Percussion-Enhanced Drilling Technology Supercharges Drilling Performance

Peter Moyes, Jamie Airnes, Marc Anderson, Sahet Keshiyev

HydroVolve & Zerdalab

Keywords

Percussion Drilling, Rate of Penetration, Drilling Costs

ABSTRACT

HydroVolve has developed and launched a novel, next-generation, percussion-enhanced drilling technology. This technology is breaking down drilling performance limitations while overcoming the technical challenges associated with drilling the deep, hard rock formations typically encountered in geothermal wells.

Perhaps the greatest challenge to scaling deep geothermal on a global scale, is drilling deep enough and efficiently enough through the hard rock formations encountered in geothermal wells to significantly reduce the initial capital burden, giving lower $/MWh cost (LCOE) and greater return on investment.

Currently, most geothermal wells are drilled using conventional rotary drilling methods and equipment. The issue with rotary drilling is that this method experiences frustratingly slow rates of penetration (ROP), particularly in hard rock applications which then has a negative impact on overall project economics. To combat these sluggish rates of penetration and high drilling costs, HydroVolve have developed a novel percussion-enhanced drilling system.

Percussion drilling, or hammer drilling, is a well-known concept and has been proven to increase drilling ROP by several factors, to extend run lengths and to increase drill bit life, providing a significantly lower overall drilling cost. Traditional incumbent hammer drilling systems are typically powered using compressed air. Air systems are however fraught with technical challenges and sub-surface limitations ranging from hole instability, power loss with depth, poor reliability, and high operating costs.

The novel percussion-enhanced drilling system is powered simply by pressurised drilling mud used in any conventional rotary drilling system, does not need compressed air and is automatically operated whenever the bit is rotated. This makes the system truly “Plug and Play”. It can be deployed in any conventional drilling assembly to significantly increase ROP while also extending

run lengths and prolonging bit life. This allows drilling companies and operators to utilise both their existing drilling rig infrastructure and expertise while also dramatically improving efficiencies. It works at any depth, introduces no pressure loss and is all metal in construction requiring no elastomeric seals: perfect for ultra HP/HT and geothermal environments.

1. Introduction

Geothermal as an energy source has no rival. It is abundant, reliable and 'always-on' providing endless baseload energy for heating and electricity generation and once installed is free from fuel cost and carbon emissions. Free and clean energy, forever!

Geothermal energy is readily accessed today at numerous locations globally where geologic conditions deliver the geothermal heat close to the surface. Drilling into this shallow heat resource presents a cost-effective opportunity to capture and utilise the endless heat energy.

Geothermal energy exists everywhere on the planet deep beneath our feet. The panacea for global proliferation of geothermal energy is accessing that deep geothermal energy supply in a cost-effective manner. Herein lies the challenge as the geothermal resource lives deep in the earth's crust within hard basement rock such as granite and basalt at temperatures up to 300 degrees C; the most challenging and extreme of drilling conditions.

Current drilling technology is capable of reaching the required depths and temperatures to access the geothermal energy; however, the drilling rate of penetration (ROP) is extremely slow in these granitic basement rocks and the hard, abrasive nature of the rock along with the high temperatures causes rapid failure of the drill bit, resulting in multiple bit changes. The high-cost burden of drilling these deep wells therefore comes from the combination of three main factors: 1) drilling rig time and cost whilst drilling with low ROP 2) drilling rig flat time cost whilst tripping changing bits and 3) replacement cost of the failed drill bits.

The high capital cost of drilling deep geothermal wells has a negative effect on the Levelised Cost of Energy (LCOE or $/MWh) of the geothermal project, with drilling costs typically accounting for somewhere in the region of 30% to 50% of overall project costs and higher in the deeper wells.

The issue of high initial capital expenditure on geothermal energy projects is one of, if not the biggest hurdles in the way of this geothermal resource proliferating globally. Many studies and reports present the extremely high levels of capital expenditure required to kick-start geothermal projects. One such report, published in April of this year by Lazard Bank, revealed the extent of the CAPEX required to develop a geothermal energy plant with the report finding that geothermal energy requires the highest capital cost of all the renewable energy options and is only second to nuclear energy in terms of CAPEX required to develop the energy plant (Lazard, 2023). Drilling costs account for a substantial share of these high capital cost with some studies finding that drilling can account for more than 75% of capex for deep EGS projects (Robins et al, 2022) and for shallower projects drilling cost still account for 30%-50% of CAPEX (Dumas, Antics and Ungemach, 2013).

