U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0002599
on
Technology Advancements for Subsurface Exploration for Renewable Energy Resources or Carbon Storage

Introduction

The purpose of this RFI is to solicit input for a potential future ARPA-E research program focused on technologies that enable high-resolution, wide-area subsurface mapping in order to identify opportunities for renewable energy technologies and the future low-carbon economy. Examples where advances in subsurface imaging will be critical include, but are not limited to, locating reservoirs for carbon capture and storage (CCS), identifying new geothermal sites, mapping natural accumulations of energy-relevant minerals, and assessing potential resources of geologic hydrogen. The goal is to better understand how subsurface imaging technologies today may need to expand, adapt, or improve beyond technologies which have been optimized for oil and gas exploration. ARPA-E is seeking information at this time regarding the state of the art in subsurface imaging technologies and transformative and implementable technologies that could:

1. Reduce frontier exploration costs for renewable energy or carbon storage projects by an order of magnitude or more, leveraging advancements in subsurface imaging, data collection, and data processing. For new renewable technologies or CCS projects, identifying potential geologic sites with the requisite properties requires honing in on sites from a much larger region, often in areas that have not been traditionally explored by oil and gas interests and where there is little prior high-quality imaging data. Isolating regions of interest could mean developing new, cost-effective wide-area subsurface exploration technologies, using a combination of imaging techniques paired with multi-physics models, using data processing or novel geostatistical methods to upgrade or augment existing datasets, and/or developing machine learning algorithms which can fill in data gaps.
2. Advance data processing to accommodate larger amounts of data and reduce processing time by orders of magnitude for wide-area and/or nationwide subsurface imaging surveys.
3. Dramatically improve project success rates. Successful technologies would result in outcomes such as reduced incidence of dry wells in geothermal energy projects or identification of new energy-relevant mineral deposits. These outcomes can be facilitated by acquiring higher-quality and/or more comprehensive data in order to discern sites with high probability factors.
4. Monitor dynamic changes in the subsurface over time (4D mapping) with more sensitive surveys techniques, more comprehensive models, and/or algorithms. ARPA-E expects that subsurface changes of interest to renewable energy or CCS projects (e.g. changes in rock morphology, active water-rock chemical reactions, fluid migration, fracture network development, biological processes) may be different than those typically modelled for the oil and gas industry and that current models may need to be expanded to include these processes.
5. Reveal opportunities for interdisciplinary collaboration, combining the expertise of groups that traditionally do not interact, in order to gain a more comprehensive understanding of dynamic geologic processes.

Note that some approaches may accomplish several of the listed items above. For example, reducing frontier exploration costs could help de-risk new energy projects. Likewise, interdisciplinary collaboration could result in a paradigm shift that would introduce new technologies or methodologies for subsurface exploration.

Historical Geologic Survey Development

The history of the energy industry and the development of subsurface imaging techniques are closely intertwined. As early as the 1920s, techniques that enabled geologists and geophysicists to probe deeper into the earth's crust offered critical competitive advantages in a rapidly growing oil and gas industry[1]. Over the last century, seismic imaging benefitted from a flurry of activity in theoretical development beginning in the 1950s and by the age of digitization and computers starting as early as 1960. Much of the early innovation in seismic imaging was narrow in scope, driven by oil and gas exploration needs. However, between 1950s-1970s seismic reflection data from basement rocks in the continental crust were reported, suggesting that its utility could be expanded to more general characterizations of geologic formations in the Earth's crust[2]. The earliest concerted effort to systematically explore the continental lithosphere of the United States was through the Consortium for Continental Reflection Profiling (COCORP)[3]. Between 1973-1992, over 11,000 km of seismic profiles at thirty sites in 28 states using an active source of frequency vibrations was collected and catalogued. More recent efforts to collect passive seismological data was conducted by the USArray program that took place over a total of 15 years, beginning in 2007[4]. Through the USArray program, a dense network of permanent and portable seismographs were placed across the continental United States and Alaska. These programs resulted in two publicly available seismic datasets with subsurface geological information of the US. It is important to note, however, that each dataset has its limitations in either total area coverage (COCORP) or resolution (USArray). To the best of ARPA-E's knowledge, there are no comprehensive publicly available seismic datasets which combine both high resolution and wide-area coverage. ARPA-E is interested in technologies that would enable the acquisition and compilation of high-resolution seismic information over the continental US; the availability of such data is expected to significantly impact future subsurface renewable energy exploration or CCS siting.

