Learning from the Oil & Gas Industry: Leveraging Innovation and Integration to Reduce the Risk and Cost of Geothermal Projects

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Keywords: Geothermal, O&G, technology transfer, innovation, integration, cost reduction, drilling, RSS, Hybrid bit, ESP, ORC, power production.

ABSTRACT

The geothermal market is a promising contributor to the renewable power mix, with significant potential and intrinsic advantages; however, it has been historically challenged by high risk and lack of investment. This dilemma has limited the growth of the sector with less than 10% of the estimated global potential developed to date. Transfer of innovation and best practices from the established oil & gas (O&G) industry is key to reducing the risk and cost of geothermal projects.

In this paper, the authors discuss the importance of learning and knowledge transfer from the O&G industry, and highlight the latest developments and trends. These trends, which resulted in fundamental changes in efficiency and cost structure, are driven by the ongoing ‘low oil price’ environment. This resulted in leaner and lower-cost operations, enabled by a higher level of integration along the value chain and innovative technologies to mitigate risk. These initiatives reduced the cost of drilling wells and processing hydrocarbons. The authors argue that a similar approach must be employed in the geothermal sector to mitigate the high initial financial and technical risks, which represents a major limiting factor facing the growth of the geothermal market.

Several case studies of innovative technologies are presented, such as the testing and deployment of the industry's first 300° C-capable drilling system, including metal-to-metal motors, drill bits, specialised drilling fluids and accompanying measurement-while-drilling systems. The deployment of proprietary hybrid drill bits in Indonesia and Turkey leading to faster drilling, lower vibration and non-productive time (NPT) and resulting in lower overall drilling cost are examined. The authors investigate how common use of sub-optimal drilling systems results in unnecessarily high NPT and wellbore construction costs, caused by downhole tool failures, additional trips and poor drilling performance. Mitigating these challenges is key to reducing the overall geothermal project cost, where drilling and wellbore construction can account for as much as 50% of the total budget.

The authors also discuss how an integrated, value-adding approach, similar to the latest trends and projects in the O&G industry, can lead to major reductions of cost and lead-time in geothermal projects. This approach requires extensive in-house expertise and manufacturing capabilities across the entire value chain, from exploration and drilling, through turbines and plant components, to Engineering, Procurement and Construction (EPC) and digital solutions. Fundamental changes in the traditional business model are required toward a more collaborative, risk-sharing methodology to unleash the full potential of the geothermal sector.

1. INTRODUCTION

The geothermal power production sector (electricity) adds approximately 800 MW of new capacity per year, or 1% of the renewable power mix. Geothermal is a competitive renewable source of power in terms of levelized cost of electricity (LCOE) with a high capacity factor of 95%. However, only 10% (14 GW) of the estimated global potential (140 GW) has been developed to date.

The combination of high exploration risk (failure to extract enough steam or water to operate the plant) and the long project development cycles (Up to 5-7 years) results in limited market take-off, except in proven geothermal activity areas.

Two main plants technologies exist: steam (direct use with steam turbines) and binary (mainly Organic Rankine Cycle (ORC) for low-temperature resources using turbo-expanders). Historically, the market had a split of 80% steam and 20% binary, but the split shifted to ca. 50%-50% for new installations in the recent years with ORC gaining more demand and acceptance and more low enthalpy resources being developed primarily in the USA, Europe and Turkey. **Figure 1** shows the geographical distribution of all geothermal power plants worldwide by country and technology type.

