Macro Energy Trends and the Future of Geothermal within the Low-Carbon Energy Portfolio.

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1.0 ABSTRACT

Exploratory analysis was conducted to understand energy diversification trends within the oil, gas and power industry and to examine whether geothermal technologies play a role in the low-carbon energy mix. Investigations were completed using the 2018 end of year financial reports for thirty-six companies. Macro-scale insights reveal a significant split between European and US-based oil and gas companies in terms of strategy which is mirrored by the power companies. Diversification into low-carbon technologies is driving an energy convergence between the oil and gas and power sectors. Presently, the oil and gas industry is not actively investing in geothermal technologies, favoring instead solar PV, onshore/offshore wind, biomass/gas, gas to power and storage. The macro-scale analysis is coupled with, twenty, semi-structured interviews with geothermal and energy specialists. The interviews provided an insight why oil and gas companies have resisted entering the geothermal industry. In addition the interviews were organized into a Political, Economic, Social, Technological, Legal and Environmental, PESTLE analysis to understand the present-day external environment of the geothermal industry in the USA today. The combined analyses indicate that the regulatory, business and finance environment for geothermal, in the USA, is challenging. Recent geothermal innovations that increase the footprint of the geothermal industry, offering new scalable, low-carbon baseload concepts, might provide an avenue for the oil and gas industry to enter the geothermal domain, while leveraging their existing core competencies, IP, technology, assets, and workforce knowledge skills and experience.

2.0 INTRODUCTION:

The availability of a fossil-fuel baseload energy supply has been the foundation of the developed world. Developing nations also desire access to high-density fuels to modernize and develop their own industries and economies. With an increasing population growth projected to hit 10 billion by 2100 [1], population growth coupled with a drive for modernization of underdeveloped economies, will put significant demand on existing resources such as oil and gas, energy critical elements, minerals, food and clean water [2]. The natural impact of population growth coupled with the modernization of developing economies in a business as usual scenario is an unavoidable increase in Greenhouse Gas (GHG) emissions. Rising GHG emissions lead to climate change and sea-level rise, potentially causing social and economic disruption [3, 4]. In addition, such population growth also will likely heighten the focus on energy security and sustainability especially for resource challenged countries.

Decarbonization, decentralization, democratization and digitization have become key mantra in a drive to avoid an increase in GHG emissions [3, 4]. Recent studies in the USA have suggested that the "*business as usual approach*" would have dramatic financial implications on the U.S. economy, arguing that inaction could lead to 10% loss of GDP by 2100 [5]. Yet, when researching energy in the USA, the dominant reference regarding the production of electricity, is the premise that energy is cheap and plentiful. Europe, in contrast, has higher electricity prices and a heightened awareness of energy security and an aging fossil-fuel infrastructure. The USA, has significant, although, finite oil resources, and this, coupled with the Trump Administration's (2016-2020) denial of the cause and consequence of anthropogenic global warming, is driving divergence of the renewable and sustainable economy in Europe vis-à-vis that in the USA [6]. Within Europe by contrast a string of high-profile Oil and Gas (O&G) companies, in response to Environmental Social Governance (ESG) pressures, are investing in renewables or announcing 2050 emissions targets [7]. Many carbon mitigation policies, to date, have supported the development of renewable technologies such as: wind, utility-scale solar photovoltaic (solar PV) and storage, leading to a dramatic fall in the Levelized Cost of Energy (LCOE) for these, easy to deploy, technologies [8-10]. Geothermal conversely has not received comparable benefits over the last ten years [11].

Ball [12] recently reviewed geothermal technologies concluding that the geothermal industry is diverse and multi-faceted covering a range of different environments, temperatures and uses. In summary there are the following categories:

(1) Conventional high enthalpy geothermal technologies (generally one of the three types - dry steam, flash steam, and closed-loop/binary) operating generally at temperatures above 150°C, and as low as 125°C if closed-loop/binary systems are installed.
(2) Conventional low-temperature geothermal technologies. These include geothermal heat pump or Ground Source Heat Pump (GSHP) and district energy systems
(3) Unconventional geothermal technologies, otherwise known as Enhanced Geothermal Systems (EGS), operating at temperatures above 150°C.

(4) Advanced low-enthalpy geothermal technologies. Low enthalpy or low temperature geothermal operates in the 70-150°C range. Advanced low-temperature geothermal can also include both closed-loop and closed-loop conduction developments.

(5) Advanced supercritical geothermal technologies. This emerging class of geothermal operates at temperatures from 150°C to 500°C. Advanced supercritical geothermal can also include both closed-loop and closed-loop conduction developments.

With the current focus on the decarbonization of the energy system and the need for a renewable baseload in order to avoid getting locked into a gas-infrastructure [13], several entities have recently suggested that the O&G industry ought to pivot into geothermal technologies. A pivot into geothermal closed-loop technologies would allow the O&G industry to leveraging core competencies, Intellectual Property (IP), technology, assets, and workforce; while meeting carbon neutrality commitments and portfolio diversification [14, 15].

The aims of this paper are fourfold, firstly to understand energy diversification trends within the O&G and power industry. Secondly, to understand whether geothermal technologies are playing a role in the evolving energy transition and their current position within energy companies low-carbon energy portfolio. Thirdly, to understand why the O&G industry has resisted investing in geothermal technologies. And, fourthly, to understand the external operating environment of geothermal in the USA.

3.0 METHODS

The research presented within this paper has been conducted using an exploratory methodology [16]. The original researched aimed to examine the paradox that geothermal, a low-carbon baseload power, was described as "*the forgotten renewable energy*" [17]. This research aimed to understand the discrete biases and opinions within the energy industry. To do this, the research was conducted using a mixed method approach [16]. Semi-structured interviews were chosen to build an understanding of a complex problem, coupled with quantitative analysis. End of year financial and sustainability reports formed a key resource used to examine the macro-energy environment.

The initial goal for the interviews was to target between 5-25 in number to provide the minimum number of interviews to make the study meaningful [18]. Invitations were extended to 32 experts, each invited expert was assigned a code which would be used for the interview to anonymize the responses, to protect the identity of the person interviewed. For example, the first person to be invited for interview was coded as GEOTH001. All the interview candidates were approached using email and LinkedIn (https://www.linkedin.com/). In total, 32 formal invitations were sent out to potential candidates between October and December 2019. In total twenty semi-structured interviews were successfully completed, representing a return rate of 62.5%. All twenty interviews took place between November and December 2019. Eighteen interviews were conducted using the video/telephone Zoom conferencing software (https://zoom.us/), and two interviews were conducted by phone. The eighteen recorded interviews were transcribed using Rev.com or Nvivo.com transcribing services. The transcribed interviews and notes from the telephone interviews were also entered into NVIVO software for qualitative analysis.

NVIVO is a software that enables qualitative analysis of the opinions expressed from the semi-structured interviews. The interviews were designed to provide flexibility, focusing on themes, rather than a strict set of questions [16]. While there were pre-prepared questions (Appendix A), no interview was the same, the questions often varied from interview to interview depending on the candidate and the discussion.

Attempts were consciously made to try to gather views from experts across different sectors of the geothermal and energy industry. All interviews conducted were guaranteed anonymity upfront in the study. This is known as cognitive access and it is an important process in negotiating participation [16]. The process of following-up initial contact with an email and an official invitation for participation enabled the interviewee to participate in an informed consent. In addition, before recording each interview, at the beginning of the interview, a face to face request for recording was again requested with the guarantee that each interview would remain confidential, this informed consent was an important step in gaining trust of the participants.

3.1. RESEARCH CONSTRAINTS AND LIMITATIONS

Potential limitations of this research can stem from: (a) the design of the analysis or data collection, (b) an inadequate number interviewees, (c) the qualitative nature of the results could be ambiguous, (d) the impact of new technologies may be uncertain; and (e) the future success of geothermal industries and the perception gained can be very different according to the experts accessed.

Data relating to company activities is not always in the public domain, and therefore activities collated in this study are only that which is public and reported publically in end of year financial reports. There may be some inherent errors present in this analysis since end of year reporting is generally delayed. This study, therefore, represents a picture that is available at the time of writing. This research was conducted from 2018 end of year and sustainability reports, which are published in early 2019, and interviews conducted in November and December 2019

4.0 RESULTS

4.1 DIVERSIFICATION TRENDS WITHIN THE OIL AND GAS AND POWER INDUSTRIES

In order to provide a quick snapshot of trends within the Power (P), Oil and Gas (O&G), Geothermal (G), and Emerging Renewable Power (ERP) companies, the end of year reports and sustainability reports from 2018 were analyzed (Tables 1a, 1b, 1c). In total 36 companies were analyzed. The analysis, while not concerned with the cash-value or the scale of energy produced, does help build an understanding whether companies are diversifying into low-carbon technologies.

