Methane Mitigation:

Roles for Artificial Intelligence in Support of FECM RDD&D Priorities

April 2023

U.S. DEPARTMENT OF ENERGY

Fossil Energy and Carbon Management

Artificial intelligence (AI) holds the potential to accelerate the transition to a carbon-neutral economy and help achieve the technology research, development, demonstration, and deployment (RDD&D) goals set forth by the DOE Office of Fossil Energy and Carbon Management (FECM) in its *Strategic Vision*. FECM and the National Energy Technology Laboratory (NETL) continuously expand, maintain, and curate extensive scientific data sets and AI tools essential to carbon management, and they are now standing up a robust AI Multi-Cloud Infrastructure to enable the DOE research community to share and leverage a collection of tailored resources to expedite progress toward equitable and sustainable solutions.

As one step toward prioritizing AI development activities, FECM is exploring specific roles for AI in meeting the top RDD&D needs identified in the Vision. This document summarizes a series of discussions in which a range of specialists from FECM, NETL, and the DOE Office of Science suggested potential roles for AI in **Methane Mitigation**. This document should be viewed as a representative sample of the types of AI applications that may be needed; it is by no means a comprehensive list.

Cover image: AdobeStock #168274790

AI for Methane Mitigation

FECM Strategic Vision:
Minimize emissions of methane during production, processing, transportation, storage, and use across the coal, oil, and gas industry to eliminate non-trivial methane emissions from carbon-based fuel supply chains by 2030. Advance cost-effective technology to identify, quantify, and predict methane leaks across sectors more efficiently and improve both the accessibility and reliability of methane emissions data.

Office of Fossil Energy and Carbon Management (DOE/FECM 2022)

Methane (CH_4) is a potent greenhouse gas emitted by both natural (~40%) and human sources (~60%) around the globe. Although methane persists in the atmosphere for a much shorter time (~10 or 12 years) than carbon dioxide (300 to a thousand years), it *traps about 80 times more heat* (UNEP 2022). As methane degrades in the upper atmosphere, it reacts with ozone to form water vapor and carbon dioxide (CO_2), which continue to warm the climate for centuries. The UN Environment Programme estimates that methane is responsible for approximately 30% of all human-caused climate change since the pre-industrial age (UNEP 2021).

Methane emissions at ground level can also endanger human health. High concentrations of this flammable gas can pose a hazard to individuals close to production facilities or near any rupture along a high-pressure pipeline. Methane also contributes to ground-level ozone, which can impair lung function and cause other serious respiratory or cardiovascular conditions (WH 2021).

In the United States, natural gas and petroleum systems are the largest industrial source of methane emissions (EPA 2021). As the primary component of natural gas, methane is emitted to the atmosphere during natural gas production, processing, storage, transmission, and distribution (EPA.gov). Traditionally, energy companies have estimated methane emissions based on the percentage believed to escape from the equipment (bottom-up approach), but recent studies based on drone, aircraft, and satellite-based sensors (top-down approach) suggest annual emissions may be severely underestimated (Bussewitz 2023). Estimates of methane emissions in some regions range widely: from 0.1% to 10% per unit of mass withdrawn (Raimi and Aldana 2018). Excessive leaks may erase the near-term benefits of shifting from coal to natural gas (Geman 2022). According to Rick Spinrad, Ph.D., NOAA Administrator, “Data show that global emissions continue to move in the wrong direction at a rapid pace. The evidence is consistent, alarming, and undeniable.”

In 2021, atmospheric methane increased by 17 parts per billion (ppb)—the largest annual increase since systematic measurements began in 1983 (NOAA 2022). In 2020, an estimated 211 million metric tonnes (MMT) of methane were emitted across the oil and gas (O&G) sector, which consists of more than two million actively producing, abandoned, or repurposed oil and natural gas wells; more than two million miles of pipelines; and more than 100,000 unit operations (DOE/FECM 2022).

In November 2021, the Biden Administration released the [U.S. Methane Emissions Reduction Action Plan], which sets a target to cut U.S. methane emissions to half of 2005 levels by the end of this decade. The U.S. Environmental Protection Agency (EPA) followed up by proposing new guidelines and standards requiring U.S. oil and gas (O&G) facilities to cut methane and other harmful emissions—including existing facilities—without compromising innovation or production of American energy (WH 2022).

“Methane is more destructive than carbon dioxide to our health and environment, so it’s crucial we develop solutions to identify and mitigate leaks at their source.”

U.S. Secretary of Energy
Jennifer M. Granholm
August 5, 2022

According to the National Energy Technologies Laboratory (NETL), the past 10 years have seen significant progress in detecting and quantifying methane emissions at the source using surface-based technologies like hand-held and vehicle-based detection sensors, but these technologies cannot quickly assess large areas. Other technologies, such as atmospheric sensing equipment attached to satellites or manned and unmanned aircraft can better estimate the volume of methane emissions across wide areas, but these measurements are not taken continuously and are typically less accurate in pinpointing sources than surface-based methods.

Key challenges to methane mitigation include the broad geographic distribution of sources and intermittent nature of releases (often during abnormal operating conditions). One study of New Mexico suggests that a relatively small number of sources (less than 4%) may be responsible for half of all observed methane leaks. Improved sensor technology may assist in rapidly locating and addressing these super-emitters to deliver climate, environmental, and health benefits (Meyers 2022).

"Reducing methane emissions could lower the stock of greenhouse gases in the atmosphere and cut the very scary risks of "tipping points"—when climate change becomes self-perpetuating. This is because methane stays in the atmosphere for only 12 years on average compared with up to a thousand years for CO_2."

Simon Black et al. IMF (Black 2022)

The Methane Mitigation team in the DOE Office of Fossil Energy and Carbon Management (FECM) works to improve technologies to better detect, quantify, abate, and prevent methane emissions across the O&G supply chain. This effort includes design of an Integrated Methane Monitoring Platform to continually collect, curate, and analyze data on thermogenic methane emissions. The platform's centralized software system and AI models will curate and analyze methane sensor data collected across various temporal frequencies, altitudes, and geographical ranges (local, basin, regional, and national scale) along with environmental data (wind speed and direction) to deliver accurate estimates of the sector's methane emissions. As the AI tools and models are improved and validated, proven accurate, and earn industry confidence, they may inform the Pipeline and Hazardous Materials Safety Administration (PHMSA) process for developing new AGI codes and standards to mitigate and prevent methane leaks.

FECM focuses current research, development, demonstration, and deployment (RDD&D) activities in methane mitigation on undocumented/orphaned wells, pipeline integrity, geologic storage for hydrogen, and crosscutting issues. As summarized in Figure 1 and on the following pages, artificial intelligence (AI) and machine learning (ML) can assist in developing the capabilities to achieve these goals and help mitigate the most severe impacts of climate change. [Note: Figure 1 reflects the structure of this document.]

Undocumented/Orphaned Wells

More than 100 years of oil and gas drilling in the United States have left millions of wells undocumented or orphaned.[1] Many wells were drilled before environmental laws were enacted and were never documented on public maps or records. Unfortunately, many are improperly sealed, allowing liquids and gases to rise to the surface (NETL 2022). Poorly sealed wells can release potent greenhouse gases (GHGs) like methane (DOE 2021). The Interstate Oil and Gas Compact Commission estimates the number of undocumented wells is between 310,000 and 800,000 across 15 states (IOGCC 2021),[2] and the EPA estimates that as many as two million undocumented orphaned wells or more were never properly plugged (Groom 2020).

FECM RD&D *Vision* for undocumented orphaned well-based methane:

- Identify, characterize, and inventory undocumented orphaned wells and associated pipelines, facilities, and infrastructure.
- Assist other federal agencies, states, and tribal entities in measuring or estimating and tracking emissions of methane and other gases associated with undocumented orphaned wells.

The Bipartisan Infrastructure Law (BIL) prioritizes efforts to locate these wells, determine the level of emissions, wellbore integrity, and overall environmental impacts so they can be prioritized for plugging and remediation by state and federal agencies. BIL funding includes $30 million for a multi-laboratory Consortium Advancing Technology for the Assessment of Lost Oil and Gas Wells (CATALOG) to achieve these goals. The participating national labs are Berkeley, Livermore, Los Alamos, Sandia, and NETL. This investment is part of the Administration's broader effort to remediate environmental issues, address legacy pollution, create good jobs, and advance environmental justice (NETL 2022a).

1 Orphaned O&G wells are unplugged, nonproducing wells for which the operator is unknown, unavailable, or insolvent, leaving no responsible party to plug the well and restore the site other than government agencies (Boutot 2022).

2 The IOGCC report states that wells on private and state lands are included in the orphaned well counts, but some states may or may not include wells on Federal or tribal lands. In addition, some tribes defer to States for regulation, while others keep exclusive authority and may not share that information with state agencies.