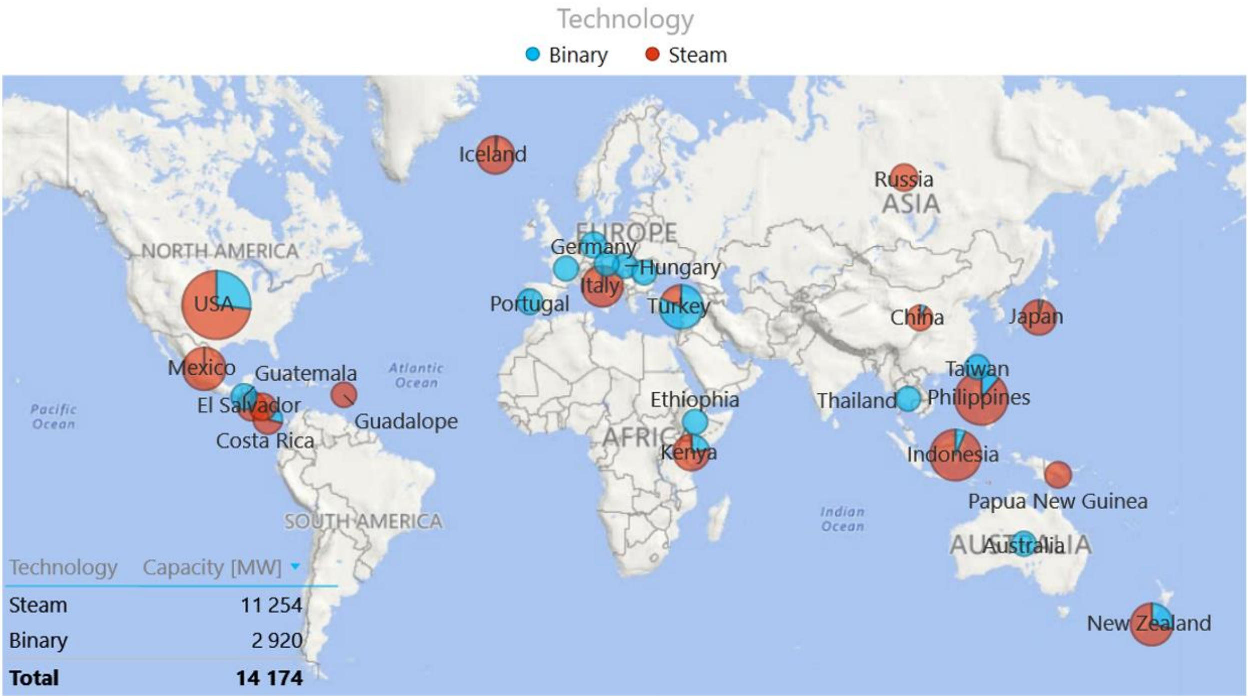

Figure 1: Installed geothermal power plants capacity by country and technology type

2. INNOVATION & KNOWLEDGE TRANSFER FROM THE O&G INDUSTRY

In this section, the authors will highlight a few technology transfers and innovations developed by BHGE that help reduce the risks and costs of geothermal projects across the entire value chain and life cycle of development and operations.

2.1 300 Degree Celsius Directional Drilling System

Commercial O&G drilling equipment can drill low-to-moderate temperature geothermal wells in a temperature range of 150-175°C, and in some cases up to 200°C. However, some geothermal applications and research projects aim to drill ultra-deep, ultra-high temperature wells to tap into high-enthalpy geothermal resources reaching as high as 250-300°C.

Leveraging its O&G technology expertise and cultivating more than 40 years of experience in geothermal applications around the world, BHGE is engaged in multiple R&D projects in ultra-high temperature technologies in collaboration with governments and research institutions worldwide. One of these revolutionary projects, partially funded by the US Department of Energy - Geothermal Technologies Office, is the industry's first 300° C-capable drilling system, comprising metal-to-metal motors, drill bits, drilling fluid and accompanying measurement-while-drilling system.

This special drilling system underwent rigorous laboratory testing of individual bottom-hole-assembly (BHA) components that exceeded traditional O&G specifications and full-scale integration tests on an in-house research rig (Chatterjee et al. 2014). It was then successfully deployed in the exploratory geothermal well IDDP-2 as part of the Iceland Deep Drilling Project where the developed system met and exceeded expectations. The well reached a measured depth of 4659m and extreme temperatures of 426° C, by far the deepest and hottest in Iceland geothermal applications (Stefánsson et al. 2018).

