenhouse Gas Reporting Program, the EPA emphasizes that "Baseline monitoring is essentially the first step in implementing the leakage detection and quantification monitoring strategy. The primary goal of establishing expected baselines is so that the reporter can discern whether or not the results of monitoring are attributable to leakage of injected CO_2". While it can be challenging to establish a reliable baseline in a naturally dynamic environment, operators can bolster their measurement with historic data, analog datasets, and by collecting data over an extended period of time leading up to injection.

Monitoring programs that extend beyond the pre-injection characterization, through the duration of injection, and past the cessation of injection, are critical to provide insight and transparency to regulators and local communities. Each storage site will have a unique set of geologic, environmental, and operational conditions that are best addressed with site-specific monitoring solutions. Within the EPA's technical guidance document, they state that: "A sampling program should be designed to ensure that it considers the appropriate frequency of sampling, aerial extent of sampling, and sample size" . This language does not stipulate minimums, maximums, or particular technology because unique projects demand unique monitoring solutions, though the need to keep the community updated on the safety and efficacy of CO_2 storage is universal.

Technologies for MRV in CCUS

MRV plans are focused on ensuring that the plume of CO_2 remains within the expected boundaries and within the injection interval. Potential leakage pathways include existing wellbores, faults, induced or natural seismicity, lateral migration, diffusion through the caprock, or from pipeline and surface equipment. A 2021 report on the state of monitoring technology in CCUS describes geochemical, and soil gas monitoring, in addition to time lapse pulse-neutron, resistivity, and diffusion logs, gravity measurements, 4-D and cross-well seismic surveys, and tracers. More recently, atmospheric monitoring techniques are becoming more common, and the options for types of monitoring are continually expanding.

The Department of Energy and EPA both segment monitoring of geologically stored CO_2 into three core areas: deep subsurface monitoring, near surface monitoring (vadose zone and soil zone), and atmospheric monitoring. Deep subsurface monitoring protocols are designed to determine the location and behavior of the plume of CO_2, while shallow subsurface and atmospheric monitoring technologies are designed to ensure that no environmental contamination has occurred. Here we focus on the latter two technologies, recognizing that data obtained from these monitoring activities are most likely to be communicated to local stakeholders to verify the safe storage of CO_2.

The technical community widely acknowledges that, with thorough geologic characterization and operational precautions, geologic storage is a reliable approach for permanent CO_2 storage. However, transporting and storing CO_2 is not without risk, and community members have reason to request that the operators of CCUS projects in their communities provide satisfactory information demonstrating that the air they breathe, the water they drink, and the ground under their feet remains safe now and in the future. In this space, shallow environmental monitoring is a tool for addressing these concerns, and although each monitoring technology has challenges and limitations, a combination of these techniques can be applied to mitigate environmental risks.

Here we assess several shallow monitoring technologies that address environmental risks associated with a CO_2 leak and are also low impact. However, we acknowledge that shallow subsurface and atmospheric monitoring cannot exist independently of deep subsurface monitoring. Understanding the plume migration behavior will dictate what areas should be monitored for potential CO_2 leakage, thus the best MRV programs will have a combination of the two that inform each other.

SOIL and VEGETATION

Soil Gas Monitoring

Soil Gas Monitoring for CCS refers to the sampling of gases present in soils to determine if there are elevated CO_2 levels in the topsoil due to a leak in a CO_2 storage reservoir. Soil gas concentration readings are taken at a depth of up to 122 cm below surface and compared against baseline samples taken at the same location prior to injection to determine if the concentration of CO_2 has increased since CCUS operations began. CO_2 sensors are a mature, low-cost, and low impact technology, and installed (in ground) sensors eliminate the need for active sampling on site (see Figure 1). By regularly gathering soil gas composition data, operators can detect anomalies.