With respect to technologies used, several macro-trends can be identified these are: (1) The dominant diversification of the studied companies is in to solar PV, onshore/offshore wind, energy storage, biomass/gas, and gas to power. (2) Hydroelectric and geothermal and heat cogeneration (waste heat) are common, the former two appear, however, to be the result of acquisition and merger, rather than exploration or development of new resources particularly in the case of the power companies. (3) There is a divergence between Europe and the USA in terms of energy diversification strategy with respect to O&G companies, the same trend is mirrored by within the power industry. (4) SHELL, is the most diversified company of the 36 companies studied with sixteen energy technologies in their portfolio. They are closely followed by followed by Equinor, TOTAL, EDF with fifteen technologies and ENEL and ENGIE with fourteen technologies. (5) Power companies are more likely to be diversified into geothermal, hydroelectric, solar PV and wind and biomass/gas than O&G companies. (6) O&G companies dominate the drive towards Carbon Capture Utilization and Storage (CCUS) and hydrogen. (7) Power companies are dominantly developing battery storage, although this trend is closely followed by the major O&G companies. (8) Power companies are dominantly in nuclear. (9) Most O&G companies have a foothold in waste heat but not geothermal energy. (10) There was one industry that does not appear to be diversified and this is the geothermal industry, where most companies rely on one to three geothermal technologies, and they are rarely diversified beyond the thermal/geothermal domain.

Geothermal Companies	Geothermal	Heat Pumps	Waste Heat	Hydroelectric	Solar PV	Wind Onshore	Wind Offshore	Biomas/ Gas	BioFuel	Landfill Gas	Reference
BHE (P)	x			x	x	x		x			[19]
CALPINE (P)	x										[20]

CLEAG (G)	x										[21]
CLIMEON (G)	x		x								[22]
EAVOR (G)	x										[23]
GreenFire (G)	x										[24]
Innergex (ERP)	x			x	x	x					[25]
J-Power (P)	x			x		x					[26]
KenGen (P)	x		x	x	x	x					[27]
ORMAT (G)	x		x		x						[28]
Razor (O&G)	x										[29]
Terra-Gen (P)	x				x	x					[30]
Power Companies	**Geothermal**	**Heat Pumps**	**Waste Heat**	**Hydroelectric**	**Solar PV**	**Wind Onshore**	**Wind Offshore**	**Biomas/ Gas**	**BioFuel**	**Land Gas**	**Reference**
Dominion Resources (P)				x	x	x	x	x			[31]
Duke Energy (P)				x	x	x					[32]
EDF (P)	x	x	x	x	x	x	x	x			[33]
ENEL (P)	x		x	x	x	x		x		x	[34]
ENGIE (ERP)	x	x		x	x	x	x	x			[35]
ELEXON (P)				x	x	x		x		x	[36]
IBERDROLA (P)			x	x	x	x	x	x			[37]
National Grid (P)					x	x	x				[38]
NEXTERA (P)					x	x					[39]
Southern Company (P)				x	x	x		x			[40]
EON (P)	x	x	x		x	x	x	x			[41]
ØRSTED (ERP)	x	x	x		x	x	x	x			[42]
O&G Companies	**Geothermal**	**Heat Pumps**	**Waste Heat**	**Hydroelectric**	**Solar PV**	**Wind Onshore**	**Wind Offshore**	**Biomas/ Gas**	**BioFuel**	**Land Gas**	**Reference**
OXY (O&G)			x		x						[43]
BP (O&G)					x	x	x	x	x	x	[44]
Chevron (O&G)							x		x		[45]
CNR (O&G)			x						x		[46]
ConocoPhillips (O&G)									x		[47]
Devon (O&G)											[48]
ENI (O&G)				x	x		x	x	x		[49]
Equinor (O&G)	x		x		x		x	x	x	x	[50]
SHELL (O&G)	x		x		x	x	x	x	x	x	[51]
Suncor (O&G)			x		x	x			x		[52]
TOTAL (O&G)				x	x	x	x	x	x		[53]
ExxonMobil (O&G)			x						x		[54]
Trend Analysis	**Geothermal**	**Heat Pumps**	**Waste Heat**	**Hydroelectric**	**Solar PV**	**Wind Onshore**	**Wind Offshore**	**Biomas/ Gas**	**BioFuel**	**Land Gas**	
TOTAL	**18**	**4**	**14**	**14**	**24**	**21**	**13**	**15**	**10**	**5**	
Geothermal (12)	**12**	**0**	**3**	**4**	**5**	**5**	**0**	**1**	**0**	**0**	
Power (12)	**3**	**4**	**5**	**8**	**12**	**12**	**7**	**9**	**0**	**2**	
O&G (12)	**1**	**0**	**6**	**2**	**7**	**4**	**6**	**5**	**10**	**3**	

Table 1a: Industry diversification trends. Extracted from Year End shareholder and sustainability reports published in 2018, (see references). Twelve companies from Geothermal (G), modified from

ReportLinker [55], Power Companies (P), top ten after Walton, [56] and western International Oil and Gas companies after Forbes, [57]. Solar PV - utility-scale solar photovoltaic.

Geothermal Companies	Hydrogen	Storage/ Li-Battery	Storage/ H2-Battery	Fuel Cell	Gas to Power	Oil to Power	Coal	Nuclear	Gas Exploration	Oil Exploration	Electricity Distribution/ Transmission	CCUS	Reference
BHE (P)		x			x		x				x		[19]
CALPINE (P)													[20]
CLEAG (G)													[21]
CLIMEON (G)													[22]
EAVOR (G)													[23]
GreenFire (G)													[24]
Innergex (ERP)													[25]
J-Power (P)							x	x			x		[26]
KenGen (P)													[27]
ORMAT (G)		x											[28]
Razor (E&P)									x	x			[29]
Terra-Gen (P)		x											[30]
Power Companies	**Hydrogen**	**Storage/ Li-Battery**	**Storage/ H2-Battery**	**Fuel Cell**	**Gas to Power**	**Oil to Power**	**Coal**	**Nuclear**	**Gas Exploration**	**Oil Exploration**	**Electricity Distribution/ Transmission**	**CCUS**	**Reference**
Dominion Resources (P)		x			x	x	x	x			x		[31]
Duke Energy (P)		x			x	x	x	x			x		[32]
EDF (P)	x	x			x	x	x	x			x		[33]
ENEL (P)		x	x		x	x	x	x			x		[34]
ENGIE (ERP)	x	x	x	x	x			x			x		[35]
ELEXON (P)		x			x	x		x			x		[36]
IBERDROLA (P)		x			x		x	x			x		[37]
National Grid (P)		x									x		[38]
NEXTERA (P)		x			x	x	x	x			x		[39]
Southern Company (P)		x			x		x	x			x		[40]
EON (P)		x			x			x			x		[41]
ØRSTED (ERP)		x									x		[42]
O&G Companies	**Hydrogen**	**Storage/ Li-Battery**	**Storage/ H2-Battery**	**Fuel Cell**	**Gas to Power**	**Oil to Power**	**Coal**	**Nuclear**	**Gas Exploration**	**Oil Exploration**	**Electricity Distribution/ Transmission**	**CCUS**	**Reference**
OXY (O&G)					x				x	x		x	[43]
BP (O&G)	x	x		x					x	x		x	[44]
Chevron (O&G)	x	x							x	x		x	[45]
CNR (O&G)	x								x	x		x	[46]
ConocoPhillips (O&G)									x	x		x	[47]
Devon (O&G)				x					x	x			[48]
ENI (O&G)	x	x			x			x	x	x		x	[49]
Equinor (O&G)	x	x		x	x				x	x	x	x	[50]
SHELL (O&G)	x	x		x	x				x	x	x	x	[51]
Suncor (O&G)	x				x				x	x		x	[52]
TOTAL (O&G)	x	x		x	x		x		x	x	x	x	[53]
ExxonMobil (O&G)		x		x			x		x	x		x	[54]

Trend Analysis	Hydrogen	Storage/ Li-Battery	Storage/ H2-Battery	Fuel Cell	Gas to Power	Oil to Power	Coal	Nuclear	Gas Exploration	Oil Exploration	Electricity Distribution/ Transmission	CCUS	
TOTAL	10	22	2	7	17	6	11	12	13	13	17	11	
Geothermal (12)	0	3	0	0	1	0	2	1	1	1	2	0	
Power (12)	2	12	2	1	10	6	7	10	0	0	12	0	
O&G (12)	8	7	0	6	6	0	2	1	12	12	3	11	

Table 1b: Industry diversification trends. Extracted from Year End shareholder and sustainability reports published in 2018, (see references). Twelve companies from Geothermal (G), modified from ReportLinker [55], Power Companies (P), top ten after Walton, [56] and western International Oil and Gas companies, Forbes, [57]..

Geothermal Companies	Total Diversification	Power Companies	Total Diversification	O&G Companies	Total Diversification
BHE (P)	9	EDF (P)	15	SHELL (O&G)	16
J-Power (P)	6	ENEL (P)	14	Equinor (O&G)	15
KenGen (P)	5	ENGIE (ERP)	14	TOTAL (O&G)	15
Innergex (ERP)	4	Dominion Resources (P)	11	BP (O&G)	12
ORMAT (G)	4	IBERDROLA (P)	11	ENI (O&G)	12
Terra-Gen (P)	4	EON (P)	11	Suncor (O&G)	9
Razor (O&G)	3	ELEXON (P)	10	ExxonMobil (O&G)	8
CLIMEON (G)	2	Duke Energy (P)	9	Chevron (O&G)	7
CALPINE (P)	1	Southern Company (P)	9	OXY (O&G)	6
CLEAG (G)	1	ØRSTED (ERP)	9	CNR (O&G)	6
EAVOR (G)	1	NEXTERA (P)	8	ConocoPhillips (O&G)	4
GreenFire (G)	1	National Grid (P)	5	Devon (O&G)	3

Table 1c: Industry diversification trends, ranked by technology. For energy technology description see tables 1a and 1b. Company type: P- Power Company, ERP – Emerging Renewable Power Company, G – Geothermal Company, O&G – Oil and Gas Company.