2.2 Alternative Wellbore Construction and Automation R&D for Geothermal Applications

The large number of geothermal projects concentrated in Germany and Europe enables BHGE experts at the Geothermal Center of Excellence in Celle, Germany to quickly transfer technology innovations from the drawing board to the project site. Research projects with focus on Wellbore Integrity, Monobore- or Lean Casing designs and Automation have been co-funded by the German government to mitigate wellbore construction challenges and reduce geothermal project costs as depicted in **Figure 2** (Oppelt and Lehr 2012, Oppelt et al. 2015).

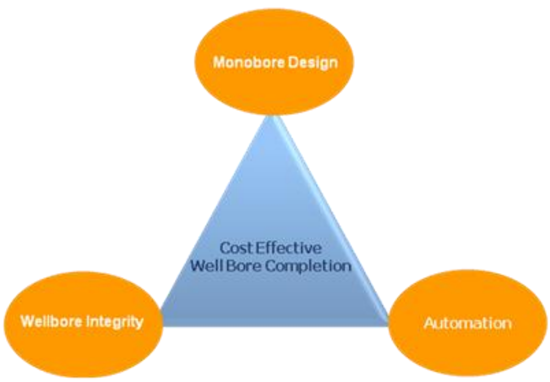

Figure 2 – Cost-effective wellbore completion sub projects (Oppelt and Lehr 2012)

Automation R&D has been conducted in collaboration with drilling rig providers to optimize drilling and completion processes with new completion designs, and the use of machine learning as well as artificial intelligence methods. A Closed Loop Drilling System is the focus of Automation Research of BHGE (Oppelt et al. 2016). The developed algorithms are already in the field-test phase.

2.3 Geothermal Drilling and Preparation of Completion with Automated Rotary Steerable Systems (RSS)

BHGE developed the first RSS in the industry (BHGE AutoTrak™) and optimized BHAs with the utilization of high-performance drilling motors as an additional power source at the bit. The additional power capability in combination with downhole weight on bit and vibrations measurement and control enables fast and secure drilling of high quality geothermal wellbores.

The high precision of wellbore placement and shape enables easy installation of casing and high-quality cementing. Non-productive time is reduced to a minimum, resulting in lower cost of drilling and faster installation of production equipment in a geothermal site in Germany. BHGE Drilling Services enabled 80% increase in drilling efficiency and saved several days of time for completion.

Figure 3: BHGE AutoTrak RSS BHA with PDC bit ready for deployment on a land rig

2.4 Hybrid Drill Bits Reduce Drilling Costs and Save Rig Time

The award-winning proprietary hybrid drill bit (BHGE Kymera™) combines polycrystalline diamond (PDC) and roller-cone bit technology for smoother drilling, remarkable torque management, and precise steerability. Leveraging the cutting superiority of PDCs in soft formations and the rock-crushing strength and stability of roller cones in hard or interbedded formations, the hybrid Kymera bit has the potential to maintain higher overall rate of penetration (ROP) for more footage than a roller cone or PDC bit could individually.

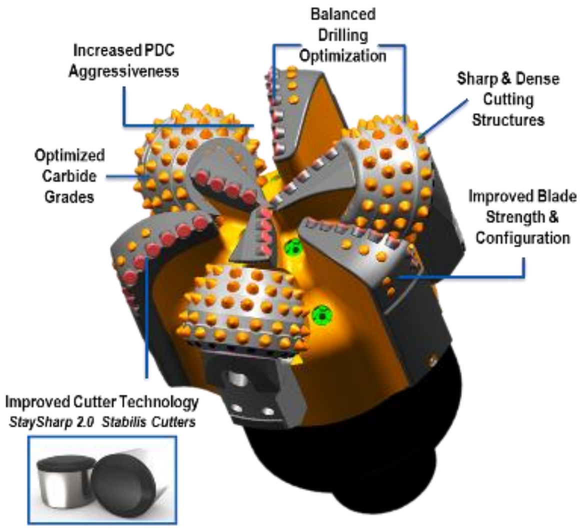

Figure 4: Kymera bit main technical innovations leading to higher performance

This innovative technology has shown great results in multiple O&G applications, saving time and the cost of drilling. In a study conducted by the Geothermal Resource Group (GRC) and BHGE, it was proven that this innovative technology also reduces cost and time specifically in geothermal wells (Rickard et al. 2014).