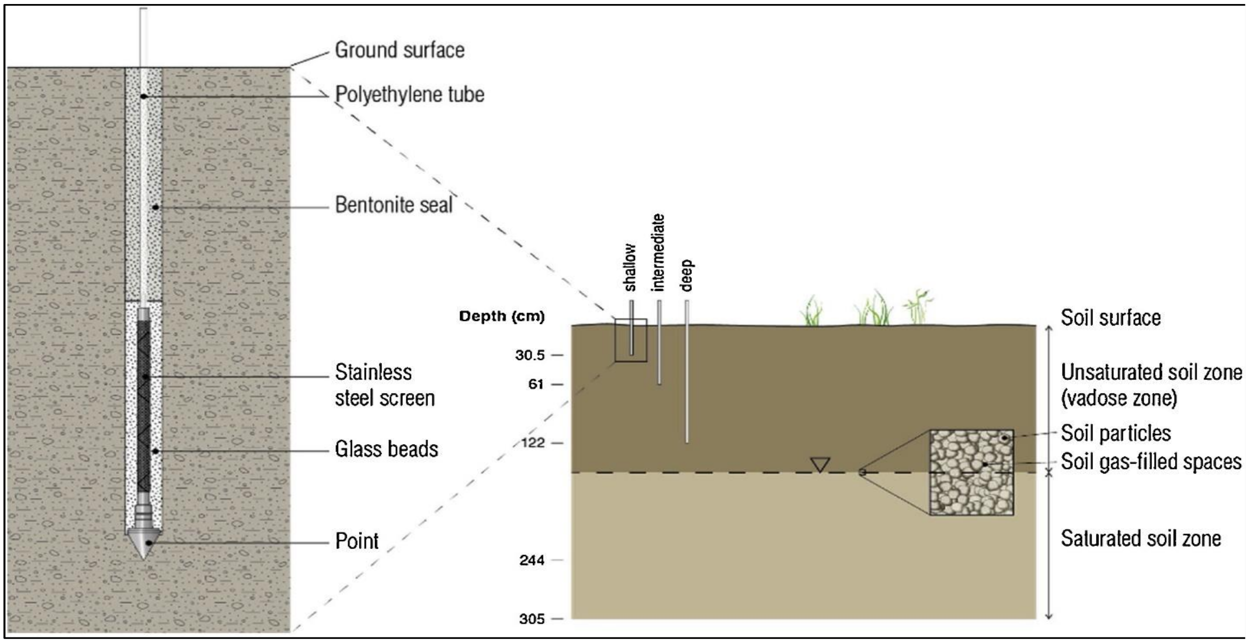

Figure 1: Illustration of a shallow soil gas monitoring installation. (Image source)

Soil environments, being exposed to natural vegetative respiration and existing in direct contact with the atmosphere, are naturally dynamic. This introduces challenges with soil gas monitoring: distinguishing between natural CO_2 fluxes and changes that indicate a leak has occurred. Improper attribution of CO_2 increases has been well documented in Romanak et al., where a measured increase in CO_2 levels in soil gas was assumed to be indicative of a leak from the Weyburn-Midale Storage site in Saskatchewan, Canada. This project demonstrated that it is not enough to observe changing CO_2 levels, further evidence must be gathered to attribute the increase to a leak or to natural fluctuations.

The Romanak et al. project presents a way to use soil gas ratios (CO_2, O_2, N_2, CH_4) to determine if elevated CO_2 is natural or attributable to a leak. Another method for addressing a suspected leak is isotopic fingerprinting, measuring the relative amounts of different carbon isotopes (commonly ^{12}C, ^{13}C, and ^{14}C). Because ^{14}C is radioactive and decays predictably over time, young organic matter has more ^{14}C than older organic matter (such as that derived from fossil fuels). Understanding the ratio of these common carbon isotopes of both the injectant and background CO_2 is another effective method for attribution.

Vegetative Stress Monitoring Using Satellite Imagery

Spectral methods are widely employed to monitor vegetative stress: as plant health deteriorates, their chlorophyll absorbs less visible radiation and reflects less near-infrared energy, leading to a distinct spectral signature. Commonly used satellite-based indices for visualizing vegetative stress include the Normalized Difference Vegetation Index (NDVI) and the Hyperspectral Vegetation Index (HSVI).