4.2. ADOPTION OF GEOTHERAM/THERMAL TECHNOLOGIES IN THE ENERGY DIVERSIFICATION

Analysis of the geothermal/thermal technology diversification of the 36 studied companies reveals additional insights into the limited uptake of this low-carbon baseload technology (Table 2). As with the analyses in Tables 1a and 1b, if the values are taken at face value, without knowing the amount spent, the power produced the following trends are observed: (1) the most popular thermal technology is the application of waste heat, which is not strictly a geothermal technology, although it shares much of the above ground technology. (2) Conventional geothermal using flash steam technologies are the second most popular geothermal technology in use. (3) The most diversified companies in geothermal/thermal technologies are: SHELL, EDF and ENEL, each with four geothermal/thermal technologies in their portfolio. (4) The most diversified geothermal company is ORMAT, with three geothermal technologies. The paradox here is that power companies and an O&G company are more diversified in geothermal/thermal than a company that exploits heat as its core business. (5) The O&G and power companies that are publicly engaged in research and development in the geothermal domain appear to be largely involved in conduction closed-loop and supercritical technologies. These companies are SHELL, Equinor, ENEL and J-Power. (6) Only EDF and Equinor are playing the EGS technology, the former with the world's first commercial power plant located in France. (7) District energy is largely developed by European renewable and power sectors (EDF, ENGIE, EON, ORSTED, SHELL). (8) In the power industry it is common for companies to be in both waste-heat and geothermal. (9) Power and O&G companies are investing in waste-heat, yet it is not common for them to have district energy or geothermal heat-pumps. The companies that diverge are ENGIE, ØRSTED, EDF, all of which are power companies. (10) only one company appears to be developing geothermal power project at existing oil and gas facilities.

	Domestic Scale		Industrial scale (Scalable 10-150 MW)								
	Domestic Scale	Industrial Heat/Electricity			Low-Enthalpy	Super-critical	High-Enthralpy				
	Thermal Products			Emerging			Unconventional	Conventional			
Company Name	Home-scale Heat Pumps	District Geothermal Cooling/Heat	Waste Heat	Oil Field CPH*	Closed-Loop Electric & Heat*	Super-critical*	EGS*	High-Enthralpy Binary /ORC	Steam FLASH/Dry (single/double)	TOTAL	Reference
Berkshire Hathaway Energy (P)								x	x	2	[19]
CALPINE (P)									x	1	[20]
CLEAG (G)					x					1	[21]
CLIMEON (G)			x		x			x		3	[22]
CNR (E&P)			x							1	[46]
EAVOR (G)					x					1	[23]
EDF (P)	x	x	x				x			4	[33]
ENEL (P)			x			x (DESCRAMBLE)		x	x	4	[34]
ENGIE (ERP)	x	x							x	3	[35]
EON (P)		x	x							2	[41]

Equinor (O&G)			x			x (IDDP)	X (DEEPEGS)			3	[50]
ExxonMobil (O&G)			x							1	[54]
GreenFire (G)					x	x				2	[24]
IBERDROLA (P)			x							1	[37]
Innergex (P)								x	x	2	[25]
J-Power (P)						x (Greenfire)			x	2	[26]
KenGen (P)			x						x	2	[27]
ORMAT (G)			x					x	x	3	[28]
ØRSTED (ERP)	x	x	x							3	[42]
OXY (O&G)			x							1	[43]
Razor (O&G)				x						1	[29]
SHELL (O&G)		x	x		x (EAVOR)	x (Greenfire)				4	[51]
Suncor (O&G)			x							1	[52]
Terra Gen (P)									x	1	[30]
TOTALS	3	5	14	1	5	5	2	5	9		

Table 2: Detailed analysis of Geothermal and waste heat technologies (extracted and compiled from End of Year Reports and sustainability reports from 2018, see references). * Emerging geothermal technology. CPH – Coproduced heat. ORC – Organic Rankine Cycle technology for closed-loop; EGS – Enhanced Geothermal System; GSHP – Ground Sourced Heat Pump. (DESCRAMBLE) indicates a research and development project or collaboration, DESCRAMBLE Project [58], IDDP and DEEP ESG [59], EAVOR [23] and GreenFire [24].

4.3 QUALITATIVE ANALYSIS

Twenty semi-structured interviews formed the basis of the primary data collection for this exploratory research (Table 3). The completed interviews ranged from 130 to 45 minutes, with an average of 81.5 minutes +/- 25.6 minutes. From the interview pool, the average work experience in geothermal industries was 8.7, +/- 9.0 years. The spread of work experience was from 1 year to 35 years. Eleven of the twenty interviews were USA based geothermal experts, eight from the European region (EU and EEA) and one from Asia. While six interviewees did not have experience in the USA geothermal markets, their experience and opinions were very useful for the understanding of issues within the geothermal markets. Overall, the dominant experience was from California with 13 of 20 candidates having experience in California. The interviews accessed a spread of backgrounds with the exception of regulatory and the Power sectors.

Code	Gender	Location	LOCATION	Experience	Technical Background	Role	Experience Base	US Experience Base	Present Company Type	Interview Length

GEOTH002	Male	USA	USA	35	Engineer	Consultant	International	California	Consulting - Geothermal Development	130
GEOTH003	Male	EEA Area	Switzerland	6	Business	Business Development	International	N/A	Geothermal Startup	84
GEOTH004	Male	USA	USA	25	Business/Economics	Leader	International	California	Geothermal Startup	102
GEOTH006	Male	USA	USA	2	Geoscientist	Leader	USA	California	Geothermal Startup	46
GEOTH012	Male	USA	USA	4	Geoscientist	Leader	International	All	International E&P Company	91
GEOTH014	Male	USA	USA	20	Geoscientist	Leader	USA	California	Institution - Geothermal Association	64
GEOTH015	Male	EEA Area	Iceland	10	Legal	Leader	International	N/A	Institution - Geothermal Marketing	97
GEOTH017	Male	USA	USA	10	Geoscientist	Consultant	International	Nevada, California	Consulting - Geothermal Consulting	96
GEOTH018	Male	Europe	France	3	Engineer	Investment	International	California	International E&P Company	59
GEOTH020	Female	USA	USA	15	Geoscientist	Leader	International	ALL	Institution - Governmental	75
GEOTH022	Female	Europe	Netherlands	2	Econocmics	Project Manager	International	Texas	Institution - Governmental	58
GEOTH023	Female	Europe	Sweden	2	Geoscientist	Investment	International	All	Geothermal Startup	67
GEOTH024	Male	Europe	Denmark	1	Engineer	Technical	International	N/A	Geothermal Startup	97
GEOTH025	Male	USA	USA	2	Engineer	Leader	USA	ALL	Geothermal Startup	57
GEOTH027	Male	Asia	Japan	2	Geoscientist	Technical	International	N/A	Geothermal Startup	90
GEOTH028	Male	Europe	Ireland	1	Geoscientist	Consultant	International	N/A	Consulting - Energy Transition	81
GEOTH029	Female	Europe	UK	8	Geoscientist	Sales	International	N/A	Consulting - Service Industry/ Software	108
GEOTH030	Male	USA	USA	10	Marketing	Leader	International	All	Geothermal Marketing	45
GEOTH031	Male	USA	USA	6	Business	Business Development	International	All	Consulting - Geothermal Development	51
GEOTH032	Female	USA	USA	10	Legal	Leader	International	All	Institution - Academic	130

Table 3: Profiles of those interviewed, with identity protected to maintain confidentiality. GEOTH001 for example is a code given to the first invited expert and their response was anonymized using this code.

4.3.1 Themes extracted using NVIVO

The benefit of semi-structured interviews is that they can be used to gain an insight into complex problems. The interviews were broad and in-depth, with some interviews lasting as long as 130 minutes (Table 3). The transcribed interviews were loaded into NVIVO v12 for quantitative analysis [60]. The interviews were semi-manually coded within the software, key words combined with their synonyms were screened across all twenty transcribed interviews. NVIVO uses basic natural language processing to aid the rapid coding of the transcriptions. Finally, the coded terms were organized into identified themes to address the research aims (Table 4). The interviews were designed to answer the following questions: What are the barriers to the O&G adoption of geothermal? And, what is the external operating environment for the Geothermal industry in the USA? For the latter the following themes were identified: Political, Economic, Social, Technological, Legal and Environmental. These themes combine to form what is known as a PESTLE analysis [61]. The PESTLE analysis is a strategic framework used to understand the present-day external environment of the geothermal industry in the USA.

Theme	Files (Interviews)	Codes (Total Including Sub-Themes)
Barriers to Geothermal	20	238
Politics	17	282
Economics	18	142
Social	14	48
Technological	19	169
Legal	7	18
Environmental	9	23

Table 4: Table showing the main themes and the number of interviews that discussed these themes and or their sub-themes. The codes were attributed to the themes after manual coding.