In a recent challenging geothermal application in Indonesia, a 12¼-in. Kymera bit was selected because it took three roller cones bits to drill a 1000-m interval in offset wells (volcanic and dacitic lava formations). The Kymera bit started drilling the cement and shoe track then continued drilling in the formation from 490m to 1559m. The proposed total depth was 2000m, it was decided to run the Kymera bit until it ran out of roller-cone revolution, which was predicted at 850 krevs. From 490m to 1225m, it maintained average ROP of 30m/hr. The 13.2 days of drilling planned for 1000m was reduced to 4.8 days with the Kymera bit. This translated to approximately $600k savings for the operator and eight fewer days of rig time.

In another challenging field in Turkey, vertical wells are drilled with rotary BHAs in interbedded formations with conglomerates, sandstones and shale. Offset wells drilled this section in 12¼ in. (smaller size) and required an average of three roller cones with an ROP of 3 m/hr. After a detailed drilling optimization review, a bigger size hybrid drill bit was proposed, targeting 850 meters at 7 m/hr.

The proposed optimized system exceeded expectations and smoothly drilled 1174 meters in 104.5 hours with an 11.24 m/hr average ROP and 700krevs. The Kymera hybrid bit replaced three roller cones in one run with 274% improvement in ROP. It saved 431 hours (18 days), which translated to ca. $450k of cost savings.

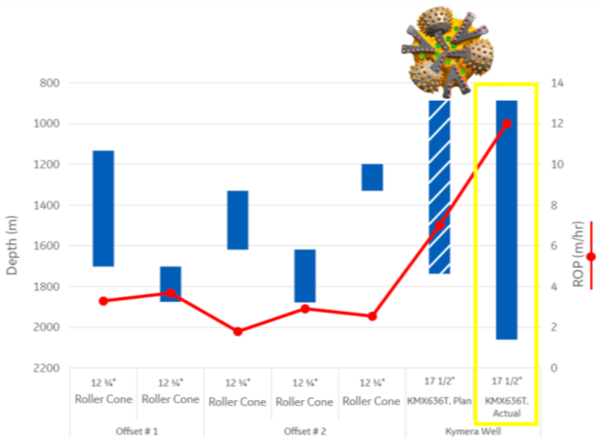

Figure 5: 17 ½-in. Kymera Mach4 performance in Turkey

2.5 Electrical Submersible Pumping (ESP) Systems Help Reduce Project Costs and Increase Returns

Widely used to lift hydrocarbons in the O&G industry, ESP systems can also play a critical role for the economic viability of geothermal projects. Especially in ORC binary and district heating applications where hot geothermal water must be pumped out of the well constantly and reliably with minimal fluctuation or down time.

With that in mind, BHGE developed, with co-funding from the German government, optimized ESPs specifically to address geothermal challenges. Proprietary computational fluid dynamic modelling was used to optimize the pump's hydraulic design and fluid flow regime within the well.

The development effort produced a unique geometric pump configuration that provides the industry's greatest lift per stage for a 7.25-in. outside diameter (OD) pump stage. It delivers higher flow rates and improves system reliability by minimizing the number of stages required to achieve a given flow, while lowering the cost of the system. The enhanced hydraulic design of the pump also improves ESP system efficiency and reduces power consumption per produced geothermal fluid volume—a major consideration in the overall economics of a geothermal project. The system is designed to operate reliably in scale-intensive and corrosive environments.

