GreenPipeline
The oil and gas to geothermal connection

2021 Green Pipeline Project

THE OIL AND GAS TO GEOTHERMAL CONNECTION

International Geothermal Association (IGA)

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Summary

The Green Pipeline is an effort to determine and contextualize the technical research and demonstration needs of the oil and gas sectors in pivoting to geothermal resources. There is a new awareness by the energy industry of the need to diversify their portfolio that was accelerated in the last 18 months from the impact of COVID-19 on world consumption changes as well as the arrival of broad political consensus to address climate change. As a result, in early 2021, a team of geothermal professionals developed and publicly distributed a survey instrument with an International Geothermal Association (IGA) supported team reviewing the results. The Green Pipeline goal is to initiate and frame ways to pivot the oil and gas sector into geothermal energy. The survey instrument was designed and executed with the intention of including a full range of voices from across the existing geothermal industry entities and constituents, oil and gas entities and constituents, and researchers outside of these industries, who might have ideas that could help push geothermal energy forward. The survey was promoted via social media, online magazines, and official websites between January 26th and February 26th. While the overall response rate was appropriate given the level of outreach, the results were relatively uneven, making it difficult to draw firm insights and set one detailed direction for a technology roadmap. However, the responses do provide some insight around the necessary technical research challenges. Survey responses include suggestions in exploration, drilling, reservoir management, closed-loop/Advanced Geothermal Systems (AGS) and surface aspects. There is also a clear, clarion call for demonstration projects -- at scale, in parallel, and at numerous locations. A sense of urgency is apparent within the responses. This effort initiated further discussion and broadly reflects the current sentiment of the industry. There is a strong interest in continuing this work to develop a clear and well-delineated technology roadmap that can be used by funding agencies to select and enable the necessary research and demonstration projects to achieve this aspiration.

The responses highlighted well-known high-level challenges, yet few provided detailed research and demonstration challenges. The range in size and types of geothermal projects makes it difficult to say any one detail or technology will increase geothermal development. Some examples of the high level challenges identified include:

- Improved rate of penetration in harder and deeper rock, at higher temperatures, and wider bore diameters,
- Derisking through improved exploration and regional 3D modelling,
- Monitoring tools and wellbore production optimization,
- Increase the rate of sustainable heat production per well,
- Control fluid permeation through large volume of rock,
- Increased heat conversion efficiency at lower delta T's and lower flows,
- Longer equipment lifetime in geothermal environments,
- Reduction in induced seismicity and subsidence challenges,
- Decreased O & M costs, lateral training of oil and gas professionals, and
- Low-cost, efficient, standardized surface power plants for low-enthalpy resources.

Introduction

The last 18 months have seen a renewed interest in geothermal energy with calls for professionals and research groups in the oil and gas sector to play an increased role in advancing the synergistic relationship.

Research opportunities in this area were explored in the successful #Pivot2020 conference (https://www.texasgeo.org/pivot2020) organized by the Geothermal Entrepreneurship Organization (GEO) at the University of Texas at Austin, and the International Geothermal Association (IGA), along with partners and leaders from the oil and gas industry, geothermal industry, academia, governments, national labs, and start-up companies.

To build on this work, The Green Pipeline Project is an effort to identify and assemble a broad list of potential research and demonstration ideas as we seek the use of geothermal energy in every practical application. As an analogy of a physical pipeline, the aim of the Green Pipeline is to connect, inspire, catalogue, and make visible the technology synergies between the oil/gas and geothermal sectors, and to inform funding authorities, research teams, and entrepreneurs of the range of technical research challenges facing geothermal adoption/adaptation.

This effort focused on technology research and items requiring demonstration to move us towards "Geothermal Anywhere". Although policy, price, permits and politics are instrumental in this transformation, those issues are not included here.

Recommendation:

Investigation of this topic should continue, but utilizing a different approach. The Team recommends a series of structured interviews with industry leaders to assist in the framing of a technology roadmap. This should be followed by a global initiative engaging salient partners and would be executed with the specific goal of outlining a technology roadmap for the pivot of the oil and gas sector towards geothermal. This effort should be funded, structured, and executed at a formal and functional level with key buy-in from major energy stakeholders.