With capital expenditure on Geothermal projects so high, one would expect that the LCOE of geothermal energy would not be competitive in comparison to other energy sources, however, this is not the case. Several bodies of work exist which analyse the LCOE of different energy sources and most find that despite its burden of high CAPEX geothermal energy has an LCOE which is comparable to other energy sources. For example, a 2020 report for the world bank found that the LCOE for geothermal energy had a median value of $56 per MWh whereas solar PV and onshore wind had median` LCOEs of $51 & $52 per MWh respectively, with the study also finding that geothermal, despite its capital burden, already had a more competitive LCOE than offshore wind and Coal (Timilsina, 2020). Geothermal is capable of achieving these competitive LCOE's because of its high energy output, low maintenance and zero fuel costs and it's high-capacity factor which is around 90%. Wind, for example, has a capacity factor of just over 40% (EIA, 2022) meaning that once the site is drilled and built it has less nonproductive generating time than other energy sources do. This high-capacity factor and the fact that this resource is, in theory, available everywhere is not only appealing from an economic standpoint but it is also exciting from an energy security perspective. If enabling technology allowed for geothermal resources to be more readily accessed globally, it could provide a sustainable source of heat and electricity and lessen the global reliance on fossil fuels.

It Is therefore impressive that despite it's high CAPEX, which is induced by drilling costs, geothermal still manages to achieve a competitive LCOE, however if these capital costs were to be reduced, geothermal has the potential to be the most cost-effective form of energy production globally. It is, however, worth noting that the above case studies mostly use data from conventional and relatively shallow geothermal projects. Enhanced Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS) on the other hand, require much deeper drilling and thus have even higher capital costs. The current LCOE for this form of Geothermal is well in excess of $100 per MWh (Flowers, 2021) and currently, drilling costs are preventing this form of geothermal energy from coming to fruition.

It is therefore vital that drilling costs are vastly reduced, to reduce the LCOE, to allow global scaling of the geothermal opportunity and to allow for the cost-effective development of EGS and AGS.

The development of technologies that increases ROP and increases bit life to reduce flat time and bit replacement cost is an imperative.

Percussion drilling, or hammer drilling and has been proven to increase drilling ROP by several factors, to increase drill bit life and to extend run lengths. Incumbent percussion drilling hammers are however fraught with technical challenges and sub-surface limitations ranging from hole instability, power loss with depth, poor reliability and high operating costs and are not technically or commercially viable for deep well applications.

Drawing from the known benefits of percussive drilling, this paper presents the development, testing and field trial results of a novel percussion-enhanced rotary drilling system

This novel percussion-enhanced rotary drilling system is deployed as a unitary "Plug-And-Play" tool into a conventional rotary drilling bottom hole assembly (BHA) behind the bit, is powered by the flow of drilling mud to hydraulically cycle a percussive axial impulse drive system. This axial impulse force is transmitted through the bit to the cutting structure and onward into the rock where the impulse force pre-fractures and breaks down the rock. Pre-fracturing the rock significantly reduces the unconfined compressive strength (UCS) of the rock and enables the penetration of the PDC cutting structure to achieve the desired depth of cut (DOC) to effectively shear, cut and remove the rock. The main benefits are that 1) the ROP is much improved 2) friction and abrasion wear are reduced 3) damaging high temperature associated with friction is reduced – significantly extending the PDC cutter and bit-body life.

In association with ZerdaLab, HydroVolve have developed a bespoke PDC drill bit designed specifically for use with the novel percussion-enhanced drilling system

Field trials have proven the system to double ROP, to triple bit life, to operate effectively for extended periods of up to 350 circulating hours and 250 drilling hours at 225 degrees C in 2.1sg high mud solids environments.