The BHGE 7.25-in. (OD) geothermal ESP helps operators save drilling costs by reducing the required well diameter and can double production in some existing wells. Drilling smaller-diameter wells can save up to 40% on drilling and well completion expenditures, providing a dramatic improvement to the cost structure of geothermal energy projects.

Significant developments have also been made on the motors and seals/protectors that are used in geothermal applications to improve reliability and reduce NPT. In wells with larger diameters, BHGE currently has the markets' largest downhole 8.80-in. OD motor that is nameplate-rated for 2800 horsepower. These high-power systems are a key component to the viability and success of many geothermal projects globally.

Recently in Turkey, a geothermal operator with a static fluid level at approximately 300m below the wellhead required an artificial fluid production method. In 2014, by using two BHGE geothermal ESPs running simultaneously, the operator was able to test the production of the 155° C-fluid and determine interaction of their wells.

In 2018, a 14-MW ORC power plant was constructed at the location. The power plant is 100% dependent on the production of five BHGE ESPs of a rate ranging from 200 m^3/hr to 600 m^3/hr and uses systems of various ODs (5.62 in. and 7.25 in.). These systems enable the operator to achieve a 5x return on investment in production costs within the first year, and to anticipate pay off of the total investment cost of the project within five years, including the ORC facilities. High-temperature Zenith™ sensors also enable the operator to continuously monitor the bottom hole conditions while operating.

The combination of observed reservoir pressure declines over time and increasing growth and popularity of enhanced geothermal systems (EGS) around the globe show that robust, efficient, and high-powered ESPs will be in greater demand. The BHGE CENtigrade™ line of high-temperature ESPs is well positioned to reliably undertake the production challenges of these harsh geothermal wells. Currently, there are more than 100 geothermal wells globally running BHGE ESPs with bottomhole temperatures as high as 220° C.

Figure 6: BHGE CENtigrade geothermal ESP pump cross section

The ESP pump can also be used to improve efficiency in existing wells, eliminating the need to drill additional production wells. It delivers the required stable flow rates in small-diameter casing, improving reliability and efficiency in geothermal projects. In a power plant in the US, an operator production was limited by the use of turbine pump systems and low flow rates despite the higher potential of the reservoir. The power plant expansion required the operator to increase existing flow rates beyond the levels that line shaft turbine pumps could deliver (410 m^3/hr). Engineers recommended geothermal ESP systems from BHGE.

The elevated temperature, high-volume systems used rugged technology. The design featured an advanced, high-strength shaft with proprietary materials that enhanced run life. The motors featured high-load thrust bearings and an advanced, hardened-rotor bearing system. The installation of these geothermal ESP systems increased the plant's hot water flow rate by 83% and added 5 MW of gross power production from the power plant expansion. Power plant revenue increased more than $9 million annually. In addition, the ruggedized pumps provided longer run life in high-temperature conditions, leading to lower operations costs of the power plant.

2.6 Organic Rankine Cycle (ORC) Power Plant Technologies for Geothermal Energy

In addition to the well-established steam turbine power plant type (80% of global geothermal installed base), the latest shift toward installing more ORC plants indicates a positive technological development and acceptance of this technology for geothermal applications.

ORC plants are commonly used to convert power from the thermal energy of medium-low geothermal water/steam (below 180° C), by boiling and superheating a working fluid in a binary thermodynamic cycle. The working fluid is usually an organic substance (hydrocarbon or refrigerant) with a low boiling point. First Principle efficiency can reach up to 20%, depending on the temperature levels involved. Typical size ranges from 0.5 MW to 18 MW, and larger sizes are typical in O&G (waste heat recovery application from gas turbine exhaust gases).
In geothermal ORCs the circuit of the geothermal fluid is usually a closed loop, avoiding any emission in the atmosphere (Vaccaro et al. 2016). The geofluid coming from the production well(s) is pumped (in case of liquid-state geofluid) to the heat exchangers (preheaters and vaporizers), and then back into the reinjection wells, closing the loop. The working fluid is superheated through the heat exchanger train, and then it generates electricity in a turbo-expander unit. It is then condensed and pumped back to the heat exchanger train, closing the binary loop. Condenser units can be air cooled or water cooled, according to the availability of cooling medium.