- *Continue project with targeted expert interviews*
- *Design, fund and execute a globally engaged technology roadmap*

Project Purpose

The last 18 months have seen an increased interest in energy transition and decarbonisation. Nations, entire industrial sectors (e.g., transport, cement, chemical) and individual companies are moving forward with commitments and policies to reduce carbon emissions by seizing on clean energy opportunities. A sharp drop in oil demand and prices has further heightened interest in this area. Geothermal energy is one of the options being considered at a higher level, in part because existing oil and gas interests see an opportunity for an alternative energy resource that aligns closely with existing technical abilities, using the same (or similar) equipment, technology, and resources that they already own.

In July, 2020, TexasGEO hosted Pivot 2020. This week-long virtual event of eleven moderated roundtables, featured thought leaders and change makers who are building the future of geothermal energy. Pivot2020 drew over 2000 attendees and spawned numerous dialogues on technical and non-technical challenges in addressing the current limitations to geothermal energy generation.

The high-level similarities between the geothermal and petroleum industrial sectors have long been recognized. Both sectors include exploration, drilling, and reservoir management. One key difference is energy density - geothermal development has been particularly challenging because of the energy density of geothermal fluids. Electric power generation from geothermal energy historically has been the purview of mid and high enthalpy resources. Advances in energy conversion technology are beginning to place lower enthalpy resources within reach. These resources are far more prolific and include many developed oil and gas fields. These fields are populated with infrastructure and a technical workforce. The stored thermal energy of the Williston Basin, a major energy basin straddling the US – Canadian border is four orders of magnitude greater than its oil reserves. Even with the poor conversion efficiencies of today's low enthalpy ORC systems the geothermal energy in the basin will outproduce the oil reserves on the electrification side. Plus the stored thermal energy will recharge on a century scale, an attribute the oil reserves do not share.

Furthermore, geothermal energy is in a kinetic form while petroleum sits in a potential state. Liquid and gas fuels are suitable for transportation and storage before combustion, while geothermal requires use immediately when it is brought to the surface, further weakening its economic value.

Advances in drilling and power generation technology during the last two decades have altered the economics and has generated interest in co-production of oil and geothermal energy as well as accessing lower temperature geothermal resources spurring exploration farther afield then traditional geothermal exploration. Multiple horizontal wells drilled from a common pad can now generate substantial, commercially adequate-fluid volumes. Organic Rankine Cycle (ORC) technology systems are now being offered commercially with viable efficiency.

Absent from this discussion has been a formal effort to clarify the technical issues facing geothermal that could be resolved through advances in the oil and gas industry.

> "The Green Pipeline was launched in January 2021 with the aim to connect, inspire, promote and make visible innovative, conjunctive and complementary petroleum and geothermal methodologies, techniques, and technology tools worldwide".
>
> "Lawrence MOLLOY, The Green Pipeline Project Director"

We recognize that oil and gas is not the only industry that can offer technical advances. Recently, the U.S. Dept. of Energy recognized the technical opportunities that may exist from the mining space. Tackling some of the high temperature challenges for electronics could possibly be found in the space program. Power generation from low temperature systems and waste heat is a much larger market from surface generated heat sources than what is available from current geothermal resources.

What we did (aka work plan)

A team within the International Geothermal Association was tasked with building a survey instrument, to solicit responses to the question of how the oil and gas and geothermal industries can work together. Following the submission of questionnaire responses, the team organized and discussed the responses with this report representing the synthesis. The conceptual framework the team worked with is presented in the figure below.