Though seismic imaging is more often and sometimes exclusively used in the context of oil and gas exploration, other survey techniques are available to yield additional information about the subsurface structure. Examples of these techniques include:

- Gravimetric techniques that measure subtle changes in the gravity field due to a change in the bulk rock density[5],
- Electrical surveys that measure changes in the subsurface resistivity as a function of depth or

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[1] Bednar, J. Bee. A Brief History of Seismic Migration. *Geophysics*. 70, **2005**, 3MJ-20MJ.

[2] Dix, C. H. Reflection Seismic Crustal Studies. *Geophysics*. **1965**, *30*, 1068-1084. Junger, A. Deep Basement Reflections in Big Horn County, Montana. *Geophysics*. **1951**, *16*, 499-505. Widess, M. and Taylor, G. L. Seismic Reflections from Layering within the Pre-Cambrian Basement Complex, Oklahoma. *Geophysics*. **1959**, *24*, 417-425. Narans, Jr., H. D.; Berg, Jr. J. W.; Cook, K. L. Sub-Basement Seismic Reflections in Northern Utah. *Journal of Geophysical Research*. **1961**, *66*, 599-603. Perkins, W. E. and Phinney, R. A. A Reflection Study of the Wind River Uplift, Wyoming. **1971**. from Heacock, G., ed., The structure and physical properties of the Earth's crust: Am. Geophys. Union Geophys. Mon. 14, p. 41 50.

[3] http://www.geo.cornell.edu/geology/cocorp/COCORP.html. (Accessed August 20, 2021).

[4] http://www.usarray.org/ (Accessed August 23, 2021).

[5] Nabighian, M. N., *et al*. Historical Development of the Gravity Method in Exploration. *Geophysics*, **2005**, *70*, 63-89.

position[6], and

- Electromagnetic/magnetotelluric (EM/MT) surveying techniques that detect changes in the subsurface electrical resistivity and magnetic fields in response to an external stimulus. Electromagnetic surveys use an active source in the form of a controlled electric field while magnetotelluric surveys are characterized as a passive technique that relies on the interaction of the subsurface rocks to Earth's constant magnetic field.

The examples listed above demonstrate the wide variety of technologies that enable researchers to probe the subsurface structure in search of potential resources. Furthermore, though not always done in practice, there is a clear advantage to combining multiple imaging techniques[7]. For example, combining EM/MT with seismic has achieved widespread adoption within the last 20 years in offshore oil and gas projects; changes in resistivity that are detected by EM/MT can differentiate between accumulations of water and hydrocarbon deposits in regions where seismic imaging indicates a potential reservoir. It is ARPA-E's understanding that combining multiple survey techniques for resource exploration is not frequently practiced in oil and gas development when seismic information is sufficient, but may be critical in resource assessment and site identification for future renewable energy and CCS projects. To some extent, this is already being done by several US government agencies who are undertaking wide-area EM/MT survey efforts to gather data over the continental US (MT and passive seismic mapping in USArray program[8]) and to identify promising geothermal energy sites (GeoDAWN[9]) or critical mineral deposits (Earth Mapping Resources Initiative[10]). ARPA-E is interested in technology developments that enhance these efforts and/or leverage datasets from multiple survey techniques to better characterize broad regions of the US that will inform renewable energy exploration and CCS site identification.