2. Sections Rotary Drilling Method

Rotary drilling is by far the most common means to drill to any significant depth either for oil and gas or for geothermal. Two drill bit types prevail today in rotary drilling 1) the roller cone bit and 2) the polycrystalline diamond cutter (PDC) bit. The mode of rock failure and removal for each is different. The roller cone bit relies on point loading of the cone inserts to compressively fail the rock. The PDC bit relies upon the diamond cutter penetrating into the rock and failing the rock through rotary shear. Of late polycrystalline diamond cutter (PDC) bits have been gaining the ascendancy over more traditional roller cone bits due to their higher rates of penetration (ROP) and their durability.

PDC bits however are somewhat limited in their performance in hard rock applications as the required cutter penetration or depth-of-cut (DOC) is more difficult to achieve. Increasing the DOC penetration requires increased weight-on-bit to overcome the higher rock strength.

Increasing WOB however can increase the frictional heat generation between the bit and the rock face which leads to increased abrasive wear and breakdown of the PDC cutters, shortening the bit life. Increase of WOB also introduces many other drill string disfunctions such as stick-slip, helical buckling, lateral instability and high-frequency torsional oscillations, thereby making an increase in WOB an unviable option.

At the same time, insufficient WOB, commonly seen in highly deviated trajectory applications, can also lead to various drilling disfunctions, such as bit whirl and other modes of lateral vibrations, causing the bit's cutting structure to fail prematurely.

3.0 Percussive Drilling Method

Percussive drilling as a method is well known, well documented and widely practiced in well construction, mining, and construction industries worldwide. In essence, percussion drilling requires a hammer to repeatedly deliver a blow through a crushing-bit to the rock with sufficient force as to exceed the compressive strength of the rock, to locally crush the rock into small particles. A fluid medium, either gaseous or liquid is used to clear away the crushed rock from the impact face and to expose undamaged rock to the hammer. The process is continually repeated at high frequency until the desired depth is achieved.

Conventional percussive drilling requires a hammer blow of sufficient axial force to fully fracture the rock with sufficient depth as to generate free particulate at the rock face. This requires an intense repeated high-magnitude impulse action which creates reliability and longevity issues not only for both the tool and the bit, but also for the drilling borehole assembly components. These systems require high degrees of power to operate, often using compressed air as the power media which requires large energy intensive compressor spreads at surface.

The performance gains that can be made as a direct result of introducing percussive drilling to a drilling campaign can be significant. As part of the research into the effects that percussive drilling can have on drilling performance, the authors conducted a detailed literature review on the performance gains that percussive drilling can deliver. These results are summarised in Table 1

Table 1 presents the performance gains that were reported as a direct result of switching from rotary to percussion drilling. As can be seen from the above table, all studies that were cited in the literature review reported an increase in the drilling rate of penetration once percussion drilling was introduced to the operation. The most impressive gain in ROP was reported by Rodgers et al from a drilling campaign in Australia in 2013. In this operation the drilling contractor was looking to improve ROP in an 8¾″ vertical hole section through the difficult Stairway and Pacoota sandstone formations (Rodgers, et al, 2015). In order to achieve these performance gains the operator decided to deploy a percussive drilling hammer. As a result: “the provider drilled the fastest and deepest percussion air hammer run in Australia's Oil and Gas history at 24 m/hr”

Author(s)	Increase in ROP over Rotary Drilling (factor)
Scott, et al, 2015	2.5
Powell, et al, 2015	1.5
Nov.com. 2021, [2]	2.22
Xu et al., 2016	2.26
Huang, et al, 2016	2
Liu et al., 2018	1.6
Li et al., 2021	1.31
Li et al., 2020	1.64
Xuan et al., 2016	1.64
Ziani et al., 2018	1.19
Rodgers, et al, 2015	7

Table 1: Percussive Drilling References citing ROP gains.

4.0 Percussion-enhanced rotary drilling method

Percussion-enhanced rotary drilling relies principally upon the rotary drilling method, using PDC drill bits to fail the rock in rotary shear. To augment the rotating WOB, a controlled cyclic axial impulse is delivered to the bit to induce an additive impulse force sufficiently large to pre-fracture the rock ahead of the cutter. The aim therefore of percussion-enhanced rotary drilling is to effectively reduce the compressive strength of the rock ahead of the bit making a softer, lower strength material to drill. The bit itself is therefore then able to progress with a much higher ROP with a much-extended bit life.