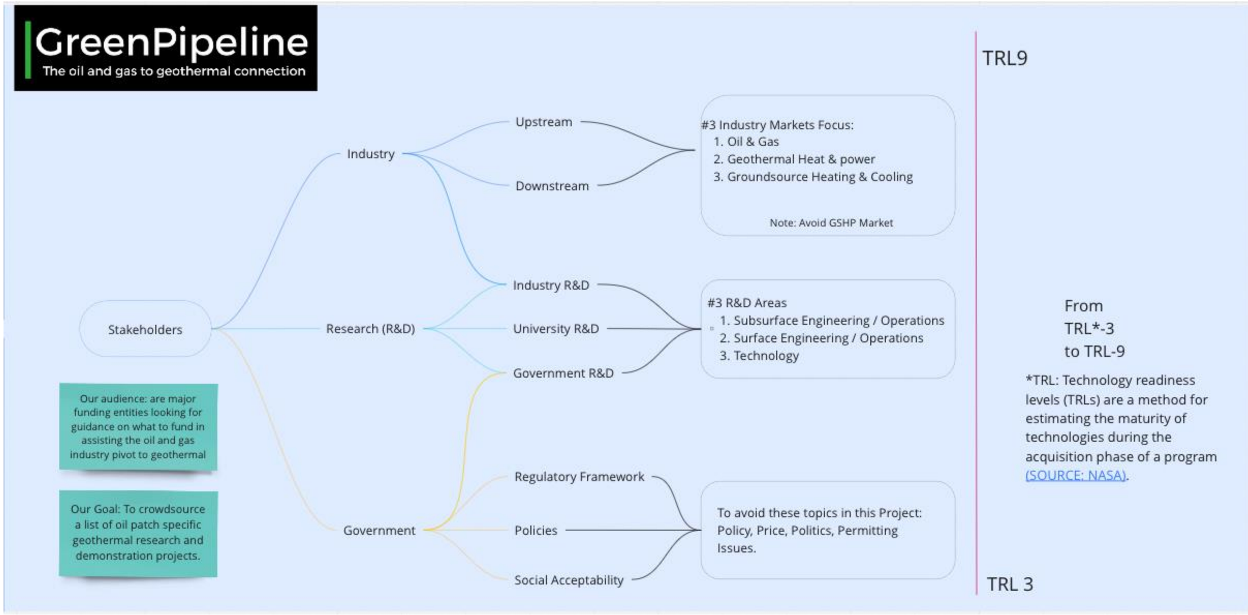

Figure 1. General diagram to contextualize the Green Pipeline project to identify Key Stakeholders and Audience of the project, framed by Technology readiness levels (TRLs).

As shown in the diagram, the framework seeks to identify the necessary technical research challenges and to frame the scope of the two industries' respective commercialisation challenges. The stakeholders and audience are major funding entities looking for guidance on what to fund in assisting the oil and gas industry pivot to geothermal projects. The responses are disaggregated into industry, research, and government tracks as each of these three stakeholders has a distinct and critical role in such an effort. Research can be conducted by industry, government, technology start-ups, individuals, investors or academia. The initial R & D areas considered were split into subsurface and surface engineering operations as well as technology. The industry market focuses on oil and gas and geothermal as they exist today. In considering the range of technology, the team used the conventional technology readiness level (TRL) convention (https://en.wikipedia.org/wiki/Technology_readiness_level. Most of the responses fell within the TRL 3 (Critical Function or Proof of Concept Established: Applied research advances and early stage development begins. Studies and laboratory measurements validate analytical predictions of separate elements of the technology) to TRL 9 (System Proven and Ready for Full Commercial Deployment: Actual system proven through successful operations in operating environment, and ready for full commercial deployment).

A series of questions were formulated for ease of response. In hindsight, their structure and use in a survey instrument was not the most effective tool for gathering insight around this inquiry. The goal was to be broad enough to attract outsiders to the geothermal community to submit responses. Although there may have been a few "outsiders", the majority of responses seem to come from "insiders" working on aspects of geothermal exploration (technology or resources). The questionnaire included the following four questions:

1. What is the main technical challenge you see facing oil and gas in its pivot to geothermal power?
2. What do you think would be the best way to solve that challenge?
3. From your point of view, are demonstration projects necessary to prove this idea as a working solution? If so, what kind of demonstration projects are necessary?
4. Are you aware of anyone who is currently conducting research in this area? If so, can you provide a reference to an online document or link?"

The survey instrument was launched using Typeform as an online survey tool. The tool was embedded within an announcement on the IGA website on January 26th, 2021 and ran for 5 weeks until the survey was closed. The survey was promoted via the TexasGeo Blog and Twitter, SMU Geothermal Laboratory newsletter, and direct postings on Linkedin by various team members. ThinkGeoEnergy promoted it via social media and the website. Spanish and Turkish geothermal sites included postings as well.

Responses gathered via the survey portal were downloaded to an excel file. The results are linked below. Many of the responses included multiple topics. The Team disaggregated these responses for improved consideration and discussion. Because of overlapping topics, survey response numbers will not necessarily add up to 100%.

Survey Results

There were a total of 178 respondents to the survey instrument. The raw data are presented here.