The rapid rise in digitalization and computing power transformed subsurface exploration, extending the capabilities of subsurface imaging data acquisition. Today, the imaging capabilities have been so augmented by digitalization that robust data processing capabilities are dwarfed by the rate of data being generated[11]. For example, within the last few years researchers have explored the potential of obtaining near-surface passive seismic information from existing and underutilized fiber optic cable ("dark fiber") networks[12]. This Distributed Acoustic Sensing (DAS) technique measures coherent optical time-domain reflectometry to detect vibrations along the length of an optical fiber; a single fiber acts as a multi-point sensor and is an efficient way to monitor subsurface conditions across extensive lengths or depths. There are tens of thousands of kilometers of dark fiber in the United States which could be used for passive seismic logging over wide areas and long periods of time, though will mean both an

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[6] Loke, M. H., *et al.* Recent Developments in the Direct-Current Geoelectrical Imaging Method. *Journal of Applied Geophysics*. **2013**, *95*, 135-156.

[7] Moorkamp, M. Integrating Electromagnetic Data with Other Geophysical Observations for Enhanced Imaging of the Earth: A Tutorial and Review. *Surv. Geophys.* **2017**, *38*, 935-962. Katterbauer, K., Arango, S., Sun, S., and Hoteit, I. Multi-Data Reservoir History Matching for Enhanced Reservoir Forecasting and Uncertainty Quantification. *Journal of Petroleum Science and Engineering.* **2015**, *128*, 160-176. Katterbauer, K., Hoteit, I., and Sun, S. EMSE: Synergizing EM and Seismic Data Attributes for Enhanced Forecasts of Reservoirs. *Journal of Petroleum Science and Engineering.* **2014**, *122*, 396-410.

[8] http://www.usarray.org/researchers/obs/magnetotelluric. (Accessed August 27, 2021).

[9] https://www.usgs.gov/media/images/geodawn-geoscience-data-acquisition-western-nevada. (Accessed August 27, 2021).

[10] https://www.usgs.gov/special-topic/earthmri. Accessed August 27, 2021.

[11] Newman, G. A. A Review of High-Performance Computational Strategies for Modeling and Imaging of Electromagnetic Induction Data. *Surv. Geophys.* **2014**, *35*, 85-100.

[12] Ajo-Franklin, J. B., *et al.* Distributed Acoustic Sensing Using Dark Fiber for Near-Surface Characterization and Broadband Seismic Event Detection. *Scientific Reports*. **2019**, *9*, 1328.

opportunity and challenge for data acquisition. In one study, over a 6600-meter-long section of dark fiber, up to 20 TB/day of data was generated in a single interrogator; over the first three months of the study, a total of 128 TB of raw data was collected. This is one example of the scale of data produced in wide-area subsurface mapping surveys. As a result of the proliferation of data today, it is estimated that approximately 40% of seismic data goes unused and, even with advances in computer technology and algorithm development, the time between data acquisition and project initiation in the field has not decreased significantly[13]. This problem is likely to be exacerbated in the future if the need for higher-resolution multi-dimensional survey maps grows, if datasets include multiple surveys (multi-physics simulations), or if changes in the subsurface structure over time and in response to external stimuli need to be monitored. Several potential solutions to this problem exist, including developing new joint and cooperative inversion techniques that combine several datasets (i.e. seismic and electromagnetic) in order to constrain certain parameters in the subsurface models[14], applying machine learning and artificial intelligence for data mining and faster, more automated data analysis[15], or incorporating novel geostatistical analyses into the workflow[16]. In some instances, more than one solution may be required. For instance, even with joint and cooperative inversion, it is still possible to obtain erroneous, biased, or multiple feasible solutions that all fit the observed data[17]. In this view, machine learning algorithms may be useful, though this is predicated on having access to high-quality datasets that can be used to train machine learning algorithms which is not always the case. ARPA-E has identified data processing as a critical area that needs to be developed in order to de-risk frontier exploration costs and shorten project development timelines. ARPA-E seeks information about the challenges and opportunities for data analytics to significantly reduce exploration costs and de-risk renewable energy and CCS projects.