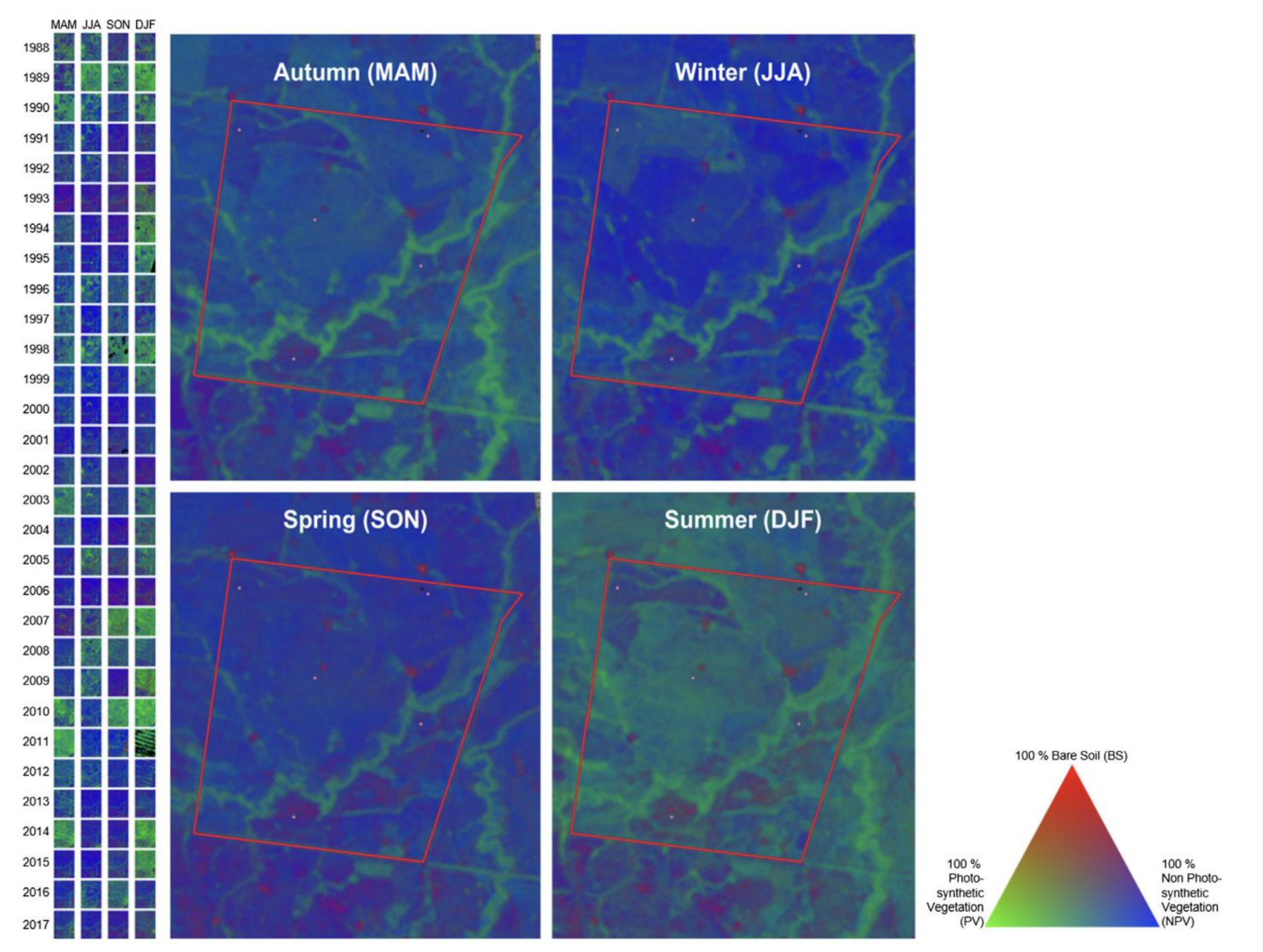

Figure 2: Maps of land-sat derived vegetation fractional coverage (1988–2017) at a planned CCS area. Left: thumbnail showing 30 years of seasonal images captured. Center: Four large maps representing the mean cover for each season, study sites plotted with yellow dots. Right: map color legend. (Image source)