2021 GREEN SURVEY RESPONSES.xlsx

Discussion

All major thematic areas (Table 1) showed strong interest in demonstration projects as well as general advocacy and agreement on each topic area. Respondents were emphatic in seeing multiple demonstration projects move forward in parallel and as quickly as possible. Over a third of responses touched upon non-technical issues (informally referred to as "the P's, policy, price, permits, and politics"). It was a consensus of the Team that the results were uneven and that the survey instrument used was only one tool, with other options for increasing engagement possible based on the nature of the topic (i.e., what are the needed research and technology projects needed in this area).

In drafting this report, submissions are disaggregated into three major groupings; 1) Technical, 2) Non-Technical, 3) General support/Demonstration. There is significant overlap across all three major groupings and within each of the technical areas.

Table 1. Categories and their descriptions of major areas discussed in the report.

Category	**Summary**
Exploration	Geochemical, geophysical, remote sensing, mapping, resource estimation, resource modelling
Drilling	Exploration and resource development drilling. This includes conventional and unconventional technologies such as plasma, laser, milliWave systems
Reservoir	Reservoir modelling and management as well as wellbores.
Closed-loop/Advanced Geothermal Systems	Closed-loop, single well systems, conductive heat recovery, engineered geothermal systems covering the full thermal suite from low-enthalpy to high-enthalpy supercritical EGS.
Surface aspects	Industrial/District heating systems, heat recovery, power generation, Organic Rankine Cycle (ORC) systems, environmental challenges, well closure.

After review of the survey results and consultation with industry experts and the technical team, the major themes and queries that stood out are:

- Training and education is needed. This covers the lateral technical transition of oil and gas professionals shifting into geothermal.
- Lower cost drilling. This was either through advocacy of increasing efficiency, improved drill bits or development of new drilling technology (e.g., laser, plasma, milliWave).
- Lower cost and higher efficiency power conversion technology that can work with lower temperature differentials for developing co-produced fluids. Standardized geothermal power plants.
- The step change that occurred in the oil and gas sector in the last two decades sets the stage for the next round of advances, but reduction in capital costs through major advances in technology and resource development practices is needed.
- Repurposing (and its related topic of well closure) of existing oil and gas wells is a big theme.
- Closed loop and Advanced Geothermal Systems garnered the strongest technical response, with a strong sentiment for conducting commercial scale demonstration projects.
- That temperature was not listed as a major issue shows the continued convergence of low/mid-enthalpy petroleum resources now producing delta T's suitable for commercially viable ORC systems.
- Non-Technical suggestions touched on policy, permits, price and politics that would accelerate geothermal uptake.

Demonstration Topics

There is a strong interest in demonstration projects in all major technical areas. *"Begin scaling projects massively"*, *"Run projects in close iteration"*, *"We need 10 wells put into production rapidly, one at a time, taking the learning from the last and applied to the next -- close iteration"* were some of the responses. As one respondee put it;

> *"The analogy is the shale revolution... <u>a repetitive, standardized, manufacturing-style approach brings massive cost decreases over time.</u>*

Submissions showed a knowledge of existing demonstration projects, but project scale emerged as a thematic difference between what was occurring and what people wanted to see.

Co-production of oil and geothermal was closely aligned with interest in exploration and development of mid-enthalpy reservoirs and long horizontal well fields. This highlights the need for better mapping of potential low temperature geothermal fields. Typical sedimentary basin temperatures require binary power conversion systems. While these efficiencies are typically low, recent advances in technology have led to the development of systems with approaching commercially viable efficiencies. Respondents called for demonstrations of standardized ORC packages that are affordable for low temperature heat. Concepts for oilfield geothermal development have emphasized the use of existing infrastructure and have focused on water available in co-production or through conversion of marginally economic oil and gas wells to water production. Though technologically feasible, both concepts face limitations in delivering adequate fluid volume. Two developments, horizontal infill drilling on multi-well pads, and the capability of binary systems to use the total oil and water flow, could possibly overcome this limitation.