Geothermal ORC plants have several advantages:

- Easy operability also in remote-controlled and unmanned plants
- Closed loop with no emissions in the atmosphere
- Possibility of keeping the liquid geofluid under a high-pressure value, to avoid release of non-condensable gases (NCG)
- ORC cycles that enable the use of once-through boilers and superheaters
- Organic working fluids that can condense at higher pressure than atmosphere, avoiding air infiltration in the cycle

BHGE ORegen™ is the Organic Rankine Cycle solution currently available for a power range between 5 and 30 MW designed to recover waste heat from gas turbines or waste heat sources (and also from lower-temperature sources such as geothermal). It is currently available for power generation or mechanical drive applications using subcritical Cyclopentane as a working fluid and with air-condensing capability.

In gas turbine waste heat recovery applications, a diathermic oil loop transfers heat from the waste heat recovery unit to the power generation loop to maximize fire safety and increase the flexibility in the plant arrangement. For low enthalpy (and geothermal) ORC cycles, no intermediate fluid loop is used, and different hydrocarbons, such as n-butane and isobutane, or other organic fluids can be deployed. By using a multi-pressure organic cycle it is possible to generate electricity from low-temperature heat sources.

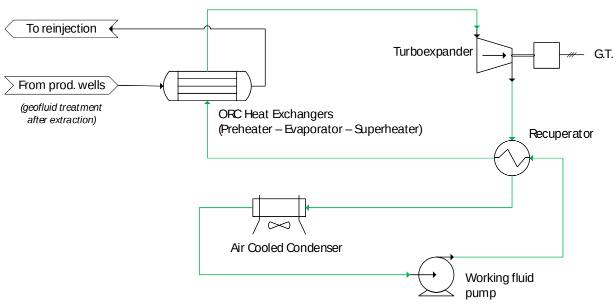

Figure 7: Typical scheme for ORC geothermal heat recovery plant (adapted from ORegen™)

3. O&G KNOW-HOW, INTEGRATION & PARTNERSHIP AS KEYS TO UNLEASH THE GLOBAL GEOTHERMAL POTENTIAL

The O&G industry underwent a remarkable transformation in the last few years, driven by the ongoing oversupply and 'low oil price' environment. This resulted in leaner and lower-cost operations, enabled by a higher level of integration along the value chain and innovative technologies to mitigate risks. These initiatives reduced the cost of drilling wells and processing hydrocarbons. It was also driven by a fundamental change in the traditional business model toward a more collaborative relationship between operators and technology providers. Recent examples have shown how a more integrated, cooperative, and risk/reward-sharing methodology fundamentally improved performance, reduced costs and increased returns and at the same time improved health, safety & environment metrics (HSE) for major projects like the Johan Sverdrup in Norway, where the innovative collaborative approach led to a 50-percent reduction in overall project cost and notable performance improvement (Øregaard et al. 2017). Another example of collaboration and radical performance improvement through integration and drilling optimization was proven in an integrated drilling operations campaign at an artificial island located in offshore United Arab Emirates. The collaborative approach and detailed analysis, planning, and optimization improved the overall ROP by 250%, reduced the drilling cost per foot by 60% and saved 3 days per section. This translated into $450k per well and a total potential of $18 million for the current drilling campaign (Paila et al. 2018).

A similar approach should be employed in the geothermal sector and can lead to major reductions of risks, costs, and lead-time of project development. This is critical to mitigate the high initial financial and technical risks that represent a major limiting factor facing the growth of the geothermal sector. This approach requires a clear, transparent, and structured partnership between operators, technology providers and EPC companies. From the technology provider side, extensive in-house expertise and manufacturing capabilities across the entire value chain, from exploration and drilling, through turbines and plant components, to digital solutions can tremendously support the overall project goals and objectives.