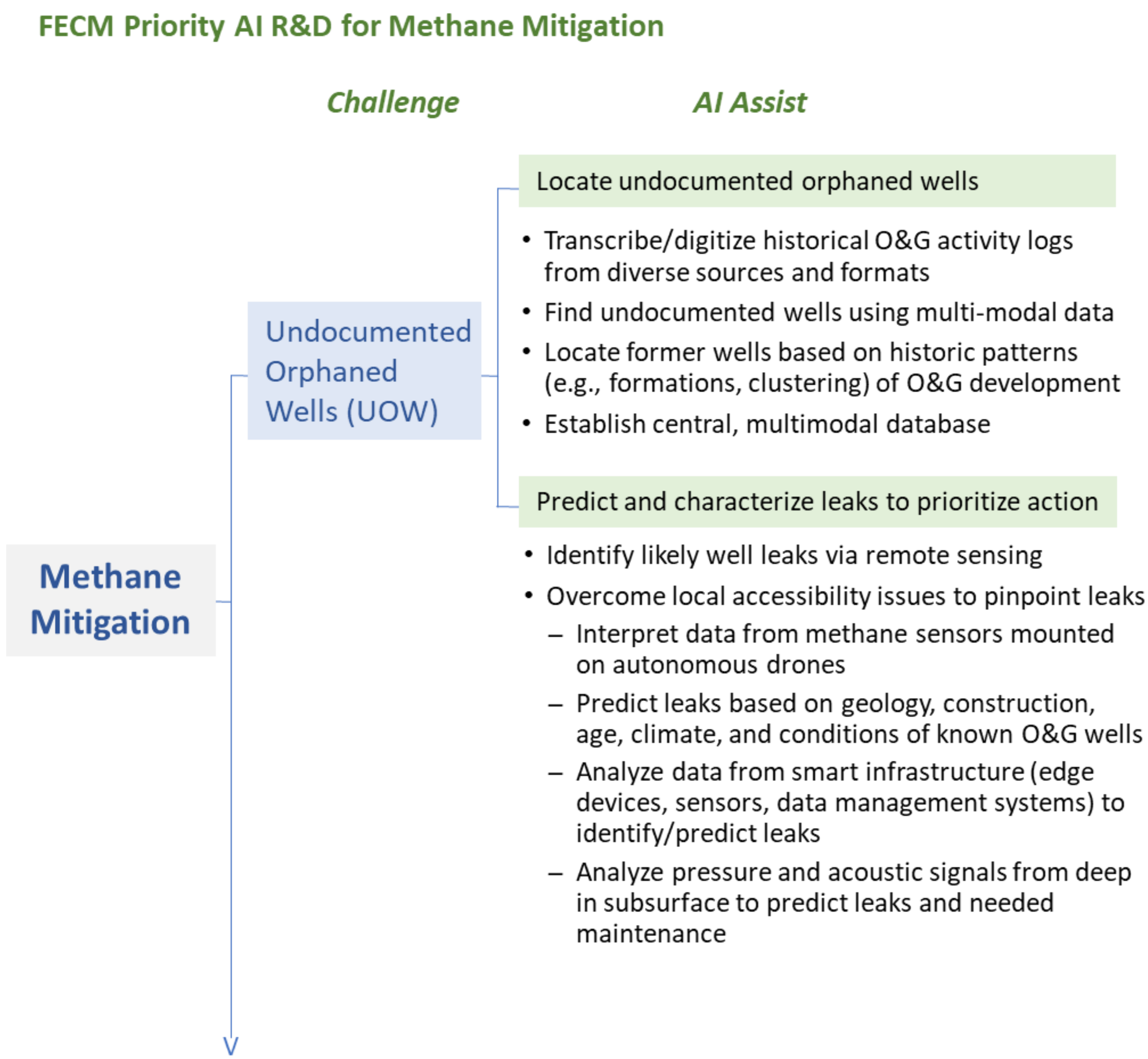

Figure 1. Summary of Potential AI Roles in Methane Mitigation

Pipeline Integrity

Leverage broader scope of data to better assess health of pipeline network

- Access, assess, and curate formerly unavailable data
- Gain insights from historical data/reported incidents
- Discover patterns to better understand mechanisms, chemistries, conditions
- Establish data parameters to improve certainty
- Identify most valuable data streams for prediction
- Fuse data across scales (local to global)

Develop novel sensors/adapt from other fields

- Design sensors for use in un-piggable pipe sections
- Identify or confirm pipe materials
- Explore wider materials databases for sensors
- Engineer MOFs/ligands that selectively attract trace metals indicating corrosion
- Continue developing indirect measurement sensors
- Develop AI-integrated sensors with edge computing
- Enable early detection of slugs or hydrate formation
- Optimize sensor placement to cover high-risk spots
- Advance sensor communication telemetry

Develop decision support models

- Integrate disparate data sets to predict/avert events
- Define range of safe operating parameters
- Validate novel, predictive signatures in data sets
- Model pipeline performance for predictive analytics
- Identify high-risk sections
- Enable predictive maintenance
- Issue alert when H_2 levels approach safety limits
- Develop visualization tools to support prioritization

Develop automated analysis capabilities

- Develop inspection systems that outperform humans
- Interpret data to detect microfractures and assess pipeline integrity at microscopic level
- Maintain operations within safe parameters
- Optimize blend mix for operations and efficiency

Figure 1. Summary of Potential AI Roles in Methane Mitigation (continued)

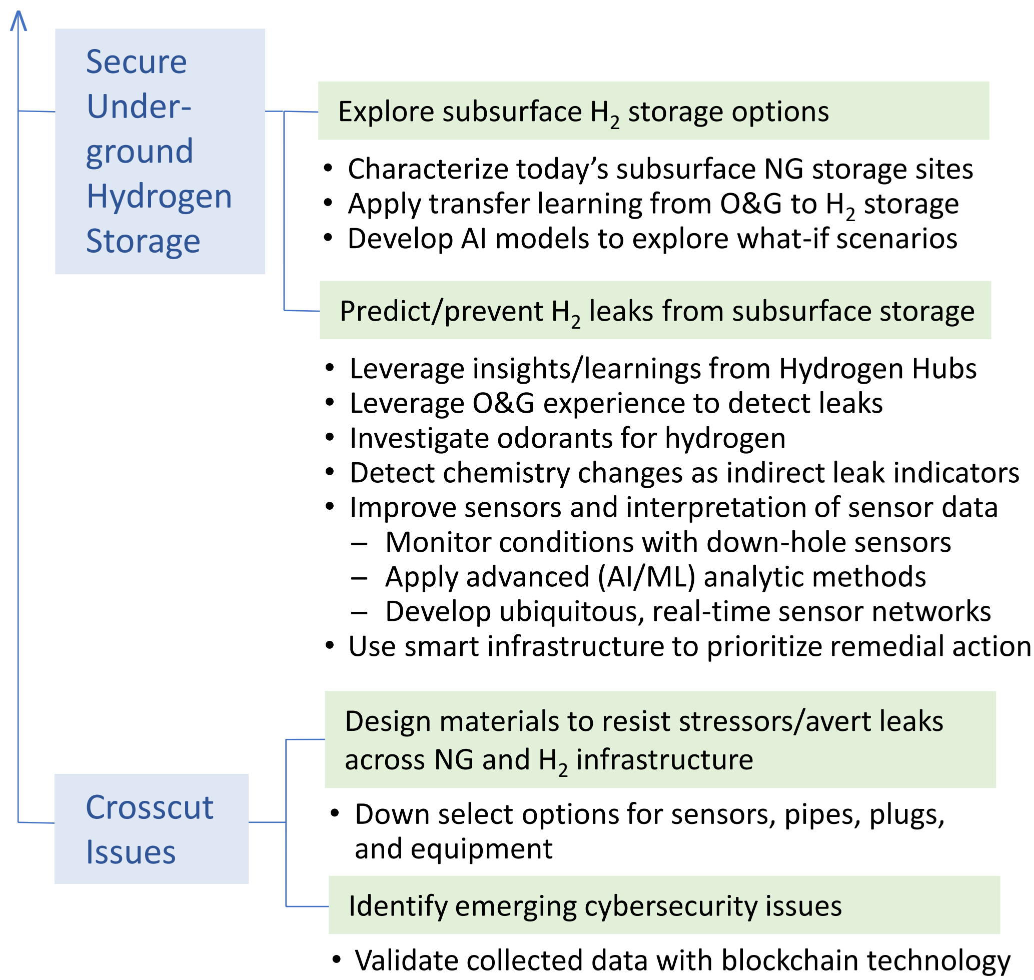

Figure 1. Summary of Potential AI Roles in Methane Mitigation (continued)

Under BIL, CATALOG is assigned to **locate** and **characterize** abandoned or undocumented wells. Likely locations of wells suspected to be leaking methane are to be delivered to the appropriate state or federal agencies for follow-up by boots on the ground. AI has the potential to expedite some of the most challenging or time-intensive steps involved in locating and characterizing abandoned or undocumented wells. Information on wells located by the approaches described below will be entered into a national database and may be enriched with other relevant data so that data-driven models can suggest additional likely locations with a high level of confidence. The following approaches were deemed potentially worthwhile applications for AI.

Locate Undocumented Orphaned Wells (UOW)

Historical O&G well records and other sources containing well locations, depths, and other important information need to be found and put into machine-readable form. It is generally a time-intensive and costly process to dig through logs, articles, files, floppy disks, microfiche, notebooks, maps, newspapers, photos, lease maps, and other records stored in dispersed locations across the public and private sector.

> "Methane emissions are avoidable—the solutions are proven and even profitable in many cases. And the benefits in terms of limiting near-term global warming are huge."
>
> IEA 2022

AI tools such as optical character recognition (OCR) and natural language processing (NLP) can help **accurately transcribe, digitize, and format records** to support future AI analysis that will help determine the locations of wells and assess the accuracy of those locations. Once a likely area is identified, a deep dive might produce a good data training set to help build useful models while protecting private records. AI may then overlay locations identified using these models with additional data to increase confidence.

AI can also interpret data on geomorphology, geography, vegetation indices around known abandoned wells (relevance TBD), and a wide range of remote sensing data to predict likely sites of undocumented wells. By extracting the most relevant data (reducing noise) and using the data synergistically, AI can strengthen the potential to gain new insights. The reliability of the data sources will influence confidence levels in algorithm outputs. **Combining multimodal data** in this way will provide various types/contexts/sources of data to maximize and leverage all data components (including changes over time)—adding new layers of meaning and generating new insights.

"The pollution threat goes beyond climate change. Leaks from abandoned wells have been found to contaminate groundwater and soil. In extreme cases, gas from abandoned wells has caused explosions."

Nicholas Groom, Reuters (Groom 2020)

Historic patterns of known O&G development (e.g., geologic formations, clustering) may help locate undocumented wells. AI could correlate land and geological characteristics (existing geospatial data) to those of areas surrounding known wells in a region to identify areas with similar characteristics and predict locations of undocumented wells. Similarly, if wells historically tend to be clustered in areas with a certain mix of characteristics, AI might suggest areas with a high probability of UOWs within the vicinity of known wells (ML excels at finding hidden patterns and can be trained on the characteristics of known well pads). To further guide the search, researchers might apply 4D analytics and use the characteristics of known wells (e.g., age, architecture, condition).[3]

Ultimately, digitized legacy data, multimodal data, and historical well patterns may be integrated into a **central database** to expedite additional identification of currently unknown wells (bottom-up and top-down approaches). As part of CATALOG, NETL has begun assembling a publicly available national database for O&G wells that have an API number and location. CATALOG is actively working with the Orphaned Wells Program Office in the U.S. Department of the Interior (DOI) to coordinate the identification of both orphaned and undocumented orphaned wells. New AI tools can facilitate the expansion, integration, and probing of this data resource.

Predict and Characterize Leaks to Prioritize Action

The initial characterization or assessment of a located well should focus first on the well location and level of methane leakage so that the super-emitters can be plugged as quickly as possible. State agencies will also want to know the leaking well's proximity to human populations, risk to water resources, and other information (some states have designed scorecards to assist in prioritization).