Mapping vegetative stress (see Figure 2) is an example of an indirect monitoring method for locating leaks of CO_2 on the surface. Indirect CO_2 seepage detection through plant health remote sensing offers a notable advantage: it can cover large spatial extents in remote areas (a limitation of many monitoring technologies) and identify potentially affected areas, making it easier to pinpoint the source (at a low cost below $30/Sq. Mi per survey). However, this method is accompanied by uncertainty of how leak size influences vegetation responses and the ability to distinguish spectral changes caused by external factors (e.g., weather or season) from those due to leaks.

In 2010, studies at the Zero Emissions Research and Technology (ZERT) site used FieldSpec Pro and Pika II spectrometric sensors to investigate the impact of CO_2 leaks on plant health. These studies revealed that leaks exceeding 200 kg CO_2 per day caused visible stress in nearby vegetation. However, conflicting results emerged from a 2008 study that used volcanic vents as proxies for leak sources. This study employed various spectral sensors to detect active vents, achieving a 47% success rate but also generating several false positives.

WATER

Aquifer Monitoring: Geochemical Analytes and Isotopes

The Class VI permitting process is centrally focused on protecting Underground Sources of Drinking Water (USDWs). To that end, operators of CCS projects are required to monitor shallow aquifers, usually through pre-injection sampling to establish a natural baseline followed by sampling during and after injection to ensure no significant deviation from those levels has occurred. Analytes that respond to CO_2 in water have been assessed in field and laboratory experiments and geochemical models include pH, alkalinity, bicarbonate, electrical conductance, dissolved inorganic carbon (DIC), dissolved CO_2, total dissolved solids (TDS), concentrations of cations, anions, and trace elements (Ba, Ca, Cr, Sr, Mg, Mn, Fe, As, Pb). CO_2 gas leaked into an aquifer and the dissolution of CO_2 into groundwater would react as follows:

$$CO_{2(g)} >> CO_{2(aq)} + H_2O >> HCO^{3-} + H^+ >> CO_3^{2-} + 2H^+$$

This process lowers groundwater pH as the hydrogen ion concentration increases. A lower pH can lead to mineral dissolution, which can then increase trace element concentrations in water. Pre-injection aquifer geochemistry and reservoir lithologies will control what chemical reactions are likely to occur in the CO_2-water-rock interface, necessitating the inclusion of both aquifer chemistry and reservoir mineralogy data to anticipate these reactions. Comparing the data collected during and after injection to the pre-injection baseline allows operators to note any geochemical variations.

The Quest CCS project in Alberta Canada published a study on their site assessment of baseline groundwater, noting the utilization of publicly available data, existing groundwater wells, and proprietary information gathered prior to injection. A thorough characterization of shallow water resources (illustrated in Figure 3) guided the strategic sampling and monitoring plan. Downhole sensors were installed to measure pH in 9 shallow groundwater wells, prior to and during injection. The results of this approach were outlined in a monitoring retrospective, published one year after injection began, and demonstrated no significant drops in pH that would indicate the presence of fugitive CO_2 in groundwater.