Respondents advocated for traditional geothermal co-production of heat and electricity. Research and demonstration programs in this area are well underway across Europe including (footnote; Iceland, EUx5, Italy, Turkey, Lowlands district, Southern Germany, Industrial heating) The last decade has seen marked growth in this sector at 10% annually. Respondents were interested in demonstration projects for district heating. An example of this is the Netherlands development of district heating systems for their existing horticultural sector. Respondents from the U.S. were particularly interested in this area. In Europe this is a core part of new urban development in geothermally viable regions across China. Bore hole technology needs further demonstration, and can play a core role in urban development. Suggested demonstration projects are:

- Standardized ORC Plants
- Closed loop systems
- Well-closure
- Minerals extraction (Lithium and other metals)
- Demonstrate that green hydrogen @scale can compete against grey hydrogen.
- Process/industrial heat demonstration for mining
- Thermal cascading
- Agricultural/Balneology/tourism
- Low-enthalpy systems
- Supercritical EGS
- Granitic and carbonate systems
- District and industrial heating from near shore oil and gas fields

Non-Technical Discussion

Over one third of the survey respondents provided answers that were non-technical and outside of the scope of the enquiry. These responses generally reflected the current industry sentiment around non-technical issues: comparison studies of geothermal, regulatory changes, clear permit guidelines, tax reform, insurance schemes, and faster approvals of geothermal permits are just some of the suggestions. The IGA notes that some of these problems are related to government and civic rules and processes discrete to each nation. It is also noted that these challenges are faced at different levels of difficulty in different countries. Geothermal electricity generation is currently used in **26 countries**, while geothermal heating is in use in **70 countries** **https://www.iea.org/reports/geothermal.** Some respondents called out the inequity between tax policy that favoured oil and gas over geothermal. We considered submissions about comparing energy economics and communicating to decision makers as non-technical, though we considered suggestions on workforce training and higher education research as technical.

Other non-Technical responses included:

- Clearer and quicker permitting processes
- Price incentives including feed-in tariffs for electricity and heat
- Legislative fairness -- apply concepts and rules similar to oil and gas
- Address long development timelines and project economics
- Develop guidelines for social and environmental aspects of geothermal
- Collaboration between Industry, governments, academia, & trade bodies
- Regulatory environment for well closure and well conversion

Technical Discussion:

Characterizing Large, Medium and Small Challenges

A spectrum of technical challenges face this pivot. These challenges are varied and disproportionate in their technological readiness, as well as in the amount of research and innovation required to get them over the line. And, if we bring these innovations to market, we must determine how big the market is and how much of a transformation such technology will bring. The responses captured a broad scope of interest, with submittals suggesting large to small technical challenges requiring various levels of effort to achieve commerciality. In considering the submissions the team looked at four factors to characterize

1. Technology Readiness Level (TRL) - where does the technology exist today
2. Impact to market - would such a solution provide incremental or transformational gains?
3. Market size - how large a market is this solution within geothermal?
4. Level of effort required - what research, funding and demonstration effort would be required to achieve commercial viability?

Some of the more innovative drilling technology has a low TRL, but would have a large market and large market impact if such innovation was achieved. Advances in conventional drilling such as better drill bits, use of robotics and reduced downtime have higher TRLs but would have a reduced impact on the market. Conversely, many of the options for education, data analytics, data management and professional training have a high TRL and require minimal investment to optimize.

Though uneven, the scope and spectrum of responses indicate the need for a comprehensive technology roadmap.

Technical Section: Exploration & Modelling

The exploration phase is a huge challenge for geothermal developers, especially as one moves away from classic (i.e., visible) hydrothermal systems to “blind” systems. In order to reduce risk for the next step of drilling, a more precise investigation is required. Exploration is where geoscientists apply knowledge and technology to generate the conceptual model of the reservoir and the locations of drilling sites. The vast majority of conventional oil and gas exploration techniques and technologies are applied when exploring for a geothermal resource. Advances would be required in improved seismic, and gravity interpretation, as well as further resource study into improved reservoir simulation of heat transfer. Data sharing and data extrapolation from small geothermal resources also touches on the need for a data repository, data access, and data rights. One suggestion was the application of geothermal resource assessments to identify the geothermal plays in deep carbonate rocks, a known hydrocarbon hotspot. We should also consider improved mathematics and modelling and the use of AI. These challenges rest in the TRL 7-9 range and require little investment.

Some of the responses included;

- Conduct cutting edge computational methods and mathematical optimisation methods that can handle variable flow behavior and spatial scales from cm to thousands of kms.
- Advances in high temperature downhole tools and sensors are challenging and advances incremental with a large effort required on multiple fronts for materials, electronics and battery life.
- Perform long-term chemistry modelling.
- Conduct laboratory tests to determine elastic constants, permeability and cohesion of rock.
- Establish and experimentally validate numerical modeling for rock fracturing and tool/rock interaction studies - make results open for industrial exploitation.
- Conduct cutting edge computational methods and mathematical optimisation methods that can handle variable flow behavior and spatial scales from cm to thousand of kms.