Alternative Energy Resource Exploration Case Studies: Geothermal Energy and Geologic Hydrogen

Geothermal energy development and geologic hydrogen resource assessment are presented as case studies to better contextualize the intent of this RFI towards understanding the technology white space related to frontier exploration beyond fossil fuel plays. They are provided as examples but with the understanding that new subsurface imaging and monitoring technologies will have broad appeal to many clean energy-related interests.

Geothermal energy is a promising renewable energy opportunity representing approximately 60 gigawatts-electric of always-on, load-following, flexible electricity-generation capacity[18]. A recent, comprehensive report from the Geothermal Technologies Office in the Department of Energy evaluated scenarios for the future deployment of geothermal electric power production. Among the key findings from the *GeoVision* analysis were that technologies which address all aspects of the project development phases, from exploration to management, were critical for identifying hidden resources, reducing exploration costs, and improving the success rates of new geothermal projects. Technology development was noted to be particularly important for deploying commercial Enhanced Geothermal

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[13] Doughty, C.; Dobson, P.; Wall, A.; McLing, T.; Weiss, C. (2018). *GeoVision Analysis Supporting Task Force Report: Exploration*. LBNL-2001120. Berkeley, CA: Lawrence Berkeley National Laboratory. Accessed September 9, 2021: https://escholarship.org/uc/item/4v7054cw.

[14] Harris, B., Pethick, A., Schaa, R., Anh Cuong, L. V. Cooperative Inversion: A Review. AEGC Australia. **2018**.

[15] LeCun, Y., Bengio, Y., Hinton, G. Deep Learning. *Nature*. **2015**, *521*, 436-444.

[16] Rose, K. K., Bauer, J. R., and Mark-Moser, M. A Systematic, Science-Driven Approach for Predicting Subsurface Properties. *Interpretation*, **2020**, T167-T181.

[17] Moorkamp, M. Integrating Electromagnetic Data with Other Geophysical Observations for Enhanced Imaging of the Earth: A Tutorial and Review. *Surv. Geophys.* **2017**, *38*, 935-962.

[18] Department of Energy, Geothermal Technologies Office. (**2019**) *GeoVision: Harnessing the Heat Beneath Our Feet*.

Systems (EGS) where the necessary thermal conditions are present but the requisite groundwater and/or rock characteristics are unknown or unoptimized. For EGS and even for conventional unidentified hydrothermal resources, opportunities for advancement in subsurface characterization, monitoring, and engineering were highlighted. In particular, geothermal exploration may require technologies above and beyond what is state-of-the-art for the oil and gas industry[19]. For example, while understanding subsurface fracture networks is important in the oil and gas industry (particularly in shale plays where hydraulic fracking and horizontal drilling is used), the fracture networks and corresponding heat exchange between the solid rock and working fluid determine the extractable thermal energy and the viability of the geothermal well. These requisites may demand a higher degree of imaging resolution or new subsurface models than those currently available[20]. As another example, some of the underlying assumptions used in conventional seismic imaging are not valid under conditions typical for geothermal environments where complex scattering of the seismic waves results from sharp material contrasts in faulted and fractured rocks. New seismic imaging approaches may be required to cater to the unique geothermal environments which are very distinct from what is typically encountered in the oil and gas industry.

Geologic hydrogen is a lesser-known phenomenon in the US but has been well-documented throughout the research literature, particularly in Eastern Europe and Russia[21]. One of the most well-known geologic hydrogen seeps is the purported site of the original Olympic flame at Chimaera in Turkey; the burning gases at this seep contain between 7.5-11.3% of hydrogen. There are many hypotheses around the origin of geological hydrogen, but perhaps the three most significant ones that might result in a net hydrogen production rate are:

- Degassing of primordial hydrogen from the Earth's core and/or the release of hydrogen from deep in the mantle[22],
- The reaction of meteoric or crustal water with ultrabasic rocks (also known as serpentinization)[23],
- Water radiolysis where energy released from radioactive decay interacts with water to produce hydrogen[24].