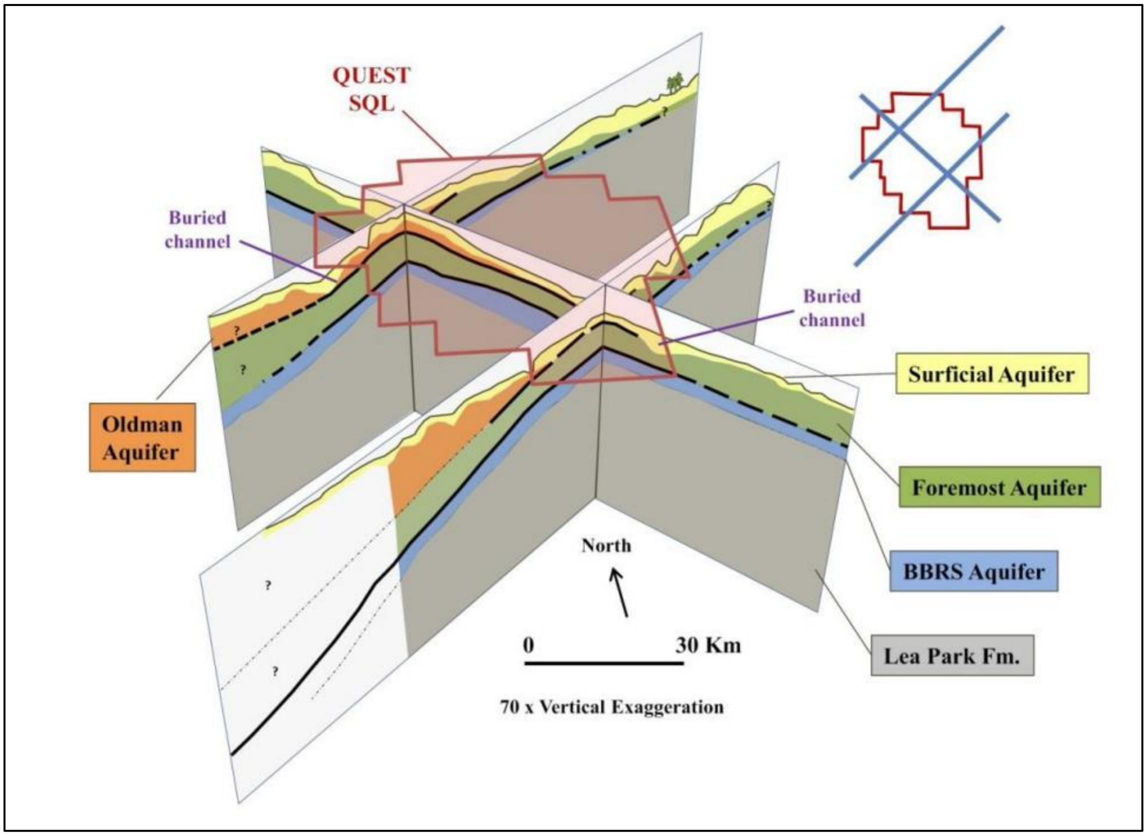

Figure 3: Fence diagram showing the position of shallow aquifers in the Quest project study area. Coal zones are indicated in black. (Image source)

However, due to the natural variation of shallow environments, even when geochemical deviations are detected, they may or may not be attributable to a leak of CO_2. To address this ambiguity, measures should be taken to appropriately attribute a signal to a leak or to natural fluctuations. Similarly to soil gas detection, aquifer monitoring is a process that isotopic fingerprinting can complement if a leak is suspected, as it will more reliably decipher between natural and anthropogenic CO_2.

AIR

Atmospheric Monitoring of CO_2

Atmospheric monitoring, like soil gas monitoring using CO_2 detectors, offers a method to detect and measure CO_2 levels directly. Installation of in-situ sensors at both the capture facility and at the injection site provides data that can be used to back up claimed injection rates and capture efficiency rates, while drone overflights of CO_2 transport pipelines and storage reservoir monitoring areas can help pinpoint active leakage pathways or fugitive emission events.

Carbon dioxide has absorption bands centered at 15, 4.3, 2.7, and 2 μm, making CO_2 especially sensitive to mid-infrared spectroscopy. MIRA (mid infrared spectroscopy) analyzers used for in-situ or UAV-based CO_2 detection can provide highly accurate, frequent readings of atmospheric CO_2

providing near real-time insight into site conditions and emission events. Similar detectors have been incorporated into stationary, mobile, and airborne monitoring systems often combined with high-resolution GPS technology to identify and measure methane (CH_4) emissions in conventional oil and gas activities.