Technical Section: Drilling

Drilling (and casing) is consistently the highest cost element in developing a geothermal project. The challenge is primarily associated with harder rock, deeper depths, and higher temperatures. Wider bores are required for sufficient flows. Or in the case of closed loop systems, longer well lengths. Conventional drilling faces the classic problems of low rates of penetration, lost circulation, casing and cementing challenges, and directional drilling in high temperature environments. Temperature poses a problem due to downhole electronic components of modern drilling equipment failing about ~180C. Drilling material contraction and extraction is an issue during hydro stimulation in high temperature environments encountered in supercritical systems. Drilling technology has advanced in the last two decades with the oil and gas sector acquiring a lot of experience through the shale gas boom. The last two decades has seen 22,000 oil and gas wells drilled in North America and 150-200 geothermal wells drilled in the same period of time.

Responses included both conventional and unconventional/step-change advances in drilling in their submissions. New drilling techniques offer the possibility of step-change improvement of drilling rate of penetration (ROP). These include plasma, laser, electrical impulse and Millimeter wave drilling. Conventional drilling has innovation opportunities in rotary percussion drilling with mud hammers, abrasive jetting, and particle impact drilling or hybrid PDC. Improvements in conventional drilling will likely be incremental. Developing robotic drilling and improved rig efficiency has a high TRL, and if resolved, would do much to reduce cost. This is the area that one industry expert [Rob Ursulmann] referred to as "drilling as a factory". However, automation and data transmission will only get you so far when drilling - the underlying physics of drill/rock interaction are a limiting factor. The technical research needed to achieve cost reductions in drilling are significant regardless of the temperature of the resource.

> *"Clearer delineation on challenges between drilling and completion of geothermal compared to oil and gas"*

Low and mid-enthalpy resources are not hindered by the upper limit of the temperature of drilling technologies today. However, significant cost reduction is still necessary. High Pressure High Temperature (HPHT) environments of 100 MPa and 300 °C have been achieved. Cementing solutions to 350 °C and New MWD/LWD are stable up to 250 °C.

Drilling has reached depths of 12+ km and horizontal wells have exceeded 13km. Most geothermal resource assessments globally have placed 10km as the upper depth limit. The issue is not technical feasibility, but advances to achieve cost reductions necessary to commercially tap the low density/kinetic aspect of geothermal fluids.

Additional drilling innovations were mentioned across the drilling sector, including:

- The need for large diameter economical conductor drive shoes.
- Improvements in drill bits, drill monitoring, drilling rates.
- Completion hardware to reduce rig time and lining hanger issues.
- Develop large diameter extruded metal liner hanger systems rated for 350 °C and high anchor loads.
- Eliminate casing thermal expansion failures, reduce in situ casing stress, and reduce casing cement requirements.
- Commercialized thermal expansion couplings for large casing sizes (13-3/8", 10-3/4" and 9-5/8") with seals that will be effective even with scale build-up.
- Development of high pressure water jet drilling, development of DTH hammer.
- Evaluation of the use of a fixed cutter PDC bit to speed up drilling in hard rock.
- Interest was also flagged for open source databases on rock fracturing and tool/rock interaction studies.

Technical Section: Closed-loop/Advanced Geothermal/Engineered Geothermal Systems (EGS)

We include closed-loop systems, advanced geothermal systems and engineered geothermal systems (commonly known as EGS) in a singular category as they seem to have the current spotlight of media coverage. Closed-loop systems, also known as deep borehole closed-loop heat exchangers (DBHE) have received strong attention as the oil and gas industry looks to repurpose existing oil wells. Advances in ORC technology allow for electricity production at lower delta T's. With advances in the drilling sector, this allows for precision connection between two boreholes creating new closed-loop system designs. Clear proof of the thermodynamic viability of such designs would open up a much larger resource base than conventional hydrothermal systems. Driving the clear need for numerous demonstrations in this area. Engineered Geothermal Systems is considered in the context of those non-HSA, non-hydrothermal, conductive systems which created fracture networks (such as Soultz) and extends into supercritical high temperature EGS systems, such as those recently demonstrated in Iceland.