By some estimates, the amount of geologic hydrogen produced annually could be significant, the highest

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[19] Doughty, C.; Dobson, P.; Wall, A.; McLing, T.; Weiss, C. (2018). *GeoVision Analysis Supporting Task Force Report: Exploration*. LBNL-2001120. Berkeley, CA: Lawrence Berkeley National Laboratory. Accessed September 9, 2021: https://escholarship.org/uc/item/4v7054cw. McKittrick, A., Abrahams, L., Clavin, C., Rozansky, R., Bernstein, D. (2019). Frontier Observatory for Research in Geothermal Energy: A Roadmap. Alexandria, VA: IDA Science and Technology Policy Institute. Prepared for the U.S. Department of Energy under contract NSF-OIA-0408601, project EA-20-4475. Accessed September 9, 2021: https://www. ida.org/idamedia/Corporate/Files/Publications/STPIPubs/2019/D-10474.pdf.

[20] Doughty, C.; Dobson, P.; Wall, A.; McLing, T.; Weiss, C. (2018). *GeoVision Analysis Supporting Task Force Report: Exploration*. LBNL-2001120. Berkeley, CA: Lawrence Berkeley National Laboratory. Accessed September 9, 2021: https://escholarship.org/uc/item/4v7054cw.

[21] Zgonnik, V. The Occurrence and Geoscience of Natural Hydrogen: A Comprehensive Review. *Earth-Science Reviews*. **2020**, *203*, 103140.

[22] Mao, H.-K., *et al.* When Water Meets Iron at Earth's Core-Mantle Boundary. *National Sciences Review*. **2017**, *4*, 870-878. Komabayashi, T. Hydrogen Dances in the Deep Mantle. *Nature Geoscience*. **2021**, *14*, 112-117. Gilat, A. L. and Vol, A. Degassing of Primordial Hydrogen and Helium as the Major Energy Source for Internal Terrestrial Processes. *Geoscience Frontiers*. **2012**, *3*, 911-921.

[23] Holm, N. G., *et al.* Serpentinization and the Formation of H2 and CH4 on Celestial Bodies (Planets, Moons, Comets). *Astrobiology*. **2015**, *15*, 587-600. Barber, S., *et al.* A Review of H2, CH4, and Hydrocarbon Formation in Experimental Serpentinization Using Network Analysis. *Frontiers in Earth Science*. **2020**, *8*, 209.

[24] Sauvage, J. F., *et al.* The Contribution of Water Radiolysis to Marine Sedimentary Life. *Nature Communications.* **2021**, *12*, 1297.

estimate suggesting an amount equivalent to about 30% of the hydrogen produced globally today (other estimates are significantly lower)[25]. These estimates, however, are not derived from proven resources; instead, they are calculated either from summing values quoted in the scientific literature or based on reaction models coupled with the known volumes of rock formations where geologic hydrogen is most likely to form. More accurate estimates based on proven resources are not available. Historically in the US, identifying geologic hydrogen resources has not been a focus for energy exploration. There were a handful of studies related to hydrogen conducted by the United States Geological Survey (USGS) from the early and mid-1980s[26], though more recent studies documenting observations of geologic hydrogen seeps have been reported in the scientific literature[27]. There may be many reasons why this potential resource has gone unnoticed in the US including, in large part, a degree of skepticism about the size of the resource itself. Another reason is that geologic hydrogen accumulations are unlikely to be co-located where traditional oil and gas fields are; geologic hydrogen migrating from deep sources would likely be consumed by reactions with thermally mature organic matter in these regions and/or go undetected because hydrogen was not of primary interest. Regardless, there is precedent for drilling geologic hydrogen, as demonstrated by the first proven economic hydrogen gas field discovery in Mali[28]. Importantly, this site does not feature any particularly unique geology which suggests that similar fields are likely to exist elsewhere. In order to assess the viability of geologic hydrogen as a potential energy resource in the US, geologic surveys in areas that are not well-characterized will be required.