AI can analyze data from a range of **remote sensing** devices to initially identify areas of suspected methane leaks, but cloud cover, wind currents, sensitivity limits, and timing may hinder the ability of some remote devices to identify precise sites. It may be possible to integrate information from multiple sensors (e.g., satellite imagery, spectroscopy/vegetation succession and die-off, terrain, etc.) to sufficiently characterize each well's condition or status. Tools developed for this purpose will need to adapt to variable characteristics across sites and regions.

"A small number of sites and pieces of equipment are often responsible for a disproportionately large amount of methane emissions. For example, a recent measurement campaign in the United States found that low-producing marginal wells are responsible for half the well pad emissions in the Permian Basin and that more than 75% of these wells are owned by major corporations."

IEA 2023

[3] To view an animation of known wells, see slides 10 and 11 of the presentation at: https://upittiscworkshop.github.io/UPittISCWorkshop/PDF/2-00.pdf; see additional resources at the end of this document.

If it is not economically feasible to move characterization equipment sufficiently close to a suspected well leak to pinpoint and characterize it on the ground, other approaches may be required to **overcome accessibility issues**. Improved and more frequent **remote sensing** may guide pathways for drone flyovers, and **drones** equipped to detect methane (using video, magnetometers, other sensors, and AI) might then interpret a range of data to determine specific well location, status, and condition. AI might draw upon **geography and climate data** in addition to knowledge and insights obtained from local operators (e.g., **well construction** techniques, age, practices, and history). Alternative data sources to feed AI tool development may include **smart infrastructure** and **pressure and acoustic signals** from deep in subsurface, like the controlled-source electromagnetic (CSEM) signals developed for monitoring geological sequestration of CO_2. FECM's Integrated Methane Monitoring Platform (page 2) incorporates many of these approaches.

Steps to consider:

- Better define the scale and challenges (e.g., patterns via maps/photo recognition can be simple or complex).
- Explore best techniques to handle "unfriendly" data.
- Work with states, the US Geological Survey, and students to develop useful AI/ML tools to help extract the data, format it, and make it accessible.
- Identify cross-cutting areas with other DOE programs and other National Labs.
- Leverage existing resources (SMART Initiative, interferometric synthetic aperture radar (INSAR), etc.)
- Determine whether there will be enough regularity in the data to train AI.
- Use common elements of records, which vary state to state.
- Use increased granularity provided by advanced models to develop probability contour maps.
- Develop hybrid sensing technologies to detect and accurately identify sources of methane leaks.
- After five years, the goal is to equip states with a complete tool set to find and plug the undocumented wells that have been discovered. Many may contract out the work.
- Maintain dialogs with DOI, ARPA-E, NOAA, NASA, and Rural and Tribal Communities.

Pipeline Integrity

The U.S. natural gas network includes approximately 2.6 million miles of pipelines, including gathering, transmission, and distribution lines that link natural gas production areas and storage facilities with consumers (EIA 2022). The main network components include:

- **Gathering lines:** These typically small-diameter, medium-pressure pipelines move raw natural gas from the wellhead to a processing plant, compressor station, or transmission pipeline. The gathering pipes are often made of steel, plastic, or cast iron (Yu 2022).
- **Natural gas processing plants:** These plants separate hydrocarbon gas liquids, nonhydrocarbon gases, and water from the natural gas before putting it into a mainline transmission system.
- **Transmission lines:** Wide-diameter, high-pressure transmission pipelines (both intrastate and interstate) transport high volumes of natural gas from the producing and processing areas to storage facilities and distribution centers. Roughly half of today's transmission pipelines were built in the 1960s or earlier.
- **Distribution lines** deliver natural gas from distribution hubs to local consumers through small-diameter, lower-pressure pipelines. Many of these lines were installed following World War II, and the network has continued expanding to serve new commercial facilities and residential areas (EIA 2022).

Methane emissions from pipelines are more difficult to detect and measure than those from more localized parts of the infrastructure like processing plants (Yu 2022). A huge hurdle is the immense geographic spread and diversity of the pipeline network. Millions of miles of pipes of various material compositions and ages run through varied topographies, climates, and ecosystems. Most pipelines run underground but rise to the surface at pumping and pigging stations, where valves, pumps, regulators, reciprocating compressors, pneumatic controllers, and meters help monitor and control the flow. These above-ground components can also emit methane (NETL 2023).

Leaks of methane gas (colorless and odorless) can occur by accident (malfunctioning equipment) or during regular operations, such as venting, valve adjustments, or periodic maintenance. Given these varied causes, the emissions can fluctuate widely over time (Leber 2021), potentially escaping detection. Increased efforts to harness hydrogen as a clean energy carrier pose an additional risk for methane leaks from pipeline systems. The small hydrogen molecules can penetrate tiny cracks and other micro-openings in pipeline materials. As higher levels of hydrogen are mixed into natural gas pipelines, the impacts of novel chemistries on pipeline materials must also be examined to protect against accelerated corrosion or other processes that could lead to leaks.

The age and material of a pipeline affect the likelihood that it will fail or leak. Materials used for gas pipelines include steel, copper, brass, ductile iron, aluminum, PVC, polyethylene (Strange 2022), and reinforced composites. Pipelines constructed of cast and wrought iron (through the 1940s) or uncoated steel (circa 1950s) are believed to pose some of the highest risk of failure, and plastic pipes manufactured in the early 1970s had become embrittled by the 1990s, leading to two advisory bulletins in 1999 (ADB-99-01 and ADB-99-02) and proposed new rulemaking in 2015 (PHMSA 2015). The Pipeline and Hazardous Materials Safety Administration (PHMSA) responded by tracking pipeline replacement and maintaining an online inventory of high-risk pipeline infrastructure by state (PHMSA 2017). Modern plastic pipe is manufactured to resist embrittlement, and steel pipes must be coated. Sections of pipe are now designed and manufactured specifically for their intended locations along pipelines. Each location may have specific requirements for pipe size, strength, wall thickness, and coating material due to varying soil conditions, geographical features, or nearby population densities (PHMSA 2022).

H_2 Is an Indirect GHG

"…Hydrogen gas reacts readily in the atmosphere with the same molecule [the hydroxyl radical, OH] responsible for breaking down methane, which is a potent greenhouse gas. If the level of hydrogen emissions surpasses a specific threshold, this shared reaction is likely to result in an accumulation of methane in the atmosphere, leading to long-term climate consequences."

Princeton, 2023

DOE and NETL are developing advanced mitigation solutions to detect, address, and prevent pipeline leakage, including best practices, advanced pipeline sleeves and liners for older pipes, inline inspection tools, and novel coatings to improve the resiliency of both new and legacy systems (NETL 2023). Artificial intelligence holds the potential to significantly expedite progress in predicting and averting methane emissions from pipelines, and industry has already put a range of AI- and ML-enabled models on the market to assist pipeline operators.

Ultimately, researchers envision sophisticated edge-computing models that can analyze real-time data from ubiquitous advanced sensors and provide robust decision support for the rapid repair or replacement of pipeline components before any methane can escape. As described below and outlined in Figure 2, key steps toward this goal are to **leverage a broader scope of data** to better understand and assess pipeline health; **develop advanced materials and sensors** to collect predictive data; and develop **automated analysis and decision-support capabilities** to predict and avert leaks.

Leverage/Curate Broad Scope of Data to Better Assess Pipeline Network Health

AI/ML techniques can harness large volumes of data to reveal hidden patterns and potentially expand scientific understanding of the ways natural gas pipelines of different materials are affected by complex interactions among gases, materials, and environments. For many decades, the industry has used down-hole sensors to collect basic data on the temperatures, pressures, and moisture levels within large O&G transmission pipelines. Operators regularly use cylindrical devices known as "pigs" to inspect the interior of transmission pipelines. Less information is widely available on the many smaller-diameter and highly diverse gathering and distribution pipeline systems. If made available, this data could potentially be used in combination with a variety of other existing data records (e.g., precipitation, heat waves, soil types, pipeline incidents) to produce deeper insight into the conditions and processes that cause leaks and failures or otherwise compromise pipeline integrity. In addition, data on changing conditions inside and surrounding the pipelines (bacteria, chemistries, microbes, presence of metals, etc.) could reveal emerging risks and enable accurate modeling of pipeline health.

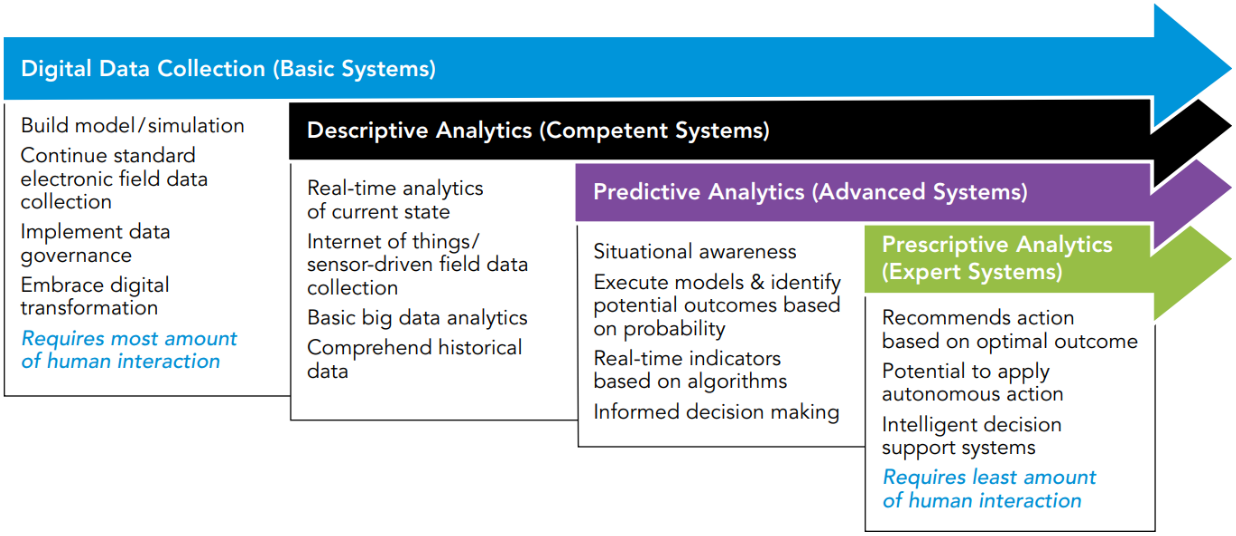

Figure 2. Progression from data collection through autonomous action Source: S. Katcher, GTI (NARUC 2020)

Access, assess, and curate formerly unavailable data: Private companies often consider data proprietary, but data may be satisfactorily anonymized so that it cannot be traced to its owner or locality. Some forward-thinking organizations may share their data on past and present pipeline conditions to advance the science and achieve new insights—leading to more durable materials, reduced leakage, improved safety, and broad economic and climate benefits. In addition, other potentially relevant types of data (e.g., weather, geologic surveys, soils, satellite imagery, pipeline age and materials) should be collected and curated to enrich data-driven ML.