Comparing open- and closed-loop systems is important in framing the research challenge. Closed-loop systems rely on conductive heat transfer and would necessitate much longer loop connections below ground for low to mid-enthalpy AGS systems. However, such systems would obviate challenges in induced seismicity, surface subsidence, fluid losses, gas emissions, and mineral scaling. Early this year, a blog post by Dr. Mark McClure on the heat flow mechanics of a closed loop system generated strong response. Though heat conduction through rock is slow, proponents of closed loop systems advocate for lower cost drilling shallow legs and longer horizontals (approaching 10's of km) to overcome the limitation of heat flow. Demonstrations in this area need to demonstrate the reduced drilling cost per foot to be able to tap viably into low and mid enthalpy AGS systems compared to a traditional hydrothermal unit.

Challenges for closed-loop and Advanced Geothermal systems include;

- over- coming the thermodynamics of the heat diffusion equation
- improving out the well materials being used
- <$500/metre drilling cost
- Rapid drilling techniques
- High efficiency low temperature heat recovery
- Supercritical environment tolerant sensors
- Low-stress, zonal isolation and reservoir stimulation techniques

Technical Section: Reservoir

Respondents were keen to see reservoir technology applied to both low and mid-enthalpy systems -a rational assumption where there are similarities in geology to oil and gas deposits. Interest was also presented for applying reservoir technology to high enthalpy systems. The primary difference between geothermal and oil and gas when it comes to reservoirs is that oil and gas is managed as potential energy and geothermal is kinetic and regenerative. Accordingly, reservoir management is geared towards heat extraction over time in a manner that allows for performance of the heat recovery system within its designed attributes. Like exploration, the paucity of geothermal reservoir data drove requests for development of reservoir modelling techniques in geothermal.

Application of oil and gas reservoir techniques to hydrothermal, closed-loop, and EGS systems poses challenges. Examples of primary challenges are controlling fluids in high temperature and high pressure systems. Typically these are metamorphic or basaltic environments with different fracture networks. Supercritical EGS continues to be the subject of multi-decade projects in Iceland, Japan and New Zealand. This is an extremely complex and multi-faceted problem.

Interest in lower temperature reservoirs is spurned in part by the belief that existing oil and gas kit can handle these physical conditions. However, it has yet to have been shown that it is quite easy to advance to the high flow rates necessary in almost any well for commercial heat recovery.

Additionally, respondents also demonstrated an awareness of the performance and efficiency gains of ORC systems working at lower temperatures at lower depths and its link to reservoirs and exploring for commercially viable resources. Interest here is in part driven by a desire to develop known systems with existing infrastructure and also to avoid the challenge of drilling deeper and harder rock. ORC systems could be included on most conversion wells from oil and gas to geothermal energy production.

There were only two responses that touched upon fracking during reservoir stimulation. Stimulation has long been practiced in geothermal exploration for 50 years with the only recent experiences in Switzerland and South Korea triggering concerns. These two projects are thoroughly documented within the research community. Additional Research efforts are underway to develop 'softer' stimulation techniques (https://cordis.europa.eu/project/id/734370)

Technical Section: Surface aspects

We defined surface aspects as technology challenges associated with power generation, industrial heat applications, district heating and environmental impacts. There was a strong response related to district heating and power generation demonstration projects. While district heating is technically mature and well demonstrated, there was a call for further demonstration projects. On the power generation side, interest was in improved organic rankine cycle (ORC) systems at lower delta T's and smaller flows. While ORC units have long been of use with geothermal heat, the larger market is surface generated waste heat. Additionally there is the common problem of suitable and available industrial heat needs proximal to geothermal sources.

Co-production of oil and electricity from mid-enthalpy reservoirs and long horizontal well fields has been demonstrated. Further study is required to identify the barriers encountered in previous pilots. As some reservoirs have water to oil ratios exceeding 30X, water treatment and re-injection can be an issue.

Well conversion of both onshore and offshore systems is a major legacy issue in the oil and gas sector that sometimes discourages interest in well conversion. Recent entrants to the small scale ORC market are looking to reduce cost and improve performance associated with lower temperature differentials. However, while this is a complex manufacturing challenge, providing fast, optimal plant design for site specific geothermal resources would have a large impact on the market.

Next Steps

The consensus from the Team was that this project should continue with a focused set of next steps. Identification of the key research challenges needs further exploration and in doing so should generate a Technology Roadmap that would assist in framing a broader, global research agenda. The ability for in-depth discussions with leaders within various aspects of the industry was suggested in a small, 2 - 10 person format, venue via zoom or possibly in-person if an event is occurring where this could take place.