Because of its long history of development and research, the technical opportunities for geothermal energy exploration are well-defined and clear. Geologic hydrogen, on the other hand, is a potentially new energy resource with very little precedent in the US. Even still, like geothermal energy, geologic hydrogen resource identification may require advances in subsurface imaging technologies and geological surveys that are not available today.

In many ways, the search for geothermal resources and geologic hydrogen may echo the early years of oil and gas exploration. The exploration paradigm in the 1860s meant first locating surface seeps followed by drilling many wells and occasionally getting lucky with a few. The oil and gas exploration guidelines have since evolved to include the use of subsurface imaging technologies. The process for new oil and gas plays begins with geologists identifying regions with promising rock formations (e.g. source rocks, reservoirs, etc.). Once a region of interest has been identified, 2D seismic lines are collected to further refine the search area, followed by the last step which involves using more expensive, higher-resolution 3D seismic (or equivalent) imaging techniques. In all, this process can last anywhere from several months to several years, even with nearly two centuries of experience and entire disciplines devoted to understanding how to locate oil and gas reservoirs. For new renewable energy resource exploration or CCS siting where there is significantly less industry experience, the process is

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[25] Sherwood Lollar, B., *et al.* The Contribution of the Precambrian Continental Lithosphere to Global H2 Production. *Nature*. **2014**, *516*, 379-382. Zgonnik, V. The Occurrence and Geoscience of Natural Hydrogen: A Comprehensive Review. *Earth-Science Reviews*. **2020**, *203*, 103140.

[26] McCarthy, J. H., *et al.* Soil Gas Studies Around Hydrogen-Rich Natural Gas Wells in Northern Kansas. *United States Department of the Interior Geological Survey*. **1986**. Report 86-461. McGee, K. A., *et al.* Hydrogen Gas Monitoring at Long Valley Caldera, California. United States Department of the Interior Geological Survey. **1982**. Report 82-930.

[27] Zgonnik, V., *et al.* Evidence for Natural Molecular Hydrogen Seepage Associated with Carolina Bays (Surficial, Ovoid Depressions on the Atlantic Coastal Plain, Province of the USA). *Progress in Earth and Planetary Science*. **2015**, *2*, 31. Guelar, J., *et al.* Natural H2 in Kansas: Deep or Shallow Origin? *Geochemistry, Geophysics, Geosystems*. **2017**, *18,* 1841-1867.

[28] Prinzhofer, *et al.* Discovery of a Large Accumulation of Natural Hydrogen in Bourakebougou (Mali). *International Journal of Hydrogen Energy*. **2018**, *43*, 19315-19326.

likely to be even longer. ARPA-E believes there may be opportunities that not only leverage current subsurface exploration technologies but also advance new technologies to accelerate project development timelines for renewable energy and CCS. ARPA-E also seeks technologies that disrupt the paradigm of resource development which has historically progressed in a linear fashion beginning with sites with known surface indicators before moving on to resources found deeper in the subsurface. ARPA-E believes that new technologies can short circuit this process so that sites with and without surface indicators are identified and developed in parallel. Finally, ARPA-E recognizes that identifying new renewable energy resources or CCS sites in the subsurface may require a shift in exploration guidelines, a fact that has already been noted for geologic hydrogen extraction[29]. To this end, ARPA-E seeks information on how technologies may need to be adapted and integrated into new exploration guidelines beyond what is currently exercised in the oil and gas industry.