Gain insights from historical data/reported incidents: Another promising route of discovery may be to correlate known pipeline/equipment failures to as much data as possible regarding the specific materials and evolving characteristics of the environments within and outside of the relevant pipeline sections during the months (or years) preceding a failure. Advanced language processing capabilities can help recover undigitized data. Sufficient data must always be reserved for subsequent verification/validation of any ML-discovered patterns.

Discover patterns to better understand mechanisms, chemistries, and conditions: As more and better data becomes available through expanded access, novel sensors (e.g., biochemical), and discoveries in related fields, researchers can use ML to explore new and potentially useful patterns and relationships in the data related to pipeline integrity. The focus should be on clarifying the specific mix of factors (e.g., for buried pipes, the soil type/structure, drainage, precipitation, temperatures across geographic regions) and their impacts on pipe surfaces over time. A better understanding of the forces affecting pipeline integrity should help to identify the most useful indicators of the presence or extent of suspected mechanisms at work in particular sections of pipe.

Identify most valuable data collection streams for prediction: Initially, ML can be used on large volumes of data to identify patterns for further study. Findings from ensuing analyses and model validation processes should help focus data collection on the most useful types of data—streamlining data processing and analysis (first column of Figure 2). AI can also be used to generate synthetic data in cases of access to sparse but accurate data.

Establish data parameters to improve certainty: As the science advances understanding of the conditions that threaten pipeline integrity, one goal should be to define the parameters within which a pipeline can operate without problems. The parameters should identify the maximum and minimum values for a selected set of data points—with a specified level of certainty. The parameters should specify the required data variety, continuity, timing (intervals and duration), confidence, etc.

Fuse data across scales (local to global): Once the data quality and quantity can support a high degree of confidence in the specific mix and intensity of factors that threaten pipeline integrity, AI may assist in scaling up algorithms to apply to ever larger sections of pipeline. Potential failures may be predicted by analyzing data on a range of stressors on a selected pipeline section/material (e.g., inside the pipe; residual stress from the manufacturing process; external stress from bending, welding, gouges, or corrosion; and stress due to earth settling or moving)—and alerting operators.

Develop Novel Sensors or Adapt from Other Fields

To check for methane leaks in pipelines, operators traditionally used ground-based systems such as extensometers, inclinometers, surveying, and visual inspections. While accurate for large methane leaks that resulted in a ground disturbance, these methods are not generally cost effective over large areas nor accurate for detecting small- to medium- sized methane emissions. Better detection methods are now available, and more advanced technologies are in development or entering the market.

Steep fines for excessive methane leaks are set to begin in 2024, and gas companies are developing diverse strategies to economically detect methane leaks in pipelines of different types in diverse locations. Operators will need to research and select from a mix of current space-, air-, and ground-based measurement approaches to identify leaks rapidly and cost-effectively (see inset for examples). Wide-scale screenings by aircraft or satellites often identify potential leaks, which are then pinpointed locally using drones and handheld devices. AI might assist in developing technologies capable of broad application in leak detection—as well as prediction and prevention.

Subset of Available Pipeline Sensing Approaches

Flowmeters: Monitoring and comparing gas flow across each section can identify blockages or leaks.

LiDAR: Light detection and ranging continuous-wave lasers attached to an aircraft scan the ground to capture data, which is then mapped.

Imaging spectrometry: Unique absorption patterns of *infrared* light detect methane from aircraft, drones, and NASA's EMIT on the International Space Station to identify point sources at facility scale (NASA 2022).

Distributed fiber optic sensing: A laser pulse from a fiber optic cable/tube (in or outside the pipeline) produces backscattered light that is analyzed to measure thermal, acoustic, and kinetic energy with 100% space/time coverage (FOSA 2021).

Design sensors for use in "unpiggable" sections of pipeline: Since the 1960s, maintenance crews have used "pigs" (named for their "squeal" when traveling through tight sections) to perform cleaning as well as find rust, thinning walls, weak seams or welds, or other signs that a pipeline needs repair or replacement. These devices could be hard to control or stop in one location because most depend solely on the pipe's pressurized fluid for propulsion (Svoboda 2011). Most of today's mechanical or foam pigs cannot be used in pipelines that lack access stations (pig traps), are damaged or fully blocked, or contain abrupt bends or changes in diameter. Many additional types of pigs, including intelligent pigs, are on the market today offering diverse capabilities (e.g., ultrasonic inspection, electromagnetic acoustic transducer tools, video cameras, liquid coupled tools). Each type has its limitations, strengths, and drawbacks, so pipeline operators must have a clear understanding of the full range of options and the types of issues they need to assess (Mohamedein 2022). The wide range and specificity of these sensor options—and the economics of deploying the right ones over long distances—present a challenge. AI may assist in developing sensors that can affordably provide an accurate picture of pipeline integrity across a broader range of pipeline characteristics, materials, and conditions.

Identify or confirm pipeline materials: Accurate knowledge of the composition of pipeline materials is critical to maintaining the integrity of a pipeline system, particularly in performing effective pipeline inspections and repairs (Global 2023). Operators of transmission lines and newer pipelines will have this information, but operators of some legacy or grandfathered gathering and distribution lines may be uncertain about materials used in all parts of their systems. AI may assist in accessing historical records of construction, confirming the accuracy of old records, or separately identifying the materials used in existing pipelines via analysis of direct or indirect sensor data.

Explore wider materials databases for sensors: AI may be used to screen candidate materials and refine material choices to expedite the development of novel sensors that offer enhanced performance and improved cost-effectiveness in predicting, detecting, and preventing pipeline leaks over extended areas. AI may be particularly useful in evaluating membranes, transition metal dichalcogenides (Gopika 2022), metal organic frameworks (MOFs), and similar structures proposed for sensors. The past decade has seen significant progress in the fabrication of MOF-based sensors, which offer high sensitivity and selectivity due to their preconcentrating and molecule-sieving capabilities (Hongye

2021). AI could also assist in adapting advancements in sensor materials from other fields, particularly materials that offer novel sensitivities or a broader range of detection, e.g., advanced sensors for real-time monitoring of natural gas pipelines (FWP-1022424, [Project No.1611133]() at NETL), sustainable energy sources, or extended service life.

Engineer MOFs with ligands that selectively attract iron or other metals to indicate corrosion: MOFs offer extremely large surface areas, tunable pore size, and adjustable internal surface properties. AI might assist in engineering MOFs to enable sensors with heightened sensitivity in detecting specific corrosive contaminants, corrosion products, or other analytes of interest in evaluating pipeline health. ML might also assist in training the models to accurately interpret the data collected by MOF-based sensors.

"Metal-organic frameworks (MOFs), featuring structural diversity, large specific surface area, controllable pore size/ geometry, and host-guest interactions, hold great promise for fabricating various MOF-based devices for diverse applications including gas sensing."

Hongye Yuan, et al, *Advanced Science*, Wiley Library (Hongye 2021)

Continue developing indirect measurement sensors: Within the massive collections of data from natural gas streams, AI can be used to detect "signatures" (e.g., chemical, electrochemical, biochemical) associated with the presence of degradation, such as axial cracking, mechanical damage, thinning, or corrosion in the pipes. Validated signatures may then be used to analyze sensor data to predict and address localized degradation sites for remedial action. The Pacific Northwest National Laboratory (PNL) has been using advances in ML and predictive analytics since 2019 to uncover Novel Signatures from Deployed Sensors for Natural Gas Transmission Pipelines (NETL 2023). The team has curated detailed data from two national pipeline operators, used ML to prioritize the pipeline attributes and environmental factors most strongly correlated with subsequently discovered high corrosion rates, and begun developing a prognostic model relating corrosion-induced pipe metal loss to pipe data (e.g., age, material, coating, location, and other factors).

Develop AI-interoperable sensors with edge processing: Increasingly sensitive and more advanced sensors may collect ever more data on natural gas pipelines, potentially overwhelming central processing, analysis, and storage capabilities. To avoid associated time and cost penalties, AI models can be increasingly streamlined for use on smaller edge computers close to collection points or on the sensors themselves. Distributed data screening could dramatically reduce data loads, retaining and transmitting required reporting data and remotely identifying anomalies or other critical indicators. Sophisticated sensors might then transmit only significant data to central operations, flag critical issues, and continuously inform analyses along the length of the pipeline.

Enable early detection of slugs and/or hydrate formation: Under certain conditions, pipelines that handle multi-phase flow (gas at the top and liquid below) may form slugs or hydrates, potentially leading to blockages or other problems such as fluctuations in pressure, increased corrosion, or structural damage, reducing productivity and safety. AI may be used to assess collected data on pipeline conditions (may require broader scope of data than currently collected) prior to the development of slugs and hydrates to identify signatures or other indicators of developing issues. If correlations prove causative, sensors can collect data to spot these signatures early and signal the need for preventive activities.

Optimize sensor placement to cover high-risk spots: AI analysis of historical pipeline data and identified problem spots may be used to develop algorithms or train models to identify the locations where problems are most likely to develop in a pipeline. Based on known pipeline factors and trends, AI can then provide strategic guidance on the most cost-productive way to deploy sensors that can monitor the most critical conditions.

Advance sensor telemetry: To facilitate pro-active maintenance, sensors deployed along a pipeline will need the capability to transmit point-sources measurements accurately, energy efficiently, in real time, and at low cost. Depending upon the design of the sensor data processing network, the data may be sent to the central operations base for processing, a distributed (edge) processor to **screen out unneeded data before transmitting** the rest to a central base, or other sensors along the pipe that promptly relay the data *or* first make basic comparisons to flag potential anomalies. The feasibility of collecting data from wireless sensors across extended lengths of pipeline may require a **sustainable passive power generation** approach that requires no maintenance (or periodic replacement) and is sufficient for operating sensors that meet current and future requirements. Research by Los Alamos National Laboratory in 2005 determined the feasibility of harvesting power from flow-induced vibrations in a gas pipeline to power wireless sensor networks on a discontinuous basis (NETL FWP 04FE12), and the European Commission funded research into harvesting energy via triboelectric nanogenerators to power sensors in O&G pipelines with temperatures above 250 degrees C (CORDIS 2018).