4.4: BARRIERS TO OIL AND GAS ADOPTION OF GEOTHERMAL

Tables 1 and 2 revealed that of the major O&G companies only SHELL and Equinor are investing resources in geothermal technology development. Yet, it is worth commenting that their investments are not in the conventional domain. Those power companies that are in geothermal appear to have entered into it through merger and acquisition activities. Although a few of the power companies are developing geothermal with ENEL, EDF, ENGIE, KenGen, and J-Power all investing in new developments and geothermal technology development.

If the USA is to meet an international target of GHG reduction by 2050, several interviewees argued that companies the scale of O&G could assist in developing the needed technological advances which could help make geothermal a sustainable baseload for the future (GEOTH020; GEOTH032). In fact 11 of 20 experts thought that engagement with O&G companies was beneficial to overcoming many of the barriers due to the scale of resources an O&G company can bring (Public Relations (PR), experience, legal, drilling, subsurface, financial, systems/control). It was highlighted that O&G's involvement in the geothermal industry would be a "*game-changer*" (GEOTH014). Furthermore, a key argument cited was that the conventional geothermal industry is "*20-30 years out of date*" (GEOTH015; GEOTH020; GEOTH028; GEOTH032).

Yet, it was acknowledged that there were significant barriers that highlight why O&G companies currently find it hard to adopt conventional and unconventional geothermal technologies. The top barriers are summarized in order of importance in Table 5. It is clear that there are many technical/operational, commercial, legal and stakeholder barriers. Furthermore, there are a clear failures to manage public relations and educational aspects. The failure to bring along governments, local administration and the public has resulted in many people simply rejecting the geothermal development concept before they know what it is. While many of these issues are directly linked to conventional and unconventional geothermal, educational ignorance and pattern of life (owner vs renter and short-term economic/policy vision), particularly for GSHP and district energy developments. It is however, clear that the stakeholder management and educational aspects extends to all existing and future geothermal technologies.

A strategic fit was proposed between the geothermal industry and the O&G industry rather than the power industry because: (a) the O&G industry is highly experienced in managing risk and capitally intensive projects over longer timelines. (b) They also have many of the required skills that can be utilized for the sub-surface, engineering, drilling and project management requirements associated with geothermal development. (c) If the O&G industry do not diversify they may not survive as an industry, they need to maintain a social license to operate, which geothermal can give them. (d) Several companies are already diversifying and entering the utility markets with other renewables, (e) Ultimately, because of the size of their PR, Lobbying and financial resources and the scale of O&G companies can lead to an "*overnight 20% cost reduction in drilling and casing, due to an economy of scale*" (GEOTH015).

With respect to O&G companies the major reason for lack of interest was simply down to the return on investment (GEOTH018). It was bluntly put by GEOTH002 "*O&G companies simply make too much money from oil and gas to be bothered with geothermal*". Other interviewees, proposed that it was (a) just too easy to turn to wind, solar PV and battery storage to appease ESG demands of investors

(GEOTH002), and (b) geothermal development timelines were "*too long*" and the resources "*too small*" and when compared to wind and solar PV when looking to "*quickly develop 25GWe"* (GEOTH018). The remoteness or miss-alignment of geothermal resources and population centers (GEOTH002) which intensifies the issues of geothermal heat and derived power in the discussion of commodity vs utility (GEOTH002). The arguments always boil down to money and this underpinning the reason for O&G not being involved in geothermal. Essentially a lack of incentives and the lack or return on investment, for example: "*You have the same risk, but you have the financial returns of a utility company*" (GEOTH015). Finally, one aspect that is insightful from the perspective of an international O&G company was scale. *"[O&G tend] to have global operations, and the problem with a new conventional geothermal business stream is that it is only available to nine percent of the world"* (GEOTH012).

Innovation within the geothermal industry including, low-temperature closed-loop and closed-loop conduction technologies, does, however, give some hope for decoupling geographic restrictions and geothermal heat and power (GEOTH020; GEOTH032). Increasing the footprint of the geothermal industry, with scalable, baseload concepts, might provide an avenue for the oil and gas industry to enter the geothermal domain, while leveraging their existing core competencies, IP, technology, assets, and workforce knowledge skills and experience (GEOTH012).

4.4.1. Recommended pathway or solutions to stimulate geothermal development

Thirteen of twenty experts offered solutions how governments can stimulate activities these are summarized also in Table 6, although not ranked in order of importance. The inclusion of the O&G industry is however not a prerequisite however to the proliferation of geothermal, there are other mechanisms or levers that governments could use to develop an industry that is ripe and innovating at high rates. A number of experts proposed that a carbon price or carbon trading scheme might encourage O&G companies [GEOTH002; GEOTH003; GEOTH012; GEOTH014; GEOTH015; GEOTH025; GEOTH029]. Major criticism in the USA during interviews, was directed at the failure of governmental policy, its inconsistency and the bias or failure of incentivization schemes that did not account for baseload development. It is clear that a long-term, baseload incentive scheme for at least 15 years would incentivize geothermal development. It was also voiced during some interviews that if government energy policy would replicate the incentives the O&G industry have enjoyed this would likely lead to significant innovation and exploration in the area [GEOTH004; GEOTH032]. A number of interesting proposals with respect to how governments can regulate were proposed these range from fast-tracking geothermal permitting and exploration licenses [GEOTH020; GEOTH025], to re-inventing O&G style tax deductions (e.g. Norway), drilling insurance, [GEOTH004; GEOTH012; GEOTH029] or conducting exploration [GEOTH012; GEOTH027]

Top technical/operational barriers to geothermal:
Subsurface risk and uncertainty
Induced seismicity
Water demand
Environmental discharges & corrosion
Heatloss
Heatflow
Fracking
Safety
Top commercial barriers to geothermal:
Return on investment
Cost drilling and casing
Policy bias or lack of importance attributed to baseload power
Access to PPA and price protection for geothermal (baseload)
Highly capital intensive & time to develop geothermal
Scale of resource size (barrier to O&G)
Commercial success rate
Remote locations & not a commodity i.e. non-transportable
Cheap US electricity - market competition
Limited geographic penetration globally (lack of running room)
Top non-technical/commercial barriers to geothermal:
Failure in Public Relations and marketing
Education i.e. lack of knowledge leading to inherent misconceptions
Stakeholder alignment
Legal framework - redevelopment of oil and gas fields
Success of E&P fracking managing land and access and drilling permits

Table 5: Top barriers to geothermal progression and recommendations stimulate geothermal development

Recommended pathway or solutions to stimulate geothermal development:
Get oil and gas interested to reduce costs and manage PR and government
Carbon Trading or Carbon Tax Schemes needed
Long-term (15-20 years) Government led energy policy incorporating low-carbon baseload energy with incentives for development of heat and power
Valorization of heat with new business models
Governments need to offer baseload Renewable Energy Certificates (RECS) – which incentivize companies to develop baseload low-carbon power.
Government tax breaks for exploration and R&D (e.g. Norway which allowed Norway allowed companies since 2005 to deduct 78% of their exploration costs from taxable income).
Fast-track geothermal permitting and exploration licenses.

Develop an energy efficiency scheme for homes/buildings which impact value of homes
Government/Industry led drilling-insurance incentive scheme for drilling (failed wells 80% return on cost – successful wells pay additional tax on development for 10 years)
Have Government led thermal and hydrothermal exploration (As recently announced in Japan/Indonesia)

Table 6: Recommendations to stimulate geothermal development

4.5: THE EXTERNAL ENVIRONMENT FOR THE GEOTHERMAL INDUSTRY

The interviews responses were organized to give a PESTLE analysis of the present-day external environment of the geothermal industry in the USA today.

4.5.1. Political

In relation to conventional and unconventional geothermal technologies many interviewees acknowledge the work of the US Department Of Energy (DOE) and the National Renewable Energy Laboratory (e.g. NREL), or the United States Geological Survey (USGS), (GEOTH012; GEOTH025). Much of this work has led to the characterization of the geological environment and heat-flow in the USA or in setting up demonstration sites for geothermal research (GEOTH012, GEOTH020; GEOTH025). Meanwhile many were critical of the “cyclicity” of policy (e.g. Public Utility Regulatory Policies Act (PURPA) which did not last long enough to enable the geothermal industry to get going (GEOTH004). The policy cyclicity has meant that no policy period has given the 15 years’ of support that the industry needs to enable it to make significant progress (GEOTH003). In addition, there was extensive criticism of the effectiveness of the Geothermal Resource Council (GRC) which is based in California (GEOTH004). It was argued that the GCR has failed to protect and market geothermal industries as a renewable and baseload source and to challenge the government with respect to its policies on global warming (GEOTH025).

Several interviewees argued that California forms the most interesting State in the USA to examine the clash between State vision and the lack of a Federal vision over climate change and energy policy. In contrast to the current Trump Administration (2016-2020), California is extremely progressive in its outlook for GHG reductions, with the revised SB-100 Bill (GEOTH025). The geographic overlap between geothermal technologies and wind, solar PV and storage and aggressive state decarbonization goals make California a potential front-line between dispatchable and non-dispatchable technologies. Because of policy-bias towards wind and solar PV, driven in part, among many other factors by the Investment Tax Credit (ITC), the growth of wind and solar PV has been exponential. The policy bias led GEOTH004 and others to argue that there is a need for honest assessment of the cost of energy, because current LCOE do not consider the costs of ramping up and down the essential backup baseload energy technologies: geothermal, hydro, coal, gas and nuclear, (GEOTH002; GEOTH004). Neither do current LCOE reveal the cost of storage facilities, grid integration costs and emissions (GEOTH002).