For example, to mitigate the challenges of the drilling and exploration phase, the proven Integrated Well Services approach can be applied. By offering a complete range of capabilities and when necessary, forging strategic alliances with other players in the geothermal sector, the BHGE Integrated Well Services group provides total wellbore planning, construction, and management. This includes a detailed, pre-well planning process to design a customized wellbore construction plan tailored to the specific needs of the geothermal project resulting in better efficiency, on time delivery, and better productivity.

BHGE is uniquely positioned as the only fullstream services and technology provider in the O&G industry to serve the geothermal sector across the entire value chain from upstream to downstream, as depicted in the figure below.

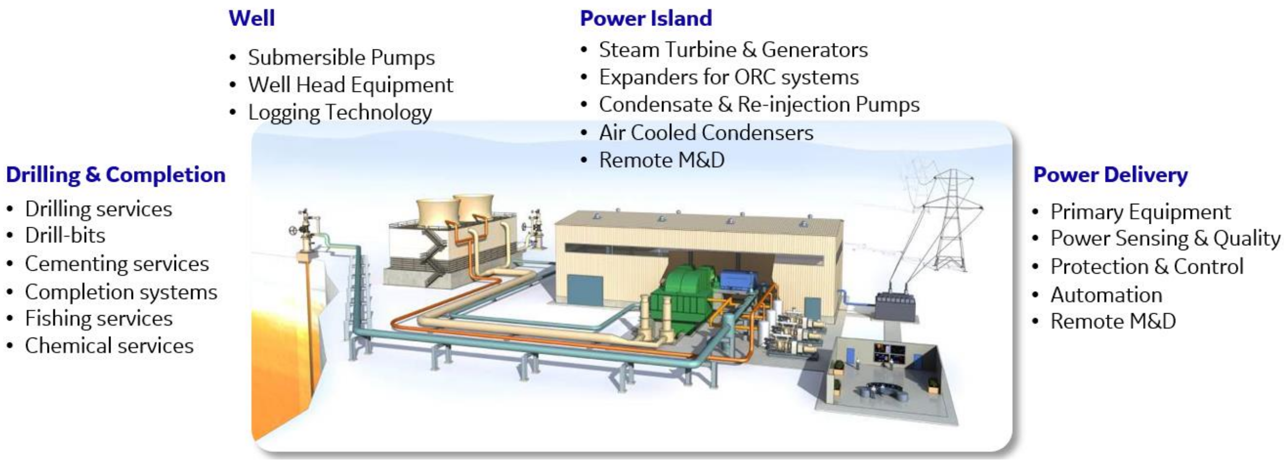

Figure 8: Geothermal Power Plant Overview - Key enablers from the underground systems to the power production

3. CONCLUSIONS

In this paper, the authors discussed the importance of innovation and knowledge transfer from the O&G industry into the geothermal sector to reduce the risks and cost of geothermal projects. This approach can help to unleash the full potential of the sector.

Case studies of innovative technologies were presented, such as the development of the industry's first 300° C-capable drilling system and an R&D project of alternative wellbore construction methods. The positive economic impact of using successful drilling (RSS and hybrid bits) and artificial lift (ESP) technologies were shown. Finally, the ORC power plant technology solution and advantages were described.

The authors also discussed how a higher level of integration along the value chain, similar to the latest trends and projects in the O&G industry, can lead to major reductions of cost and lead-time in geothermal projects. However, fundamental changes in the traditional business model are required toward a more collaborative and risk/reward-sharing methodology between operators, EPC companies and technology providers. To have the highest impact on cost and time, technology providers should preferably provide extensive in-house expertise and manufacturing capabilities across the entire geothermal value chain, from exploration and drilling, through turbines and plant components, to digital solutions.

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