Develop Decision Support Models

The AI-enabled expansion of data assessment and pipeline sensor capabilities is expected to improve early identification of methane leaks and indicators of conditions that can cause methane leaks. Building on these achievements, AI decision support models should be able to recognize **validated predictive signatures** in collected data and alert operators when **preventive (predictive) maintenance** is needed to avoid future leaks. The Pacific Northwest National Laboratory is currently using ML trained on inspection and operational data to build a prognostic model for prioritizing pipeline inspections based on novel signatures (NETL 2022b). AI/ML can help build detailed **pipeline performance models** and continuously improve their predictive analytics as additional system data is acquired and analyzed. Sophisticated AI tools may provide digital twins that simulate in detail entire pipelines (geometries, flows, materials, environments, etc.) to help **identify high-risk sections** and **define safe operating parameters**. Decision support models can then **issue alerts** when operating conditions approach those safety limits. To further **assist operators** in understanding the issues and making the right decisions, these AI models might provide **visualization tools** and tools to support prioritization.

Develop Automated Analysis Capabilities

Ultimately, AI may enable diagnostic and analytic capabilities that minimize the need for human decision making. These systems, which may interpret data to **detect microfractures** and assess pipeline integrity at the microscopic level, may support automated systems that **maintain pipeline operations within safe parameters** and **ensure operations efficiency** without risk of human error. Such developments underscore the need to fully understand what the AI models are doing and why. Models may become trusted through advancements in explainable AI (XAI) and by increasing model transparency and traceability, including layers of probabilistic or Bayesian statistics, and involving subject matter experts in the validation process (NARUC 2020).

Secure Underground Hydrogen Storage (UHS)

Hydrogen with carbon management is expected to play an important role in the transition to a clean energy economy. The 2022 draft *DOE National Clean Hydrogen Strategy and Roadmap* estimates that annual U.S. clean hydrogen demand will be at 10 million metric tonnes (MMT) by 2030, 20 MMT by 2040, and 50 MMT by 2050. (DOE 2022). In addition to improving H_2 production processes, system efficiencies, economics, and end uses, researchers are exploring options to securely store and efficiently retrieve large volumes of hydrogen from underground sites. Underground formations could offer the large storage volumes urgently needed to balance the inter-seasonal supply and demand differences confronting some energy sources and meet the demands of hard-to-decarbonize industrial processes (e.g., steelmaking, cement, chemicals refining) and maritime shipping.[4]

> "…Hydrogen's indirect warming potency per unit mass is around 200 times that of carbon dioxide and larger than that of methane (Forster et al., 2021). However, like methane, hydrogen's warming effects are potent but short-lived. Some of hydrogen's effects are shorter-lived than methane's—occurring within a decade after emission – but its impacts on methane can affect the climate for roughly an additional decade (Warwick et al 2022)."
>
> I. Ocko and S.P. Hamburg, *Atmospheric Chemistry and Physics,* 22, 9349-68 (Ocko and Hamburg 2022)

4 Deploying hydrogen in hubs focused on these end uses will limit the need for transmission and distribution systems and the potential for leaks from such systems (Koch 2022).

Natural gas has been stored in depleted oil and gas fields, saline aquifers, and salt caverns for decades, so the subsurface seems a plausible option for low-cost, high-volume H_2 storage. A recent study by NETL, PNL, and Lawrence Livermore National Laboratory (under the DOE/FECM Subsurface Hydrogen Assessment, Storage, and Technology Acceleration [SHASTA] Project) estimates that more than 70% of existing U.S. underground gas storage facilities might viably store hydrogen-methane blends (up to 20% H_2 by volume).[5] This storage capacity would provide about 24% of the projected high H_2 demand in 2050 or about 44% of the projected low H_2 demand in 2050—suggesting that use of depleted hydrocarbon reservoirs might reduce the need for new H_2 storage facilities (Lackey 2023). In comparison to natural gas, however, the biogeochemical properties of H_2 in underground storage make it more likely to engage in chemical, biological, and microbial reactions. In addition, the low viscosity and high mobility of H_2 can lead to hydrodynamic behavior like fingering and gravity segregation (Kanaani 2022), which may interfere with H_2 recovery/withdrawal processes.

Formations for UHS: Opportunities and Challenges

Salt caverns: Most favorable conditions for rapid storage and delivery rates, but costs are high, capacity constrained, and nationwide distribution limited.

Depleted hydrocarbon reservoirs: Lowest cost option with well-established flow and seal properties but may have hydrocarbon contamination issues and potential leakage risks due to existing wells.

Saline aquifers: Highest potential capacity but have uncertain reservoir and seal properties.

Hard Rock Caverns and Mines: For regions with no conventional options, caverns may be excavated in metamorphic or igneous rock and completed as unlined or lined (plastic, steel, or cementitious grout) cavities. Water curtains or refrigeration may address issues with pressure and permeability.

Coal Mines: Despite favorable capacities and locations, use of abandoned coal mines for UHS has been limited; two projects were tried and decommissioned.

(SHASTA 2022)

To date, commercial field experience with subsurface H_2 storage is scarce and widely limited to salt caverns (SHASTA 2022), so all options and sites will require careful characterization and monitoring to make sure that the injected hydrogen will not escape containment, become contaminated, react with minerals, be eaten by microbes, or migrate to regions from which it cannot be retrieved. The small, lightweight H_2 molecules find their way into microscopic cracks and pores and interact with minerals and microbial communities throughout the subsurface, potentially leading to hydrogen losses (Gregory 2019). In addition, scientists need a better overall understanding of the likely impacts of hydrogen injection on reservoirs, leakage risks, and flow behaviors (hydrogen and blended mixtures), which may affect both storage capacity and deliverability. Moreover, hydrogen's low volumetric energy density can be affected by the type and amount of cushion gas (often methane) used to maintain sufficient pressure in the cavern to facilitate injectivity and production.

AI can help characterize potential underground sites for H_2 storage and cycling and to predict and prevent leaks through accurate modeling and monitoring to ensure reliable containment and safe and efficient operation.

> "Hydrogen atoms when diffused into certain metallic lattices may accumulate within and at the tip of an existing crack thereby accelerating its growth. Material failure may happen much earlier in the presence of hydrogen than for other gases under the same conditions. This process is a complicated interaction which depends on the type of crystal lattice, microstructure of the material, gas pressure, condition of the metallic surface, and stress in the material. This makes it **difficult to qualify a metallic material as principally suitable or unsuitable for hydrogen use** as it depends on the details of the application."
>
> Thomas Hubert et al, CRC Press (Hubert 2016)

Explore Underground H_2 Storage Options

Hundreds of potential underground storage sites will need to be evaluated to find sufficient secure hydrogen storage for the planned clean energy economy. To assist in this massive screening process, AI could help define the acceptable range of parameters that a candidate site should meet. For example, only those sites that meet the established minimum and maximum acceptable levels would be considered for further study.

---

[5] Existing underground gas storage sites can hold about 327 TW-h (9.8 million metric tons) of pure hydrogen, but the transition from natural gas to pure hydrogen storage would reduce the total energy stored in existing facilities by ~75% (Lackey 2023).

Since depleted natural gas fields represent a promising option for H_2 storage, AI could help **characterize and assess today's subsurface natural gas storage sites** to determine the feasibility of types of formations or specific sites for conversion to H_2 storage. To better understand predictive factors, AI could potentially uncover patterns in the available data on a wide range of existing subsurface natural gas storage sites (including volume, permeability, porosity [in millidarcys], long-term caprock integrity, injectivity, seismic activity risk, cushion gas levels, well design, production rates, management issues, etc.). Convincing private companies to share their existing data is not a role for AI, but partnership and policy incentives might effectively assist planetwide progress. AI could assist in the recovery of data from historical or nondigital sources (geologic data on existing maps and from legacy records) using OCR or NLP.

Existing subsurface models for natural gas or carbon dioxide (CO_2) storage may similarly provide a useful starting point for modeling underground H_2 storage. AI **transfer learning** techniques (reuse of a pre-trained model on a new problem) as well as synthetic data generation could help train models and facilitate this adaptation. Once developed, AI models could be used to **explore what-if scenarios.** Virtual learning from high-fidelity simulations could help to identify the best alternative future pathways in the event of policy or budget changes, shifts in public attitude, or impacts on local or national infrastructure. Alternatively, simulations might inform choices among potential development pathways (e.g., if a model confirms the suitability of a depleted methane reservoir, it would be considered for H_2 storage; if the model deems the reservoir unsuitable, consideration may shift to a salt cavern).

The deliverability of an underground H_2 storage system depends on several fundamental factors:

1. The H_2 energy content per volume of rock occupied by the H_2/CH_4 working gas
2. Sweep efficiency, which is the percentage of the storage zone occupied by the H_2/CH_4 working gas
3. Production rate during the withdrawal cycle
4. Injection rate during the injection cycle
5. Degradation of injectivity and productivity by microbial and geochemical mechanisms
6. Asset loss, caused by stranding, microbial conversion of H_2 to less-valuable forms of energy, and leakage of the H_2/CH_4 working gas from the storage formation.

(SHASTA 2022)

Predict and Prevent H_2 Leaks from Subsurface Storage

Vastly expanding the use of hydrogen will help achieve the national goal of net-zero carbon emissions by 2050 *only* if hydrogen (and methane) leaks are minimized (and kept below a threshold level) throughout the supply chain. To address this and other challenges, DOE launched an $7 billion program to create six to ten regional hydrogen hubs (H2Hubs) across the country (DOE/OCED 2022). Each hub will demonstrate a tight network of hydrogen producers, potential consumers, and connective infrastructure. The opportunity elicited a large initial response, and full proposals are due in April 2023. The development of secure, large-scale hydrogen storage and recovery capabilities are critical to the overall success of this historic investment.

The H2Hubs will be closely monitored and are expected to generate large volumes of useful data. AI can benefit from **insights and knowledge gained from the H2Hubs** to enhance predictive models, sensors, and materials—but robust tools will be needed earlier to design secure storage for these Hubs. For this reason, AI can be used now to **leverage O&G experience to detect leaks.** AI can take available data on the geology, construction, climate, and other conditions affecting O&G storage facilities and adapt it to H_2 storage to help predict and avoid material corrosion at the well heads and optimize infrastructure maintenance.