Other policies that have been extensively discussed in relation to California or sometimes Texas are the Renewable Portfolio Standards (RPS) which are placing geothermal at a disadvantage because there is no expression of which energy technology should be used (GEOTH002). This therefore leads businesses and investors to look at what is the fastest and cheapest to deploy, and with the other tax incentives this is wind and or solar PV (GEOTH002). It was proposed that if these policies are renewed they need to have a component that protect energy from baseload sources (GEOTH002).

In summary, the U.S. federal, political environment of climate denial (GEOTH025), inaccurate assessment of energy pricing (GEOTH004), policy bias with respect to tax credits and financial incentives provides a challenging business environment for the conventional and unconventional geothermal industry within the USA (GEOTH002; GEOTH003; GEOTH004; GEOTH006; GEOTH012; GEOTH018). The biggest issue was that there was no coherent energy policy that valued a renewable and sustainable baseload energy (GEOGH004; GEOTH032). This is driven by political short-termism and a refusal to address energy security and climate change in the USA, largely due to a long-term belief that the USA should have cheap electricity and a central reliance on the oil and gas industry and policies that favor it or do not limit its production or use. Because of these combined factors in the USA the direct application of geothermal technologies, which is a mature technology, is severely under-utilized. Finally, the expectation that policy bias may change is low, largely because in the USA regulation and government interference is not tolerated, unlike many other parts of the world (GEOTH027). In some respects, the future of the geothermal industry in the USA, seems to be in the hands of climate-aware private investors, unless there is a significant change with respect to governmental policy (GEOTH002; GEOTH006; GEOTH012; GEOTH017; GEOTH025; GEOTH032).

4.5.2. Economic

A positive economic case for the geothermal industry is that in the USA there is a hugely skilled workforce in large part due to crossover with the oil and gas industry (GEOTH012). Plus, there are many university specialist departments and research groups and institutions in the USA (GEOTH025; GEOTH032). However, a key energy characteristic of the USA is its history of low-cost electricity and abundant oil and gas. Historically the fluctuation of oil and gas price, worries over energy security, and government policy has influenced the involvement of O&G companies in the geothermal industry, over time (GEOTH004). When the price of oil was high or there were geopolitical issues and energy security issues, geothermal was on the agenda. More recently, the overwhelming success of the oil and gas industry with fracking has served to give the USA an oil and gas surplus which no one would have thought possible 15 years ago (GEOTH032).

Short-termism and low-cost are the apparent barriers to advancement of geothermal energy, with investors prioritizing quick returns with investments in wind and solar PV (GEOTH002). Secondly, the fact that investors earn more money from the development of fossil-fuel infrastructure (GEOTH002). Thirdly, the distances from resource to population centers, combined with value mechanism for heat means that many geothermal projects remain uneconomic. A discussed example that was brought up is the San Diego Gas and Electric company. This company has zero megawatts of geothermal, but it has big investments in both in solar PV and wind and gas turbines, even though they operate in a region where some of the best geothermal resources have been characterized (GEOTH002). While rate payers are not affected, the problem is both economic, political and educational. Because, it is investors who benefit from the building of combined cycle gas turbines, which are constructed cheaply to support and supplement the development of, cheap, non-dispatchable wind and solar PV. Gas turbines were selected rather than using a local sustainable geothermal resource, which is considerably lower in emissions. The lack of planning, combined with inconsistent carbon mitigation policies allow power companies to follow the cheapest economic solution, regardless of the environmental impact. The resulting fallout is that while rate payers are not economically affected, their power supply does not align with the Paris Treaty Agreement, even though a low-carbon baseload is available on their doorstep (GEOTH002).

The proliferation of renewables in California has also had other impacts. The drive to develop solar PV in California did demonstrate an ability to reduce GHG emissions, however it has resulted in daytime prices crashing, this is problematic when an unregulated market allows the energy company to simply buy the cheapest power. With abundant solar PV, geothermal energy is not able to compete especially when prices are negative (GEOTH025). GEOTH025 explained that there may be some geothermal optimism in the next ten years for geothermal power industry. The Californian integrated resource plans show that somewhere between 2022 and 2026 the state will have so much solar PV that daylight hours will be supplied by solar PV derived power. The implication is that cheap gas will fill the gap. But the SB-100 bill requires up to 60% decarbonization of the energy infrastructure, meaning geothermal could gain some traction looking forward. However, there is a new emerging threat to geothermal and this is from battery storage (GEOTH004). Some interviewees, identify a possible economic window of opportunity to develop geothermal resources, in order to supply a flexible, low-carbon, baseload power at night-time (GEOTH004; GEOTH025).

Geothermal ultimately cannot compete head-to-head with onshore wind and solar PV, however, the hidden costs of non-dispatchable technology are not reported in LCOE calculations. This lead several interviewees to propose there is no honesty in the reporting of energy costs which in turn leads to policy bias (GEOTH002; GEOTH003; GEOTH004). A key question was proposed by GEOTH002, which is that the discussion on economics should not be can geothermal compete, but rather how can it reduce GHG emissions in a cost effective way over the long-term? Whether we talk about Conventional heat and power or indeed direct use via GHSP or district energy, the discussion should also focus on the value of grid stability geothermal brings as a result of its baseload nature and combined with the fact it provides cost-efficient carbon emissions abatement.

At the scale of GSHP, GEOTH002 provided a good argument for the role these simple technologies can play. Yet the advantages are not spoken of and it is ultimately the homeowner who shoulders all the risk of the investment. The GSHP, is the perfect example of distributed benefits without the beneficiaries paying. All the investment is made by the homeowner, yet his/her investment impacts the ratepayers because of the grid stability the GSHP brings. GSHP behave as a baseload and help to reduce the peaks and troughs in the energy supply. Therefore, everyone benefits but the Power company has not had to contribute a penny (GEOTH002). Cost is largely cited as a prohibitive issue for GSHP because individual projects can become costly. One solution proposed was that innovation could impact the costs and entrepreneurial businesses could develop business models, building partnerships with banks, suppliers, drillers that open up economies of scale, thus dropping costs (GEOTH002).

Ironically geothermal companies repeat the process, but at scale, because a barrel of steam, it is not a commodity like oil, which can be transported (GEOTH002; GEOTH017). A geothermal developer has to invest in converting the steam to electricity and selling the electricity. This requires a Public Purchase Agreement (PPA) or selling electricity on the marketplace, where prices can vary according to demand (GEOTH012). When trying to win investment the economics of a geothermal plant fail without the guarantee of a PPA (GEOTH017). This poses a second problem, as an independent electricity or heat producer, there are three fundamental economic issues: (1) electricity is cheap and plentiful in the USA (GEOTH002); (2) heat is a commodity that does not have a clear business value at least in the USA; (3) when selling electricity, no one makes significant money from the sale of electricity on a 30-year contract, especially not the geothermal distributor who does not benefit from the peaks or variability of non-dispatchable technologies. The only group that would ultimately benefit are the rate-payers. The general problem with this is that currently the environment and rate payer interests and those of the investors, are not aligned (GEOTH002). No investors earn money if power is bought from a geothermal developer. Investors earn money if a utility company owns and builds its own power plants (GEOTH002; GEOTH004). One solution perhaps is that geothermal companies could develop themselves as integrated energy companies.

One of the issues relating to the economics of geothermal developments is that geothermal is often identified as a niche industry with boutique development that are non-reproducible. In relation to how to drive costs down, several interviewees had opinions (Table 3b). Critically, smarter integration of oil and gas technology and exploration methods were cited (GEOTH015; GEOTH020; GEOTH032). Oil and gas practices using a portfolio approach improve chances of locating and drilling the best resources (GEOTH006; GEOTH015; GEOTH032). Finally, economies of scale were argued for because a company the size of an oil and gas company could bring down costs because of the scale of its business.

4.5.3. Societal

The interviews reveal that there is an unfortunate problem that most stakeholders, investors, decision makers and the general public do not know or understand what geothermal is and what it can mean to them. Geothermal needs to educate and challenge people's perceptions, for example geothermal does not require that you live next to a volcano, neither does geothermal cause environmental damage.

The issues of global warming and climate change are complex, and many stakeholders do not understand them, or deny they exist (GEOTH004; GEOTH006; GEOTH015; GEOT017; GEOTH22; GEOTH025; GEOTH027; GEOTH030). It is not surprising therefore that when it comes to policy geothermal technologies do not get considered, because no one fully understands the grid stability and the environmental benefits, meaning lower GHG emissions and flexible baseload heat and power, that geothermal can bring (GEOTH002; GEOTH025). Geothermal companies have historically failed to educate the stakeholders, with the GRC coming under fire in several interviews (GEOTH004, GEOTH025). Currently in the USA most geothermal projects are limited to power production. But in reality, a creative use of the heat which could be daisy-chained or cascaded down into the community for different uses, could provide significant benefits to an ecosystem of businesses and communities (GEOTH012).