Approaches Not of Interest

This potential program is focused on novel technologies that enable wide-area subsurface exploration. Approaches not of interest include:

- Work focused on basic research aimed at discovery and fundamental knowledge generation.
- Work that emphasizes resource characterization using existing technologies without indicating opportunities for a significant step-change in the state of the art technology.
- Work that is focused on identifying new fossil fuel resources since the emphasis will be on subsurface imaging in regions more relevant to renewable energy or CCS.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

REQUEST FOR INFORMATION GUIDELINES

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential**.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on December 1, 2021.** Emails should conform to the following guidelines:

- Please insert "Response to Subsurface Characterization - <your organization name>" in the subject line of your email
- In the body of your email, include your name, title, organization, type of organization (e.g.

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[29] Boreham, C. J., *et al.* Hydrogen in Australian Natural Gas: Occurrences, Sources, and Resources. *The APPEA Journal*. **2021**, *61*, 163-191.

university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise.

- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Respondents are strongly encouraged to include preliminary results, data, and figures that describe their potential processes.

Questions

ARPA-E is interested in surveying stakeholders interested in subsurface exploration and resource identification for renewable energy and CCS. The questions posed in this section are classified into several different groups as appropriate. Please provide responses and information about any of the following. ARPA-E does not expect any one respondent to answer all, or even many, of these prompts. Simply indicate the group and question number in your response. Citations are encouraged as appropriate. Respondents are also welcome to address other relevant avenues/technologies that are not outlined below.

General

1. What are the biggest pain points for frontier exploration costs (time, money, permitting), and how might new technology developments impact them? What are the potential technological improvements?
2. How do exploration costs and drilling/project installation costs compare?
3. How does exploration in the context of renewable energy developments and/or CCS differ from traditional oil and gas exploration? What unique information is required that is not typically sought in oil and gas exploration?
4. What subsurface survey datasets are available publicly and what information is contained in them?
5. What kind of price premium is industry willing to pay for higher confidence intervals for site selection? What is the confidence interval that is necessary to justify proceeding forward with a renewable energy or CCS project? How does that interval change for different projects (i.e. geothermal versus carbon storage versus geologic hydrogen, etc...)?

Seismic Imaging (Data Acquisition)

1. What costs and time (order of magnitude) for data acquisition are typical when conducting seismic imaging? How do these costs depend on location, resolution, depth of target, lithology, etc...?
2. How might seismic imaging processes need to be adapted for renewable energy exploration or CCS siting? Will new technologies or capabilities need to be developed and what are they?
3. What kind of price premium is industry willing to pay for higher-resolution seismic imaging? Is there a practical resolution limit where it is “good enough” to give reasonable confidence about the potential of a new energy resource and what is that limit? Is achieving higher resolution always desired? Why or why not?
4. In general, what would be the next frontier in seismic imaging? What is the next “transformational” technology that would be meaningful to the renewable energy or CCS industry?

Electromagnetic Imaging (Data Acquisition)

1. What advantage do EM/MT surveys offer, different from seismic? How do costs or time of acquisition compare (order of magnitude)?
2. What kind of price premium is industry willing to pay for higher-resolution EM/MT imaging? Is

there a practical resolution limit where it is “good enough” to give reasonable confidence about the potential of a new energy resource and what is that limit? Is achieving higher resolution always desired? Why or why not?

3. In general, what would be the next frontier in electromagnetic imaging? What is the next “transformational” technology that would be meaningful to the renewable energy or CCS industry?

<u>Multi-Physics Approaches (Data Acquisition)</u>

1. Are there approaches where cost savings can be achieved by combining or coordinating data acquisition techniques? What are they?
2. When combining more than one survey technique, what data acquisition parameters enable more seamless integration? Is there a new technology opportunity that leverages more than one subsurface characterization technique and what is it?
3. What capabilities are there to expand the use of existing datasets and/or to integrate with new data?
4. What has prevented multi-physics approaches from being used more broadly?
5. What new physics or mathematical approaches are required for subsurface imaging in crystalline basins or geologic contexts not typically found in oil and gas exploration?