The goal is to ensure no emissions or H_2 losses from the storage facilities during injection, storage, or recovery and transport. The next-best strategy is immediate identification of any leaks followed by rapid plugging. To facilitate detection, it may be worth investigating the **addition of odorants** to the stored H_2. AI may help screen potential options to identify an effective chemical odorant that would work well with the tiny H_2 molecule.

A related approach is to collect and analyze multi-dimensional, multi-modal data to **detect chemistry changes as indirect indicators** of a leak. For example, after H_2 is injected into subsurface storage, permanent, *in situ* sensors may detect shifts in near-surface geological chemistry that would predict or identify hydrogen leakage. *Existing* electro-chemical sensors can measure subsurface and near-surface changes in geological chemistry to a degree, but continuous *in situ* monitoring of subsurface chemistry is rare, and the sensors, which are designed for use along natural gas pipelines, would need to be adapted to detect hydrogen impacts. One role for AI could be to identify the best sensing or signal pathways (chemical, physical, etc.) and statistical approach (e.g., Monte Carlo simulation) to properly align the combinations of attributes that reliably predict or provide early detection of an incipient hydrogen leak.

To determine whether injected H_2 is being acted upon by microbes within a reservoir, AI could help calibrate sensors to detect leading secondary indicators in the form of resulting changes in the reservoir biochemistry. Depending on the specific biological reaction and byproducts, AI might calibrate a sensor to detect specific byproduct molecules. Better understanding of the likelihood, timing, pace, and scale of detrimental microbial action within reservoirs would inform decisions regarding the need for continuous down-hole sampling versus periodic use of logging scopes at the surface to discover harmful microbial action. The goal is to predict and prevent or mitigate leaks before they happen.

As noted earlier, AI can assist in the development of **improved sensors and the interpretation of sensor data** to detect and mitigate or predict and prevent leaks across the natural gas and hydrogen supply chains. Pipelines, compressors, and storage facilities for natural gas are expected to accommodate increasing levels of CO_2 and H_2, and sensors must adapt to the novel challenges of higher blends (multi-fluid and multi-phase flows)—though H_2 levels above 10% may lead to problems with materials, seals, metering, separations, etc. (Hubert 2016). AI can assist in figuring out the most important types of data to collect, the best means (including novel sensor technology) and frequency of collection, optimal sensor placement, new sensor materials, effective edge processing to streamline data flow, and autonomous analysis for robust decision support.

Existing sensors range in sophistication from the simple down-hole pressure and temperature gauges in use for decades by the natural gas industry to LIDAR and wireless surface acoustic wave (SAW) sensors (see Table 1). A new generation of smart, ubiquitous, real-time sensors is on the horizon as AI tools expedite progress in understanding, design, and advanced analysis.

Table 1. Existing representative H_2 sensors compared to emerging sensor technologies (Hubert 2016)

Sensor	Temporal	Spatial	Advantages	Disadvantages	TRL
Catalytic Pellistors	Real-time	Point sensor	Most common (33%), commercial, mature, robust	Not H_2 selective. Require O_2 to operate correctly. Heated coil.	9
Electrochemical Sensors	Real-time	Point sensor	29% market. Linear, ppm sensitivity, <30s response time	Require electrolytes. Cross-sensitivity to CO. Aging.	9
Thermal conductivity sensors	Real-time	Point sensor	16% market. No need of O_2. Stability, fast response	Nonspecific. Cross-sensitivity.	9
Resistive sensors	Real-time	Point sensor	13% market. Small size, 10s response time.	Humidity and T effect. Cross-sensitivity	9
Work function sensors	Real-time	Point sensor	2% market. Small size. High selectivity.	Drift. Hysteresis.	6-9
Optical schlieren imaging. Shadowgraph	Real-time	Standoff sensor	Stand-off, wide area monitoring	Limited in beam direction, not H_2 specific. Interferences.	6-8
Raman Lidar	Real-time	Standoff sensor	Remote, wide area monitoring, 10-50 m distance	High-intensity laser safety. Limited to field of view.	6-8
Acoustic leak detection	Real-time	Standoff sensor	Wide area monitoring, >10 m range, millisecond response	Not specific to H_2. Not quantitative	9
Optrode	Real-time	Point Sensor	No source of ignition in explosive atmosphere.	Drift due to aging and poisoning by SO_2, H_2S	6-8
Distributed Optical Fiber Sensors	Real-time	Distributed sensor	Distributed sensing, long distance, multi-parameter, Non-electrical, high sensitivity, fast response.	Cost of interrogation instrument.	5-8
Passive wireless SAW sensors	Real-time	Point sensors	Passive, Wireless capability, Low cost, High sensitivity.	Interference from humidity and T	5-6

Operators of subsurface H_2 storage facilities should harness smart infrastructure to prioritize remedial action. Systems can take advantage of AI, edge computing, and wireless communications to remotely analyze data and flag anomalies for immediate attention. In the future, widespread deployment of advanced, multi-parameter sensors equipped for distributed analysis, network communications, and energy scavenging should be able to detect and locate evolving biochemical conditions in the subsurface to alert operators and avert developing problems.

Crosscut Issues

Efforts to prevent methane leaks across the O&G infrastructure face daunting challenges, particularly as H_2 is mixed with natural gas at increasing levels in pipelines and storage facilities—and the need for dedicated H_2 delivery and storage rises. AI offers the capability to expedite solutions on multiple fronts, particularly in the design of novel materials and robust cybersecurity.

Design Materials

As mentioned above in the sections on pipelines and underground H_2 storage, materials for use with natural gas and natural gas/hydrogen blends present a growing challenge for mitigating or eliminating methane emissions. The mature natural gas industry is adopting increasingly sophisticated materials and sensors to inspect, improve, and assess the soundness of its critical infrastructure; however, plans to increase the levels of hydrogen mixed with natural gas and new methane regulations significantly elevate the challenge.

> "There is insufficient research on how to prevent and mitigate hydrogen leakage. Moreover, the commercial products that currently exist for this purpose do not meet the requirements of device level, high sensitivity, and distributed small hydrogen leakage source detections."
>
> Zhiyuan Fan et al, Center for Global Energy Policy (Fan 2022)

To mitigate methane emissions in the decades ahead, novel materials are needed for several key functions, such as:

- Securely containing large volumes of hydrogen under pressure for months (seasonal subsurface storage facilities), despite its ability to penetrate microscopic cracks and metallic lattices (pipes, compressors, well heads, liners, and cement casings).
- Enabling highly sensitive, low-energy sensors that cover extended areas and distances to continuously detect and pinpoint the locations of even small leaks (e.g., MOFs) at affordable cost
- Enabling sophisticated sensors (e.g., based on transition metals, etc.) to continuously measure indicators of hidden degradation processes within the critical supporting infrastructure (e.g., pipes, compressors, well heads), pinpointing locations and dimensions.
- Protecting sensors from extreme (high temperature, high-pressure) environments (e.g., natural gas/H_2 mixtures above 10%, 20%, and 50% H_2) to ensure their long-term accuracy and service.

Researchers have developed innovative material technologies for the existing natural gas infrastructure, including those using fiber optics (Shih 2022), ultrasonic guided wave (SwRI 2022), and piezoelectric active sensing and convolutional neural network (Yang 2023) as examples. Sensor innovations in other fields (e.g., micro electrochemical) can be monitored for potential adaptation for methane mitigation. Using AI and advanced computational analysis, researchers can **screen properties of novel materials** for potential selection and application in natural gas/H_2 storage and delivery.

Cybersecurity

Cybersecurity has become an omnipresent issue in every sector of the economy as information and operational technologies become increasingly integrated. Equipment providers serving the O&G industry recognize the risks and are developing layered defenses. FECM works with industry to review, test, and provide feedback on cybersecurity innovations and refers emerging concerns to experts in the DOE Office of Cybersecurity, Energy Security, and Emergency Response (CESER), which addresses emerging threats to energy infrastructure security, including supervisory control and data acquisition (SCADA) systems.

AI systems are poised to transform the O&G industry and continuously improve as they receive and process large quantities of high-quality data from sensors. AI outputs, however, are only as reliable as the data input. For this reason, developer should look to **validate collected data using blockchain technology**, which could provide increased security for SCADA systems by acting as an instrument for authentication, authorization, and non-repudiation of critical data.

Sources

Black 2022. Simon Black et al. "Methane Emissions Must Fall for World to Hit Temperature Targets," International Monetary Fund (IMF) Blog, November 2, 2022. www.imf.org/en/Blogs/Articles/2022/11/02/methane-emissions-must-fall-for-world-to-hit-temperature-targets

Boutot 2022. Boutot, Jade, et al. "Documented Orphaned Oil and Gas Wells Across the United States," *Environ. Sci. Technol.* 2022, 56, 20, 14228–14236, Sept. 26, 2022. American Chemical Society. https://pubs.acs.org/doi/full/10.1021/acs.est.2c03268

Bussewitz 2023. Bussewitz, Cathy, "Difficulty measuring methane slows plan to slash emissions," *AP News,* January 31, 2023. https://apnews.com/article/drones-business-climate-and-environment-0a1ab9be3427818cfe5f33521b9b05c2

CORDIS 2018. Community Research and Development Information Service (CORDIS), European Commission, "Oil and gas pipeline flow powers sensors in extreme conditions," Perpetual Sensing in Harsh Environments: Self-powered sensors for the Oil Gas industry. https://cordis.europa.eu/article/id/252263-oil-and-gas-pipeline-flow-powers-sensors-in-extreme-conditions

DOE 2021. U.S. Department of Energy, "DOE Awards $35 Million for Technologies to Reduce Methane Emissions," December 2, 2021. www.energy.gov/articles/doe-awards-35-million-technologies-reduce-methane-emissions

DOE 2022. U.S. Department of Energy, DOE National Clean Hydrogen Strategy and Roadmap (Draft), September 2022. www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf

DOE/EERE 2023. HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines, Hydrogen and Fuel Cell Technologies Office. www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines

DOE/FECM 2022. U.S. Department of Energy, Fossil Energy and Carbon Management, *Strategic Vision: The Role of FECM in Achieving Net-Zero Greenhouse Gas Emissions*, 2022. www.energy.gov/sites/default/files/2022-04/2022-Strategic-Vision-The-Role-of-Fossil-Energy-and-Carbon-Management-in-Achieving-Net-Zero-Greenhouse-Gas-Emissions_Updated-4.28.22.pdf