Geothermal whether conventional, unconventional, low-temperatures, or advanced can also create jobs and importantly it can save people money in the long-term, because they do not need to purchase electricity or gas (GEOTH002; GEOTH004; GEOTH012; GEOTH15; GEOTH020). "*There are huge societal benefits of geothermal – district heating and heat pumps, but no one is talking about them openly. They want us to keep buying fossil fuel derived power"* (GEOTH002). It was also noted that installing a GSHP while saving 50% of required energy, it may even add value to the price of a property (GEOTH012). It was highlighted furthermore that geothermal ultimately contributes to energy stability, and could reduce energy poverty, particularly for lower income families, if the costs of installation can benefit "*kitchen table economics*" (GEOTH028)

In summary, the geothermal industry needs to market the value of power and direct use heating and cooling. This can be achieved by working with architects, city/town planners and business to develop geothermal ecosystems so businesses and homes can maximize benefit from the technology and developments. The geothermal industry also needs to better highlight the local/regional economic benefits, in particular jobs creation. The geothermal industry needs to engage with universities to protect the supply of geoscientists entering the work force, and help retrain those redundant from the O&G industry. Additionally, the geothermal industry needs to engage with the oil and gas industry, if not for participation or support, but to learn from these organizations and capitalize and on the potential cross-overs and skills overlap (GEOTH012; GEOTH032).

4.5.4. Technological

Conventional geothermal is only seen as viable in about 9% of the world (GEOTH012). While unconventional (EGS) is seen as a technological breakthrough by some (GEOTH014; GEOTH025) a significant number of others do not see it as having potential (GEOTH002; GEOTH004; GEOTH012; GEOTH15; GEOTH20; GEOTH031). A major problem that was cited, is that despite years of research EGS is still not deployable as a commercial technology in the USA. Currently conventional and EGS technologies are stigmatized as being expensive, time intensive, and capital intensive with significant risk and little reward (GEOTH012; GEOTH018). Some were critical of the recent DOE "GeoVision" report that pushed EGS-geothermal as the solution to the USA's energy problem (GEOTH020). Others also highlighted that overblown promises in the past had damaged the industry, in reference to the MIT 2006 report, although the lack of progress is coupled with a lack of sustained policy, investment and innovation (GEOTH015).

On a positive note, existing conventional geothermal technology may have a new lease of life in the next 10 years and it may play a pivotal role in meeting the 2030 and 2050 GHG reduction targets.

However, the industry needs to improve its marketing because given the timeline it takes to develop there is a risk that expensive alternatives will be deployed for example solar PV and battery storage, even in states like California where geothermal is currently deployed (GEOTH025). There is one limitation of existing conventional geothermal power, this is the fact that many of the best resources are not co-located with population centers or existing industry. Moreover, the average size of geothermal resources is too small to be of interest for the O&G industry (GEOTH012, GEOTH018). Yet, the innovation within geothermal including low-temperature closed-loop and closed-loop conduction technologies, does give some hope for decoupling geographic restrictions and geothermal heat and power (GEOTH020; GEOTH032). There is considerable low-temperature geothermal (heat and power) potential in the USA, however this is hampered by the best locations being occupied by oil and gas operations and the post-life legal and contractual issues surrounding the redevelopment of orphaned oil and gas wells (GEOTH002; GEOTH004; GEOTH032).

One area where geothermal has remained underutilized is in the deployment of existing technologies that utilize geothermal heat, including both district energy systems and GSHP (GEOTH002; GEOTH003). This failure is largely linked to economies of scale and difficulties of retro-rifting into homes and businesses and the time it takes to be breakeven (GEOTH002; GEOTH003; GEOTH028). Why greater take-up of this technology has not occurred is clearly linked to a failure to market and educate and is partly linked to a bias for geothermal industries in the USA that dominantly focus on electricity production (GEOTH002).

Emerging innovations that could revolutionize the geothermal industry are because they enable larger scalable developments are the technologies that develop closed-loop conduction and low-temperature heat and power projects. These innovative ideas allow for heat to be harvested for direct heat or power purpose (GEOTH012; GEOTH030; GEOTH032). GEOTH012 and GEOTH032 both indicated that closed-loop conduction at both low-temperature and supercritical temperatures enable geothermal technologies to access 80% of the USA. If these technologies can be demonstrated to be technologically and economically viable in the next 10 years, then they have the potential to revolutionize the power industry with or without the participation of the current O&G or power industry. Successful development, however, requires simultaneous advances in legal frameworks, PR, marketing, education and technological developments (GEOTH032).

Existing geothermal technologies are technologically mature GSHP, district energy and conventional geothermal, they are unfortunately viewed externally as immature and high risk. Dramatic improvements in marketing, public relations and lobbying are needed. The industry needs to fight to re-insert itself into the minds of governments and decision makers, so that it is recognized as a low-carbon and sustainable baseload. The industry needs to educate and manage all potential stakeholders (individuals, companies, policy makers and regulatory bodies at the State and Federal levels).

4.5.6. Legal

Presently the legal situation is relatively well understood with respect to conventional geothermal exploration and production. This understanding is linked to the production and re-injection of a fluid (water) in a geothermal reservoir. Despite this familiarity in states like California, the timelines for geothermal drilling permission remain prohibitively long (GEOTH025). New technological developments however, also highlight three pressing legal issues that need to be further developed and which impact the present and future geothermal industry.

The first of these is linked to the future exploration of heat. The legal blue-sky component of thermal exploration has not been properly considered, "*who owns the heat?*" (GEOTH032). New closed-loop supercritical thermal explorations are forcing the issue. GEOTH032 argued that *if the oil and gas industry decides to flip the switch, and heat becomes their asset. Who owns the heat is a really important [future] question"* (GEOTH032).

Secondly, as the number of depleted oil and gas fields and orphaned wells grow, these sites are potential future geothermal resource areas. However, until the legal framework is settled these potential resources will not be developed (GEOTH003; GEOTH032). The problem is, no geothermal developer would touch these wells without guarantee that it is not responsible for the environmental aspects relating to the former oil and gas activities. An example where the legislation is changing is British Colombia, Canada (GEOTH003). The issues for geothermal development are the liability that sits on capped wells *"which is gigantic when it comes to methane emissions, and when it comes to anything that can happen in the future regarding anything essentially* (GEOTH003; GEOTH032). What needs to happen is governments need to forgive any future liability may exist for those wells, then there is a possibility that someone may investigate the possibility of redeveloping these fields into geothermal reservoirs for direct heating or cooling or power purposes (GEOTH003; GEOTH012; GEOTH022; GEOTH032). Unfortunately, there are also future liability issues which private entities could introduce, such as induced earthquakes or subsidence linked to geothermal operations in the subsurface (GEOTH012; GEOTH027; GEOTH032)

Thirdly, the redevelopment of abandoned mineral or coal mines, may carry similar legal issues, which are also a future development opportunity for geothermal resources (GEOTH002). The development potential for abandoned mines therefore rests largely on a governmental desire to improve its energy stability and independence.

4.5.7. Environmental

The geothermal industry including the GRC, in the USA, does not successfully market or develop geothermal energy as a critical player in a low-carbon world (GEOTH025). The industry therefore, really needs to market the environmental benefits it brings. Geothermal heat and power can bring a baseload stability to the grid (GEOTH002). Moreover, geothermal energy, across the board, can provide significant benefits to the environment providing low-carbon energy, it is renewable and it can be sustainable, if developed and managed properly (GEOTH002; GEOTH004; GEOTH014, GEOTH15; GEOTH027). Geothermal is also easy to decommission when compared to solar PV and wind which have significant environmental risk associated to their disposal (GEOTH012; GEOTH018). The industry therefore, needs to provide case studies publishing performance metrics; LCOE data, GHG emissions via Full Life Cycle Analyses (FCLA), and integrate this data into carbon abatement metrics to highlight potential energy savings, abatement costs and its impacts and benefits on grid stability and society.

Land use is also an important aspect of geothermal heat and power, geothermal uses the same or less in terms of land footprint as a nuclear plant does. Therefore, in terms of energy density or kilowatts per acre, geothermal is highly efficient, unlike wind or solar PV (GEOTH012; GEOTH029). In addition, the geothermal industry needs to celebrate the technological advances that allow it to mitigate all the environmental issues that have traditionally hampered the industry (GEOTH006; GEOTH012).

The industry however needs to develop standards in order to prevent conventional lower cost, or unconventional technologies from tarnishing its image, leading people to question its safety (GEOTH015). There is a perceived risk element with flash steam technologies, which can make them as polluting as coal power plants in limited end member scenarios. This occurs where the geothermal wells intersect hydrothermal resources in volcanic or carbonate rich reservoirs, for example in Turkey (GEOTH012; GEOTH015; GEOTH023). Generally speaking it should be noted that many flash steam development emissions are on the order of 75-150 kg (CO_2)/MWh which is significantly lower than coal or gas power plants (GEOTH002). In relation to geological variability the geothermal industry needs to deliver a global code of business and standards regarding permissible GHG emissions, subsurface recommendations, skills required and standards for testing, observing, drilling and engineering geothermal wells and building energy plants.

Another aspect that the geothermal industry needs to manage is its sub-surface image, how it impacts drinking water reservoirs and how it uses water reserves. In theory it does not interfere with drinking water supplies neither does it provide a drain on water resources, particularly in closed-loop geothermal configurations. The industry also needs to manage the earthquake risk particularly linked to its unconventional (EGS) and conventional development (GEOTH012; GEOTH018; GEOTH027; GEOTH031).