Building from the initial Green Pipeline Survey and additional expert interviews, the panel would discuss and identify testing, design, and target challenges that would need to be tackled to prove out and resolve some of the technical challenges the industry faces in getting projects started. This would require the recruitment of a skilled moderator who understands the technical framework of this challenge. A live graphic designer providing illustrations that mirrored the discussion could potentially assist those participating in visualizing the technical challenges.

A global initiative engaging salient partners should be executed with the specific goal of outlining a technology roadmap for the pivot of the oil and gas sector towards geothermal. This effort should be funded, structured and executed at a formal and functional level with key buy-in from major energy stakeholders.

- Continue project with targeted expert interviews
- Design, fund and execute a globally engaged technology roadmap

Technical Team

MARIA RICHARDS. Maria Richards is a member of the Technical Team as an expert in the field of geothermal resources. She is the SMU Geothermal Laboratory Coordinator in Dallas, Texas where she researches the conversion of oil fields to geothermal production. With 25 years in the geothermal industry, her experiences include the Geothermal Map of North America, Future of Geothermal Energy Report, SMU Node of the National Geothermal Data System, SMU Power Play Conferences, and outreach efforts that included becoming the first female president of the Geothermal Resources Council Board. Her Masters of Science degree in Geography is from University of Tennessee, Knoxville.

MALCOLM I. ROSS. Malcolm I. Ross is a member of the Technical Team of the Green Pipeline as an expert in the field of oil & gas and geothermal resources. Dr. Ross is an innovation-focused geoscientist. Now a consultant, he recently worked for the New Energies Research & Technology Team at Shell, focusing on pre-strategic opportunities in the New Energies space, especially geothermal energy. He continues to teach a GIS class at Rice University. While in the Shell GameChanger team, he discovered, funded, and mentored numerous startups, including those focused on geothermal topics, and helped lead the Shell Ocean Discovery XPRIZE as a science advisor and judge. He holds degrees from Rice University (Ph.D.), the University of Texas (M.S.), and Colgate University (B.A.). He is currently focused on building networks of people and companies involved with accelerating commercial geothermal opportunities and R&D to meet the rising tide of expectation for a sustainable low-carbon world.

GRAEME BEARDSMORE. Graeme is a member of the Technical Team of the Green Pipeline as an expert in the field of geothermal resources. Dr Beardsmore's tertiary studies in physics, mathematics and geology culminated in a PhD in Geophysics from Monash University in 1996. Since then, he has focused on geothermal energy through parallel commercial and academic careers. He co-authored the monograph 'Crustal Heat Flow' published by Cambridge University Press in 2001, and 'Geothermal Exploration' by the International Geothermal Association in 2016. His research and consulting work in the global geothermal energy sector since 2000 has given him a broad grounding in subsurface energy sources, energy delivery systems, technology development, and energy markets. Dr Beardsmore has been Technical Director of geothermal consultancy Hot Dry Rocks since 2006. He is also currently a Senior Fellow at the University of Melbourne, a Director of the Australian Geothermal Association, Secretary of the Asia Western Pacific Regional Branch of the International Geothermal Association, and a member of the steering committee of the International Partnership for Geothermal Technology.

LAWRENCE MOLLOY. Lawrence served as the project director of the Green Pipeline Project and is a member of the Technical Team. Previous work includes The Global Geothermal Challenge, a technical incentive prize for a high temperature downhole geothermal pumps, and Geothermal Washington, a state level geothermal policy initiative. He worked with Hot Dry Rocks Pty, Ltd, an Australian Geothermal Consultancy and has conducted preliminary geothermal surveys in the Western Pacific. The start of his career was as a mining geologist in the coal fields of West Virginia. He served as a federal official with the US EPA and wrote some of the first policy analysis on environmental justice. Mr. Molloy holds an M.S. in Water Resources Engineering and an undergraduate degree (with honours) in Geology.

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MARGARET KRIEGER. Margaret Krieger is experienced in risk management, social perception, and stakeholder engagement. She is responsible for communication and international public relations, business development, design, and online campaigning. She conducts research and analysis of data to support the IGA in outreach and publications of various research documents and papers. Education: MS in Renewable Energies: Business, Ethics & Law.

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