DOE/OCED 2022. U.S. Department of Energy, Office of Clean Energy Demonstrations, "Funding Notice: Regional Clean Hydrogen Hubs," September 22, 2022. Accessed April 7, 2023: www.energy.gov/oced/funding-notice-regional-clean-hydrogen-hubs

Dopffel 2021. Nicole Dopffel, Stefan Jansen, and Jan Gerritse, "Microbial side effects of underground hydrogen storage – Knowledge gaps, risks and opportunities for successful implementation, *International Journal of Hydrogen Energy*, Volume 46, Issue 12, 2021, pp 8594-8606, ISSN 0360-3199. https://doi.org/10.1016/j.ijhydene.2020.12.058

EIA 2022. U.S. Energy Information Administration, Natural Gas Pipelines, 2022. www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php

EPA 2021. Environmental Protection Agency (EPA), Proposal To Reduce Climate- and Health-Harming Pollution from the Oil and Natural Gas Industry: Overview, fact sheet, 2021. www.epa.gov/system/files/documents/2021-11/2021-oil-and-gas-proposal.-overview-fact-sheet.pdf

EPA 2022. U.S. EPA, Estimates of Methane Emissions by Segment in the United States, from US EPA DE-FOA-0002616, August 2022, p. 9. www.epa.gov/natural-gas-star-program/estimates-methane-emissions-segment-united-states

EPA.gov U.S. EPA, Overview of Greenhouse Gases webpage. www.epa.gov/ghgemissions/overview-greenhouse-gases

Fan 2022. Zhiyuan Fan, Hadia Sheerazi, Amar Bhardwaj, Anne-Sophie Corbeau, Kathryn Longobardi, Adalberto Castaneda, Ann-Kathrin Merz, Dr. Caleb Woodall, Mahak Agrawal, Sebastian Orozco-Sanchez, Dr. Julio Friedman. "Hydrogen Leakage: A Potential Risk for the Hydrogen Economy," Columbia, SIPA, Center on Global Energy Policy, July 2022. www.energypolicy.columbia.edu/wp-content/uploads/2022/07/HydrogenLeakageRegulations_CGEP_Commentary_063022.pdf

Forster 2021. Forster, P. et al, The Earth's energy budget, climate feedbacks, and climate sensitivity, in: *Climate Change 2021: The Physical Science Basis*, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on

Climate Change, edited by Masson-Delmotte et al, Cambridge University Press, Chapter 7, pp 923–1054, July 11, 2021. Accessed March 23, 2023: www.ipcc.ch/report/ar6/wg1/

FOSA 2021. Fiber Optic Sensing Association, Retrofitting Existing Pipelines for Fiber Optic Monitoring webinar (video), February 18, 2021. www.youtube.com/watch?v=TKtWkZMkscA

GAO 2022. Government Accountability Office, *Oil and Gas: Federal Actions Needed to Address Methane Emissions from Oil and Gas Development*, April 2022. www.gao.gov/assets/gao-22-104759.pdf

Geman 2022. Ben Geman, "Study: Methane leaks from U.S. oil-and-gas region worse than estimates," *AXIOS, Energy & Environment*, May 25, 2022. www.axios.com/2022/03/25/study-methane-leaks-oil-gas-worse-estimates

Global 2023. Global, Information Systems, "Pipeline Material Identification (or Verification)," website accessed March 17, 2023. www.globalinformationsystems.com/pipeline-material-identification

Gopika, 2022. Gopika G., Ph.D. "Transition Metal Dichalcogenides in Sensing Devices," AZoNano, April 22, 2022, www.azonano.com/article.aspx?ArticleID=6096 +

Gregory 2019. Gregory SP, Barnett MJ, Field LP, Milodowski AE. "Subsurface Microbial Hydrogen Cycling: Natural Occurrence and Implications for Industry," *Microorganisms*. 2019 Feb 15;7(2):53. doi: 10.3390/ microorganisms 7020053. PMID: 30769950; PMCID: PMC6407114. www.ncbi.nlm.nih.gov/pmc/articles/PMC6407114/

Granholm 2022. Energy Secretary Jennifer M. Granholm, quoted in "DOE Announces $32 Million to Reduce Methane Emissions from Oil and Gas Sector," August 5, 2022. www.energy.gov/articles/doe-announces-32-million-reduce-methane-emissions-oil-and-gas-sector

Groom 2020. Nicholas Groom "Special Report: Millions of abandoned oil wells are leaking methane, a climate menace," *Reuters*, June 17, 2020. www.reuters.com/article/us-usa-drilling-abandoned-specialreport/special-report-millions-of-abandoned-oil-wells-are-leaking-methane-a-climate-menace-idUSKBN23N1NL

Hongye 2021. Hongye Yuan et al. "Metal-Organic Framework Based Gas Sensors," Advanced Science, Wiley Online Library, December 22, 2021. https://onlinelibrary.wiley.com/doi/full/10.1002/advs.202104374

Hubert 2016. Thomas Hübert, Lois Boon-Brett, William Buttner, "Sensors for Safety and Process Control in Hydrogen Technologies," Boca Raton, FL: CRC Press, 2016. www.routledge.com/Sensors-for-Safety-and-Process-Control-in-Hydrogen-Technologies/Hubert-Boon-Brett-Buttner/p/book/9781138894341

IEA 2022. International Energy Agency, *Global Methane Tracker 2022.* www.iea.org/reports/global-methane-tracker-2022/overview

IEA 2023. International Energy Agency, *Global Methane Tracker 2023*, February 2023. www.iea.org/reports/global-methane-tracker-2023/strategies-to-reduce-emissions-from-oil-and-gas-operations

IOGCC 2021. Interstate Oil and Gas Compact Commission, *Idle and Orphan Oil and Gas Wells: State and Provincial Regulatory Strategies,* December 2021. https://iogcc.ok.gov/sites/g/files/gmc836/f/iogcc_idle_and_orphan_wells_2021_final_web.pdf

Kanaani 2022. Mahdi Kanaani, Behnam Sedaee, Mojtaba Asadian-Pakfar, "Role of Cushion Gas on Underground Hydrogen Storage in Depleted Oil Reservoirs," Journal of Energy Storage, Volume 45, 2022, 103783, ISSN 2352-152X, www.sciencedirect.com/science/article/pii/S2352152X21014560

Koch 2022. Thomas Koch et al, "Hydrogen Reality Check #1: Hydrogen Is Not a Significant Warming Risk," Rocky Mountain Institute, May 9, 2022. https://rmi.org/hydrogen-reality-check-1-hydrogen-is-not-a-significant-warming-risk/

Lackey 2023. Greg Lackey, Gerad M. Freeman, Thomas A. Buscheck, Foad Haeri, Joshua A. White, Nicolas Huerta, Angela Goodman, "Characterizing Hydrogen Storage Potential in U.S. Underground Gas Storage Facilities," *Geophysical Research Letters*, Advancing Earth and Space Science, February 10, 2023. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022GL101420

Leber, Rebecca, "It's time to freak out about methane emissions," Vox, November 3, 2021. www.vox.com/22613532/climate-change-methane-emissions

Lindauer 2022. Alicia Lindauer, U.S. Geological Survey (USGS), DOI Orphaned Well Data Collection and Integration, briefing (slides 24 -37) presented April 5, 2022, at the Undocumented Orphaned Wells Workshop. www.energy.gov/sites/default/files/2022-04/DOE%20Undocumented%20Orphan%20Wells%20Workshop%20April%205th%20Presentations.pdf

Mia 2015. Mia, "Data Empowers Pipelines," North American Energy Pipelines, June 8, 2015. www.napipelines.com/data-empowers-pipelines/

Mohamedein 2022. Mohamed Adel Mohamedein, "The Ultimate Guide to Pipeline Pigs," *Corrosionpedia*, March 8, 2022. www.corrosionpedia.com/the-ultimate-guide-to-pipeline-pigs/2/7397

Myers 2022. Myers, Andrew, "Stanford-led study: Methane leaks are far worse than estimates, at least in New Mexico, but there's hope," *Stanford News*, March 24, 2022. https://news.stanford.edu/2022/03/24/methane-leaks-much-worse-estimates-fix-available/

NARUC 2020. National Association of Regulatory Utility Commissioners, Burman, Kimbrel, Pridemore, Thanos, and Zitelman, *Artificial Intelligence for Natural Gas Utilities: A Primer*, October 2020. https://pubs.naruc.org/pub/F74D4EC2-155D-0A36-310F-F5B22DC3E286

NASA 2022. National Aeronautical and Space Administration, "Methane 'Super-Emitters' Mapped by NASA's New Earth Space Mission," October 25, 2022. www.nasa.gov/feature/jpl/methane-super-emitters-mapped-by-nasa-s-new-earth-space-mission

NETL 2022. National Energy Technology Laboratory, "NETL's Natalie Pekney tackles energy research with an "all things connected" philosophy, September 26, 2022. https://netl.doe.gov/node/12090

NETL 2022a. National Energy Technology Laboratory, "NETL Team Traveling Appalachia To Address Abandoned Wells, September 12, 2022. https://netl.doe.gov/node/12043

NETL 2022b. Pacific Northwest National Laboratory project FWP-72954, Novel Signatures from Deployed Sensors for Natural Gas Transmission Pipelines, accessed March 17, 2023. https://netl.doe.gov/node/9865

NETL 2023. National Energy Technology Laboratory, Methane Emissions Mitigation webpage. Accessed March 10, 2023. https://netl.doe.gov/oil-gas/ngi/mitigation

NETL 2005. National Energy Technology Laboratory, Power Generation in NATURAL Gas Pipelines (FWP04FE12), Los Alamos National Laboratory, completed 2005. https://netl.doe.gov/node/2989

NOAA 2022. "Increase in atmospheric methane set another record during 2021," April 7, 2021. www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021

Ocko and Hamburg 2022. Ocko, I. B. and Hamburg, S. P.: Climate consequences of hydrogen emissions, Atmos. Chem. Phys., 22, 9349–9368, https://doi.org/10.5194/acp-22-9349-2022, 2022. https://acp.copernicus.org/articles/22/9349/2022/

PHMSA 2017. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, "Pipeline Materials," May 3, 2017. www.phmsa.dot.gov/technical-resources/pipeline/pipeline-materials

PHMSA 2022. Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation, "Phases of Pipeline Construction: An Overview," webpage, updated April 18, 2022. www.phmsa.dot.gov/pipeline/pipeline-construction/phases-pipeline-construction-overview

Princeton 2023. Princeton University, "Switching to Hydrogen Fuel Could Cause Long-Term Climate Consequences," *SciTechDaily*, April 2, 2023. https://scitechdaily.com/switching-to-hydrogen-fuel-could-cause-long-term-climate-consequences/

Raimi & Aldana 2018. Raimi, D., and Aldana, G. (2018, June 25). Understanding a New Study on Oil and Gas Methane Emissions. www.resources.org/common-resources/understanding-a-new-study-on-oil-and-gas-methane-emissions/

Ruth 2020. Ruth, Mark, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy. 2020. *The Technical and Economic Potential of the H2@Scale Concept within the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP- 6A20-77610. www.nrel.gov/docs/fy21osti/77610.pdf.