Finally, and slightly tangential to the geothermal business, geothermal energy could be used in the production of green-hydrogen, desalinated water or in the production of green diesel by using geothermal heat to produce these products (GEOTH003; GEOTH012; GEOTH022; GEOTH028). Integration of geothermal energy or power in the production of food for example could also bring significant green benefits reducing the carbon intensity of many products, fuels and foods (GEOTH012; GEOTH017).

4.5.8. PESTLE-Summary:

There are many different facets within the geothermal industry making it a complex industry to analyze. The external environment assessment provided by this PESTLE analysis reveals a challenging financial, regulatory, and operational environment for geothermal energy in the USA. In combination with marketing and stakeholder management, the question that needs to be answered in the next 5-10 years is: can geothermal technologies demonstrate commercial viability, baseload flexibility and emission abatement potential at an attractive cost for grid power and direct heat, compared to other renewable energies?

5.0. DISCUSSION

Exploratory research conducted here integrate the opinions of twenty geothermal and energy specialists via semi-structured interviews, with an analysis of low-carbon technology diversification activities of 36 energy companies. The analysis highlights several themes that will be discussed further below.

5.1: EMERGING MACRO-TRENDS WITHIN THE ENERGY INDUSTRY AND GEOTHERMAL WITHIN THE LOW-CARBON ENERGY PORTFOLIO

Based on the discussions and results of this research, it is possible to ask the following questions: (i) Are we witnessing a dramatic shift in strategy of O&G companies? (ii) Is diversification leading to energy convergence between traditional power and O&G Industry? (iii) What is the role of geothermal in this diversification?

Results indicate that we are indeed witnessing a change in strategy of O&G companies, moreover it is possible to make the sweeping statement that this change in strategy is dominantly restricted to European-based companies. US-based oil and gas companies appear not to be transitioning into renewable industries. This statement is backed up by the fact that recently public declarations by SHELL, BP, ENI, Equinor, TOTAL and Repsol, the six major European O&G majors, have all proposed strategies to get to zero emissions by 2050 [7]. This diversification trend appears to be closely linked to ESG concerns and the link between fossil-fuels and global warming.

With respect to the provision of electricity a convergence trend is observed between the power, O&G and ERP companies. The lines of commodity and utility company are blurring, particularly, as the O&G companies are investing in non-fossil fuel technologies, that require them to produce and sell electricity. This observed energy convergence, will likely drive increasing competition within the decarbonization and electrification markets. To some extent this transition is largely occurring in Europe, rather than the USA, but its impacts will likely be felt globally. The Europe-US divide in strategy is intriguing. Recently IRENA [8], estimated Europe stands to make significant GDP, employment gains as a result of its progressive actions in transforming its energy mix. The driving factor appears to be a greater focus on national independence and self-sufficiency that is more urgent in the EU, whose petroleum reserves do not match those of the USA [6]. Using qualitative analysis another recent study [62] proposed a similar theory, arguing for a strong linkage between the oil majors' investing in renewables and the size of their proven reserves. Their analysis suggests that the US-majors do tend to have larger proven reserves at low breakeven oil prices [62]. Under the Trump (2016-2020) US-led administration, renewable strategies are lacking and are not currently being pursued at a Federal level. Although, this may change in the future, several democratic and even bipartisan proposals have been proposed which could have a progressive policy for example the Green New Deal [63], and the bipartisan alternative green deals which involve tax credits and zero percent interest loans, for geothermal energy development and investment in research [64].

In terms of geothermal strategy and geothermal diversification, the picture is less clear. Table 1a, indicated that geothermal technologies are part of the energy mix, however most of the geothermal activity is through geothermal development companies. Detailed analysis of the geothermal technology development (Table 2) reveals that not many companies are heavily invested in the technology despite its low-carbon baseload benefits. It is observed that EDF, ENEL and SHELL were more diversified than the "pure-play" geothermal companies. Although, that conclusion is limited by the omission of power produced and dollars spent on the technology, nonetheless it is startling to see how focused geothermal companies are within the geothermal industry, rather than developing integrated energy systems. Of the power companies that develop geothermal differences are observed, EDF operates the first commercial EGS plant in Soultz-sous-Forêts, France [65, 66]. Whereas ENEL is involved in research and development of supercritical geothermal power via the DESCRAMBLE project [58]. At the lower temperature range ENGIE and The most diversified geothermal development and power company was ORMAT, with a focus on waste heat, and conventional geothermal power. Future research needs to focus on the amount of power produced to better rank the companies.

Regarding greenfield geothermal development and the power companies many US-based companies appear to have added geothermal power production through merger and acquisition activities rather than greenfield exploration and development. The O&G companies that are publically involved in geothermal are SHELL and Equinor, which are European, but these projects remain in their demonstrator phase for the technologies. Both these companies have research and development activities in supercritical geothermal power, although SHELL's focus is on closed-loop conduction technologies whereas Equinor is focusing on EGS. It is possible that many are working privately behind the scenes because there are a number of consulting groups that offer geothermal consulting, for example, the Boston Consulting Group (BCG), LuxResearch, FutureBridge, and TGE Research. Whether other companies diversify into geothermal remains to be seen. Based on the 2018 end of year reports, it is clear that not all companies are developing strategies low carbon technologies and in particular geothermal. Future research should also extend this analysis qualitative analysis to the members of the Oil & Gas Climate Initiative (OGCI) to get qualitative metrics on investment levels and demonstration projects created per energy technology.

5.2: BARRIERS TO GEOTHERMAL DEVELOPMENT IN THE OIL AND GAS INDUSTRY

This study has identified many barriers to geothermal development across all scales of geothermal as shown in Table 5. The barriers are technical, commercial, marketing, legal, educational, stakeholder and deceptive competition from other technologies particularly gas, wind, solar PV, storage, biomass. These results are in alignment with previous studies [67-72]. One factor not considered here but raised by Kutschick, [70] was competitive reservoir utilizations (e.g. carbon sequestration and storage and nuclear waste). Young *et al*. [67] identified growing environmental and land-use restrictions impacting geothermal developments, For example: (1) Land access, (2) permitting, (3) baseload set aside (including, baseload tax credit; baseload set-aside and VRE transmission charge), (4) the impact of Federal versus State incentives and (5) the cost of natural gas. The analysis presented here is largely qualitative, however the analysis of Young *et al*., [67] tried to analyze quantitatively the impact of improvements. Young *et al*., [67] also observed that high R&D budgets in the USA correlated with the fastest growth in geothermal increase in terms of MW added.

When trying to understand whether O&G companies will enter the geothermal industry the paradox is that many companies are already engaged in thermal applications of waste heat utilizing all the above ground technology that makes geothermal work. Therefore, why naturally occurring heat is not used in the earth to produce electricity remains unknown, rather than burning fossil fuels. However, the limited geographic scope, size, and environmental hazards of conventional geothermal developments, combined with the issues of profitability appear to have stigmatized the O&G's industries view and therefore involvement in geothermal. This was reinforced by several interviewees during the interviews (GEOTH012; GEOTH020; GEOTH031; GEOTH032).

New geothermal innovations that detach geographic constraints, remove environmental issues, that are low-carbon and scalable may well change the future appetite of O&G companies involvement in geothermal technologies. The closed-loop conduction is ironically born out of oil and gas technology, which may be applied to all temperature ranges. The new DOE funded project GEO at UT Austin [14, 15] was funded to get O&G companies closer to innovation in the geothermal industry. It is argued that the O&G sector ought to pivot into geothermal technologies, because it leverages core competencies, IP, technology, assets, workforce and existing expertise; while meeting carbon neutrality commitments and portfolio diversification requirements.

Several interviewees commented that O&G's involvement in geothermal could drop the cost of drilling from 20-40% (GEOTH015; GEOTH032). Such claims are supported by the Equinor presentation which suggested learnings from the drilling of the IDDP wells in Iceland led to several identified improvements that could drop future drilling costs by 40% [73]. One example of how well the O&G industry has innovated to lower cost is in Brazil, where the original sub-salt discovery well, Tupi, was drilled offshore Brazil, in 2006 by BG Group and cost ~US$300 million [74]. Recently, the lowest cost of drilling in the sub-salt was Ecopetrol claiming that Gato do Mato wells cost US$50-60 million

(Lubetkin, R., *pers. comm*., November 2019). Welligence data analytics reveals that with experience the drill days are reducing dramatically over the last 5 years (Lubetkin, R., *pers. comm*., November 2019). With reduced days drilling the costs have dropped by ~80%. If Geothermal companies could innovate their drilling on a similar scale, perhaps they could reduce the costs geothermal exploration and development. Closed-loop conduction combined with and cheaper drilling and completion costs with could enable the co-location of thermal and power resources adjacent to population centers. With scalable and flexible low-carbon baseload assets on the horizon perhaps that would really be of interest to O&G companies. A mutually beneficial relationship may be possible for the geothermal and O&G industries.