<u>Other (Data Acquisition)</u>

1. Gravimetric imaging is a useful technique for bulk rock characterization over wide regions of interest. What would the next frontier in gravimetric imaging be? What is the next “transformational” gravimetric technology that would be meaningful to the renewable energy or CCS industry?
2. Optical fibers are becoming more commonplace for active wells and detecting small acoustic vibrations. What would the next frontier in optical fiber imaging be? What is the next “transformational” technology that would be meaningful to the renewable energy or CCS industry?
3. In today’s 4D mapping, what changes are being monitored? Where does the state of the art stand in terms of modelling processes like active water-rock reactions, changes in the rock morphology (i.e. carbon mineralization), or biological activity which may be more relevant for renewable energy subsurface plays than for oil and gas?
4. Surface exploration geochemistry has been applied in traditional oil and gas exploration. Are there new technologies that could be developed to adapt and enhance existing surface methods to specifically target hydrogen seep detection? Could remote sensing (e.g. drone, satellite, etc.) techniques be developed for surveying broad areas for hydrogen seeps?
5. Are there other technologies that are not traditionally used in oil and gas exploration but would find unique applications for alternative energy exploration and CCS siting?

<u>Big Data Analytics (Data Processing)</u>

1. What are the major efforts that are underway today for big data analytics in subsurface imaging analysis? What are the technical challenges that these efforts are targeting? Are these efforts specific for a single use case or can they be generalized for broader subsurface modelling efforts?
2. What minimum amount of information is required for any dataset that is used in ML/AI training? Are there enough public datasets available that contain the necessary information for ML/AI training?
3. What are the typical data volumes that are managed from any given survey and what does the timeline look like between data acquisition and data processing? How does that timeline scale

with amount of data to be processed or change when new/underexplored areas are being characterized?

4. What opportunities are presented when analyzing data from multiple survey techniques? What are the challenges?
5. Do the current subsurface models track dynamic processes in the source rock (i.e. active chemical reactions, biological activity, gas migration, or changes in the rock over time) which may be important for new energy plays? How much will modelling these processes matter?
6. Can ML/AI techniques be used to “upgrade” lower-resolution data or predict subsurface rock formations outside of the initial region of interest? Can ML/AI enable geologists to do more with lower-quality data or smaller areas of exploration? What potential cost or time savings could be expected with this kind of approach?
7. What opportunities exist to increase the signal-to-noise ratio in otherwise very noisy data?
8. In general, what would be the next frontier in data analytics related to subsurface imaging? What is the next “transformational” technology or paradigm that would be meaningful to the renewable energy or CCS industry?

Opportunities for Cross-Disciplinary Interaction

1. What opportunities exist for enhancing cross-disciplinary interaction?
2. What limits cross-disciplinary interactions, at present? How might this be impacting new energy developments (i.e. geothermal, geologic hydrogen, carbon sequestration)? How might this be overcome?
3. What new technology developments might be expected with more cross-disciplinary interactions?

Potential Metrics

1. Would reducing frontier exploration costs by an order of magnitude for new energy plays be meaningful to the industry? Why or why not? If not, what would be meaningful?
2. Would reducing the data acquisition and processing time by orders of magnitude be transformational? Why or why not? If not, what would be meaningful for reducing frontier exploration costs and risks? How does time for data analysis translate to the cost of new projects?
3. For new energy projects, there’s always a risk of drilling unproductive wells. Where does that percentage stand today for ongoing pilot projects and what would the risk profile of drilling unproductive wells need to be in the future to be competitive with incumbent energy markets?
4. Besides the metrics that are identified in this RFI, what are the most salient metrics related to subsurface imaging that matter to the renewable energy or carbon capture industry?