SHASTA 2022, NETL, PNL, and LLNL, SHASTA: Subsurface Hydrogen Assessment, Storage, and Technology Acceleration Project, *Subsurface Hydrogen and Natural Gas Storage: State of Knowledge and Research Recommendations Report*, DOE/NETL-2022/3236, April 2022. www.netl.doe.gov/projects/files/SubsurfaceHydrogenandNaturalGasStorageStateofKnowledgeandResearchRecommendationsReport_041122.pdf

Shih 2022. Joseph Shih, "The Growth of Fiber Optic Sensing in the Industry," New Equipment Digest, June 15, 2022. www.newequipment.com/learning-center/article/21244421/growth-of-fiber-optic-sensing-for-sensitive-pipeline-concrete-and-subsea-cable-applications-greene-tweed

Storrow 2020. Benjamin Storrow, “Methane Leaks Erase Some of the Climate Benefits of Natural Gas,” *Scientific American*, May 5, 2020. www.scientificamerican.com/article/methane-leaks-erase-some-of-the-climate-benefits-of-natural-gas

Strange 2022. Madison Strange et al. *Leak detection methods for natural gas gathering, transmission, and distribution pipelines*, Technical Report, Highwood Emissions Management, January 12, 2022. https://highwoodemissions.com/wp-content/uploads/2022/04/Highwood_Pipeline_Leak_Detection_2022.pdf

Svoboda 2011. Elizabeth Svoboda, “Pigging the Unpiggable: Robots Keep Gas Lines from Blowing Up,” *Popular Mechanics*, February 10, 2011. www.popsci.com/technology/article/2011-01/pig-robots-keep-gas-lines-blowing/

SwRI 2022. Southwest Research Institute, “SwRI improves corrosion-detecting technology that detects leaks in pipes before they occur: New generation of Magnetostrictive Transducer Collar is more accurate, flexible and efficient,” News release, October 25, 2022. www.eurekalert.org/news-releases/968972

UNEP 2021. UN Environment Programme, “Methane emissions are driving climate change. Here’s how to reduce them,” 29 August 2021. www.unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them

UNEP 2022. UN Environment Programme, “What’s the deal with methane?” 18 October 2022. www.unep.org/news-and-stories/video/whats-deal-methane#:~:text=Due%20to%20its%20structure%2C%20methane,warming%20to%201.5%C2%B0C.

Warwick 2022. Warwick, N., Griffiths, P., Keeble, J., Archibald, A., Pyle, J., and Shine, K.: Atmospheric implications of increased Hydrogen use, Department for Business, Energy and Industrial Strategy, 75 pp., April 8, 2022. Accessed March 23, 2023: www.gov.uk/government/publications/atmospheric-implications-of-increased-hydrogen-use

WH 2021. The White House, *U.S. Methane Emissions Reduction Plan*, November 2021. www.whitehouse.gov/wp-content/uploads/2022/11/US-Methane-Emissions-Reduction-Action-Plan-Update.pdf

WH 2022. The White House, *Delivering on the U.S. Methane Emissions Action Plan*, November 2022. www.whitehouse.gov/wp-content/uploads/2022/11/US-Methane-Emissions-Reduction-Action-Plan-Update.pdf

Yang 2023. Dan Yang, Xinyi Zhang, Ti Zhou, Tao Wang, and Jiahui Li, “A Novel Pipeline Corrosion Monitoring Method Based on Piezoelectric Active Sensing and CNN,” *Sensors* 2023, 23(2), 855; January 11, 2023. www.mdpi.com/1424-8220/23/2/855

Yu 2022. Jevan Yu et al. “Methane Emissions from Natural Gas Gathering Pipelines in the Permian Basin,” Energy and Climate, American Chemical Society Publications, October 4, 2022. https://pubs.acs.org/doi/10.1021/acs.estlett.2c00380 www.mdpi.com/1424-8220/23/2/855

Sources for Undocumented/Orphaned Wells (list and annotations provided by NETL)

Background*:* Undocumented Orphaned Wells Workshop, April 5, 2022, PPT and PDF

Dilmore 2015. Robert Dilmore et al, “Spatial and Temporal Characteristics of Historical Oil and Gas Wells in Pennsylvania: Implications for New Shale Gas Resources,” Environ. Sci. Technol. 2015, 49, 20, 12015–12023, August 12, 2015. https://doi.org/10.1021/acs.est.5b00820 [The analysis uses a conventional data science approach, but it and most of the other resources shown could be used to drive supervised AI/ML.]

Glosser, D., Rose, K., and J. R. Bauer, **2016**. “Spatio-Temporal Analysis to Constrain Uncertainty in Wellbore Datasets: An Adaptable Analytical Approach in Support of Science-Based Decision Making.” *Journal of Sustainable Energy Engineering*, 3(4): 299-317*.* [Builds on work by Dilmore; adds GIS and geostatistical elements in WV use case. Opportunities here are to look at spatio-temporal analyses, not for individual states but for the 24 or so states with significant drilling records and forecast areas with likely undocumented orphaned wells (UOW) and use these more conventional big data, data science-based studies to integrate AI/ML methods to derive insights and forecast trends from a multi-variate perspective.]

Bauer, J., Justman, D., Mark-Moser, M., Romeo, L., Creason, C.G., and Rose, K., “Exploring beneath the basemap,” *in* Wright, D.J. and Harder, C. (Ed.), *GIS for Science: Applying Mapping and Spatial Analytics: Volume 2*, Redlands, CA: Esri Press, pp. 51-67, 2020, plus supplemental material. [See chapter on page 54 of the book (pp 9-12 of the pdf file). Includes graphical analyses of well construction history insights. The opportunity is for AI ML to seek out information to enrich this type of big data framework and layer in details about well construction and mine information from patent filings and other innovations. It may be unnecessary to go to the well construction files for *each* well, but if we understand and use NLP and image AI tools to assess the evolution of well materials and construction elements (when casing or cement were initially used, impacts of these changed, etc.), that might enrich insights for that early well history component and then integrate with multi-modal contextual geologic data to predict integrity, identify patterns, and forecast well material failures.

NETL experience in developing the open-source, Global Oil and Gas Infrastructure (GOGI) database highlights the opportunity to use this work as a template for supervised ML to automate development of a well and infrastructure database with continuous updating.

Rose, K.; Bauer, J.; Baker, V.; Bean, A.; DiGiulio, J.; Jones, K.; Justman, D.; Miller, R. M.; Romeo, L.; Sabbatino, M.; Tong, A. Development of an Open Global Oil and Gas Infrastructure Inventory and Geodatabase; NETL-TRS-6-2018; *NETL Technical Report Series*; U.S. Department of Energy, National Energy Technology Laboratory: Albany, OR, 2018; p 594; DOI: 10.18141/1427573. [Use the link to access the report and the higher-res appendices.]

Sabbatino, M., Romeo, L., Baker, V., Bauer, J., Barkhurst, A., Bean, A., DiGiulio, J., Jones, K., Jones, T.J., Justman, D., Miller III, R., Rose, K., and Tong., A., Global Oil & Gas Infrastructure Features Database Geocube Collection, 2019-03-25, https://edx.netl.doe.gov/dataset/global-oil-gas-infrastructure-features-database-geocube-collection, DOI: 10.18141/1502839. [Web mapping application that enables exploration of the GOGI database; also see link to download the database via the report and tool sites.]

The following resources tie to topics raised above. Dyer et al is not wells specific, but the model is being adapted for offshore wells in the FECM Advanced Offshore Research R&D FWP and may suggest ideas for how AI/ML models could inform UOW challenges and needs. The same is true for the Morkner publication about big data aggregation for a Carbon Storage use case.

Baker, D.V., Rose, K., Bauer, J., and Rager, D., *2016*, Computational Advances and Data Analytics to Reduce Subsurface Uncertainty https://www.onepetro.org/conference-paper/ARMA-2016-493, *ARMA 16-493*, June 26-29, 2016, p16.

Baker, D.V. et al, 2022, Carbon Management Program Review meeting, SmartSearch, A scalable data search and aggregation in the Cloud for CCS and beyond, https://netl.doe.gov/sites/default/files/netl-file/22CM_CTS17_Baker.pdf

Dyer, A.S., Zaengle, D., Nelson, J.R., Duran, R., Wenzlick, M., Wingo, P.C., Bauer, J.R., Rose, K., and Romeo, L. (2022). Applied machine learning model comparison: Predicting offshore platform integrity with gradient boosting algorithms and neural networks, *Marine Structures*, Volume 83, 103152. https://doi.org/10.1016/j.marstruc.2021.103152.

Morkner, P., Bauer, J., Creason, C., Sabbatino, M., Wingo, P., Greenburg, R., Walker, S., Yeates, D., Rose, K. 2022. Distilling Data to Drive Carbon Storage Insights. *Computers & Geosciences*. https://doi.org/10.1016/j.cageo.2021.104945

Rose, K., 2016, Signatures in the Subsurface – Big & Small Data Approaches for the Spatio-Temporal Analysis of Geologic Properties & Uncertainty Reduction, 162 pgs, http://hdl.handle.net/1957/59459

Scarpelli, T. R., Jacob, D. J., Maasakkers, J. D., Sulprizio, M. P., Sheng, J.-X., Rose, K., Romeo, L., Worden, J. R., and Janssens-Maenhout, G. 2020. A global gridded (0.1° × 0.1°) inventory of methane emissions from oil, gas, and coal exploitation based on national reports to the United Nations Framework Convention on Climate Change, Earth Syst. Sci. Data, 12, 563–575, https://doi.org/10.5194/essd-12-563-2020, 2020.

Wenzlick, M., Mamun, O., Devanathan, R., Rose, K., Hawk, J. "Assessment of outliers in alloy datasets using unsupervised techniques." *JOM*, 2022. https://doi.org/10.1007/s11837-022-05204-4