UAVs serve as a vital link between ground surveys and conventional aircraft. While traditional aircraft can handle extensive equipment, they come with high costs and require substantial data processing. In contrast, UAVs provide a valuable alternative, despite their limited coverage capabilities.

In 2021, the Subsurface Evaluation of CCS and Unconventional Risks (SECURe) a partnership formed by the European Union, published a paper on the applicability of UAVs for monitoring large-scale sites and the impact of remote sensing on decisions of baseline characterizations. Preliminary results of SECURe's study indicate that the drone with a CO_2/CH_4 dual sensor successfully recorded gas emissions (see Figure 4). This is an important contribution to the SECURe assessment for overall UAV-based monitoring systems, suggesting that miniaturized UAV monitoring systems can be successfully deployed even for the detection of small and dispersed ground emissions as low as tens of $g/m^2/h$.

Figure 4: Left: Deployment of an atmospheric monitoring equipped drone. Right: Aerial image showing drone flight path, with each color-coded dot correlating to changing CO_2 levels. (Image source)

UAV-based detectors offer mobility, flexibility, and the ability to cover challenging terrains, making them valuable tools for dynamic monitoring needs. Meanwhile, fixed-point detectors provide consistent, long-term data collection at specific locations, ensuring data continuity and precision. Optical sensors do, however, face limitations. There is significant variation in atmospheric CO_2

levels due to both natural and anthropogenic sources and sinks of gaseous carbon. Variations in plant cover, land use, and topography may create challenges in verifying CO_2 leakage from the storage reservoir. The incorporation of tracer gases and/or integration of CO_2 isotopic measurements is a means for CO_2 detectors to differentiate between biogenic and anthropogenic sources of CO_2, but both options come at a much higher price point and higher operational impact than traditional optical sensors.

Conclusion

The use of advanced Monitoring, Reporting, and Verification (MRV) technologies is essential in addressing the health, safety and environmental concerns of local communities in carbon capture and storage (CCS) projects. Emerging and established technologies in soil gas, vegetation, aquifer, and atmospheric monitoring are enabling dynamic and in-situ methods to ensure environmental preservation at CCS sites. Each technology faces limitations due primarily to the challenge of monitoring dynamic natural environments for a gas that occurs naturally. These techniques for monitoring the shallow subsurface are most effective when used in tandem with deep subsurface monitoring and can be most successful when applied strategically based on unique site conditions. Monitoring shallow environments, though critical to ensuring environmental and community well-being, can only offer retrospective insight; the emphasis should therefore be on proactive risk management to prevent potential hazards.

The CCS sector is poised to benefit from greater transparency and improved economic and operational efficiencies as these monitoring technologies evolve and are more widely deployed. As of mid-2023 the International Energy Agency (IEA) identified 500 CCS projects globally, at various stages of development. This ramping up of activity underscores the urgency of applying holistic monitoring approaches that can strengthen partnerships between project operators and communities. For operators, this means rethinking stakeholder engagement, and the role of monitoring technology as both a tool for ensuring community wellbeing and environmental preservation and as a means for communication, education, and outreach.

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Anna Littlefield is the Program Manager for Carbon Capture Utilization and Sequestration for the Payne Institute at the Colorado School of Mines. As a current PhD student in the Mines geology department, her research focuses on the geochemical impacts of injecting CO2 into the subsurface as well as the overlap of geotechnical considerations with policymaking. Anna joins the Payne Institute with 8 years' experience in the oil and gas industry, where she worked development, appraisal, exploration, new ventures, and carbon sequestration projects. Her academic background is in hydrogeology with an M.S. in geology from Texas A&M University, and a B.S. in geology from Appalachian State University. Anna is passionate about addressing both the societal and technical challenges of the energy transition and applying her experience to advance this effort.

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