5.3: THE EXTERNAL ENVIRONMENT OF THE U.S. GEOTHERMAL INDUSTRY

The interviews yielded key insights which highlight a difficult political environment in the USA for geothermal operators and the future of the industry, mainly dominated by a lack of a U.S. cohesive energy policy. Criticism of biased and dishonest government policies was present in many of the discussions relating to the geothermal industry which has placed geothermal at a disadvantage over solar PV and wind, particularly in California, (GEOTH002; GEOTH004). The exception to this are GSHP, which have perhaps the best tax/incentive situation of the geothermal technologies with the federal investment tax credit which was part of the Energy Policy Act of 2005, enabling up to 30% of the amount spent on purchasing and installing a geothermal heat pump system to be deducted from their federal income taxes [75]. However, the general lack of knowledge of this technology appears to have limited the overall adoption in the USA [76].

The results of the interviews and research conducted into the geothermal business essentially show five key general observations: (i) the industry is large, ranging from low temperature to supercritical conditions (~7°C to >350°C), (ii) it is multi-faceted, and as the water cools it can be cascaded and re-used by different industries who have different heat requirements , (iii) despite significant successes the industry is expensive with boutique or niche products, thus the view is that it is not always considered mature or viable by the general public and decision makers/governments, and (iv) it is largely unknown and (v) it is stigmatized by issues that blighted its early development, even though these environmental risks have been mitigated.

Macro analysis of the Geothermal industry reveals several important behavioral aspects regarding the companies that develop geothermal and their relationships with the energy industry. The following observations are made (i) there are very few integrated geothermal companies, with companies specializing in niche geothermal areas; (ii) the industry appears not to be well integrated with other energy producers meaning that the developers of geothermal are independent and not integrated power companies: (iii) many O&G and power companies are have not invested in geothermal even though they are comfortable with thermal industries such as waste-heat which utilizes the exact same technology. (iv) Power companies that own geothermal assets appear to have acquired these through merger and acquisition (M&A) activities.

Within the USA, geothermal development is challenged and hampered by a longstanding tradition of cheap energy, and the policy bias that supported the growth of the wind, solar PV and gas to power. Even in areas where conventional geothermal is traditionally successful it is struggling to compete despite it providing flexible baseload power that fits in a low-carbon economy. Geothermal, at all scales also fights against the issues of climate denial in the USA. Critically, geothermal energy has declined to such an extent that it is not even featuring in debates about global warming and sustainability, which are dominated by wind, solar PV and storage or even CCUS [77, 78]. The negative trends observed within this study are somewhat unique and they tend to go against the recent publications from the geothermal industry [79-81]. With respect to promoting geothermal, studies that over promote or rely one technology, e.g. EGS, [79-82], may be damaging to the industry,. If the experts interviewed are a gauge of industry opinion, then it seems existing US-DOE faith in EGS is misplaced. Geothermal needs a balanced promotion and it needs continued policy and funding.

However, negativity is not the only picture for geothermal. There are innovations occurring which could unlock geothermal technologies. If geothermal energy could be marketed better, stakeholders engaged and if costs reduced, then geothermal could compete. Recently, Ball [12] examined the LCOE and carbon abatement perspective of geothermal. It is clear from this analysis that the industry needs to underscore its place in the integrated low-carbon energy portfolio. If future predictions are correct, there are possibilities that low-temperature closed-loop, and closed-loop conduction and district heating geothermal technologies are highly competitive with or without a carbon price, if existing gas or coal are the abated fossil-fuels.

At the low-temperature end of the geothermal business studies for example Hamm, [79] or Lui *et al.* [83] argue for the massive benefits GSHP's can bring to the grid and to the country in terms of reducing the carbon footprint of heating and cooling. The story is similar for district heating, recent reports giving district heating a strong credibility [84, 85]. But similarly these reports are failing to develop scenarios and mechanisms for integration and penetration into the USA's energy market. The lack of publically available data coupled with education and marketing gaps, are damaging for the long-term growth and stability of the geothermal industry. This requires urgent fixing because these largely matures technologies that could significantly help in the drive for decarbonization. Ball [12] recently studied the carbon abatement potential of geothermal highlighting that today certain matures technologies can challenge both existing coal and gas power providing significant long-term removal of carbon from the energy grid. Further work is needed however, to better define where in the USA geothermal can cost-effectively make these impacts. Ball [12] also highlighted that several emerging technologies could be cost effective, however it is not clear at the current development rates if geothermal can follow the experience and learning curves of wind and solar PV.

6.0. CONCLUSIONS:

This study has examined trends from within the energy industry to provide a snap-shot of the macro-environment, activity and current trends in the industry, for the period 2018-2019. In addition this study utilized the views of twenty geothermal and energy specialists to understand the complexities that challenge the geothermal industry in a low-carbon portfolio.

Macro-scale insights reveal there is a significant split between European and US-based oil and gas companies in terms of strategy which is to a certain extent mirrored by the power companies. Presently, the oil and gas industry does not appear to be actively investing in baseload geothermal energy, favoring easy to deploy solar PV, onshore/offshore wind, biomass/gas, gas to power and storage. Diversification into low-carbon technologies is driving an energy convergence between the oil and gas and power sectors. Although energy diversification is occurring geothermal technologies are not currently a technology that companies are developing as part of their baseload low-carbon energy portfolio. Traditionally the oil and gas industry has avoided geothermal technologies because of technical/operational, commercial, legal and stakeholder barriers.

The geothermal sector is however replete with established and emerging technologies that enable its deployment in a variety of locations and scales. Yet, the geothermal industry in the USA and Europe remains largely a niche, pure-play industry. There are signals, however, that in the near future innovative geothermal energy technologies will play an increasingly important role in the low-carbon energy mix. With continued innovation geothermal has the potential to become a much more versatile energy source than is generally understood. Geothermal is not only useful for power, it can be utilized for heating or cooling, even flexible storage for example hybrid plants that combine geothermal and solar PV with thermal energy storage. There is considerable innovation within the geothermal industry, developing advanced geothermal concepts, for example, Eavor, GreenFire, CLIMEON, CLEAG. Furthermore, applications such as desalination, green hydrogen production and lithium extraction from brines, increase the spectrum of products geothermal can deliver. Recent geothermal innovations that increase the footprint of scalable geothermal development might provide an avenue for the oil and gas industry to enter the geothermal domain. The advanced closed-loop conduction and low temperature geothermal innovations that could unlock the concept of "geothermal anywhere". If technological and cost barriers can be overcome, oil and gas companies looking to develop low-carbon baseload heat and power, may see these new technologies align with their interests, in addition to leveraging their existing core competencies, IP, technology, assets, and workforce knowledge skills and experience.

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APPENDIX A

Pre-interview set of starter questions and themes. This was sent in advance to interviewees or used during the interview depending on the requests prior to the interview.

Interview Questions
3 sections: structured, open questions, more specific (interviewer biased) depending on the open questions
Structured
How experienced in Geothermal are you?
Is your experience technical/sector /economic/ management
Dominant experience base (EU, USA, Other)
If US-based where in the USA (California or Texas or?)
Explerience in Geothermal - Academia, Startup, Established, E&P company or Power company?
Open Queistons/ Discussion Topics
Historically, why do you think geothermal has not made a bigger penetration?
What do you make of the comment by Bierman et al 1977 (pg 227/571) that Power and Oil and Gas companies deliberately ran a monopoly on resrouces and controlled the best agreage?
Do you think geothermal will play a role in the future low carbon energy mix?
What are the biggest rivals to geothermal energy in a low carbon world?
EIA 2019 published a MW value of geothermal of 39 USD. This is by far the cheapest of all energies even without subsidies?
Why is it Power and oil and gas companies have not adopted geothermal energy?
Do you think geothermal can or should market itself better with Power and E&P companies?
Should depleted fields be re-developed as a geothermal resource?
How willing are corporate stakeholders in key industrial sectors to engage in geothermal low carbon energy solutions?
I observe that Power companies are more integrated than E&P. But why are E&P not taking geothermal when they are optimally placed? Why this contradiction?
What are the biggest challenges to re-integrating Geothermal into the existing energy system/housing stock?
One of the obstacles I hear is geothermal is not efficient for electricity produciton, but I was amazed when studying CPH - Gas Turbines are only 50% efficient! Why this bias?
What are the key industrial sectors that would most benefit from the uptake of geothermal energy generation solutions?
How would you recommend improvements to increase optimal take up of geothermal low carbon energy solutions in today's wider energy mix?
Are the existing financial incentives to corporations seeking to pursue low-carbon energy production strategies at state, federal and international levels suitable?
Do you think carbon tax should be introduced over subsidies?
What structural (energy/policy) changes are needed?
Why is it so hard to get PPA for geothermal energy?
How can we change the mindeset of the value of geothermal?
Regarding the modelling of geothermal energy production, in the wider context of low carbon energy solutions should heat and electicity be valued the same?
How would you estimate the value of heat? Vs Electicity?
IF risk is seen as a limiting factor for geothermal what do you think closed loop or EGS will do to this perception?
I have seen CO2 proposed as a conductor of heat in closed loop, why is it the industry has not used H2?
Im amazed at the maturity of HEAT technology. Why do you think geothermal is not as widely accepted or known?
CPH is an accepted technology, why do you think there is more opposition towards geothermal?
Heating/Cooling is about 50% of energy demand. Equates to 39% of GHG emissions - why is thermal not used more?
Additional Insights
On a different scale geothermal Heat-pumps how can companies/govermnents increase uptake? (e.g. Solar now interest free and leasing)