5.0 Design of the Hydraulic Percussion Drive System

The aim of the development of the percussion drive generator was; to develop a tool or system capable of ‘supercharging’ conventional drilling assemblies by delivering reliable, sustainable percussive axial impulse to a rotary drill bit, to do so without the need for the addition of any surface delivery systems, power systems or control systems; to deliver a simple plug-and-play device which would bring all of the known and proven benefits of percussive drilling to rotary drilling without any of the downsides.

The system was required to be powered by the pressurised flow of any known drilling fluid in the drill string from fresh water to high density drilling mud laden with loss control material (LCM). The system was required to introduce minimal negative effect to the hydraulic design of the drilling system by avoiding introduction of a significant pressure drop, additional flow volume or flow velocity requirement. The system was not to affect equivalent circulating density or wellbore pressure management. The system was required to be operable to 300 degrees C. The system was required to not induce unwanted damaging impulse or impact forces to the drilling bottom hole assembly (BHA).

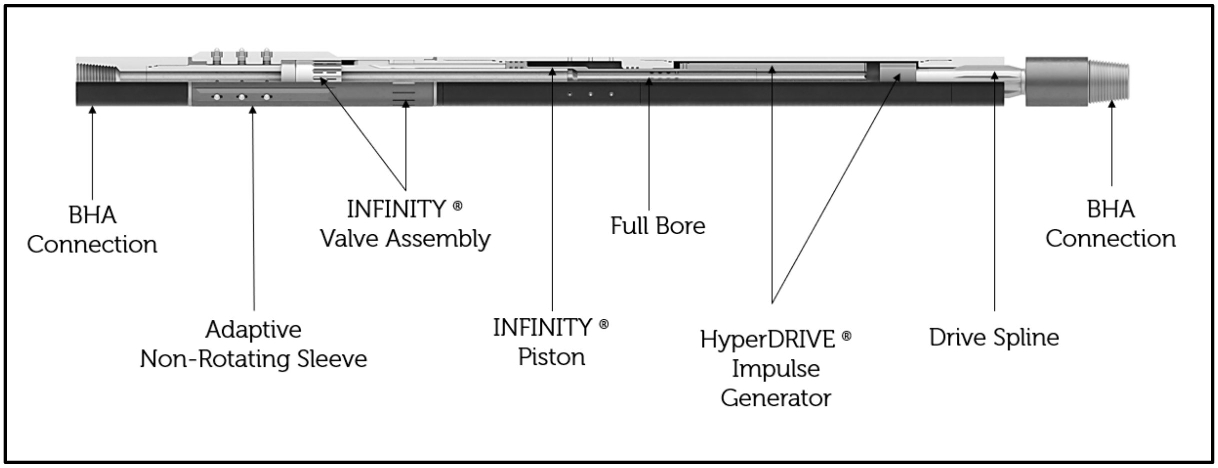


Figure 1. Layout of the System

When rotary drilling, it is essential, always, that a constant pressurised flow of drilling fluid is delivered through the drill string to the bit nozzles to cool and wash the bit, to clear cuttings and to transport them to surface. This flow generates a differential pressure between the bore of the drill string and the annulus between the drill string and the wellbore.

The system capitalises on this differential pressure to power the impulse generator by utilising a novel hydromechanical engine designed by HydroVolve.

The engine is a positive displacement reciprocating piston engine featuring an inlet valve aligned to the drill string bore and an exhaust valve aligned to the annulus as shown in Figure 2 and Figure 3.

When the inlet valve is aligned to the drill string bore, the piston is exposed to the full differential pressure between the bore and the annulus. The piston is driven under power in the forward direction to deliver an impulse.

When the exhaust valve is aligned to the annulus, the piston is pressure balanced and is spring returned to the start position.

The timing of the engine valves are governed by the rotation of the drill string. The non-rotating indexing sleeve as shown in Figure 1 uses the differential pressure to energise adaptive gripping pads into contact with the wellbore. As the drill string rotates, the sleeve remains rotationally stationary and indexes the valve mechanism from inlet to exhaust in a continuous cycle. This two-stroke reciprocating piston engine cycle is infinitely repeatable.

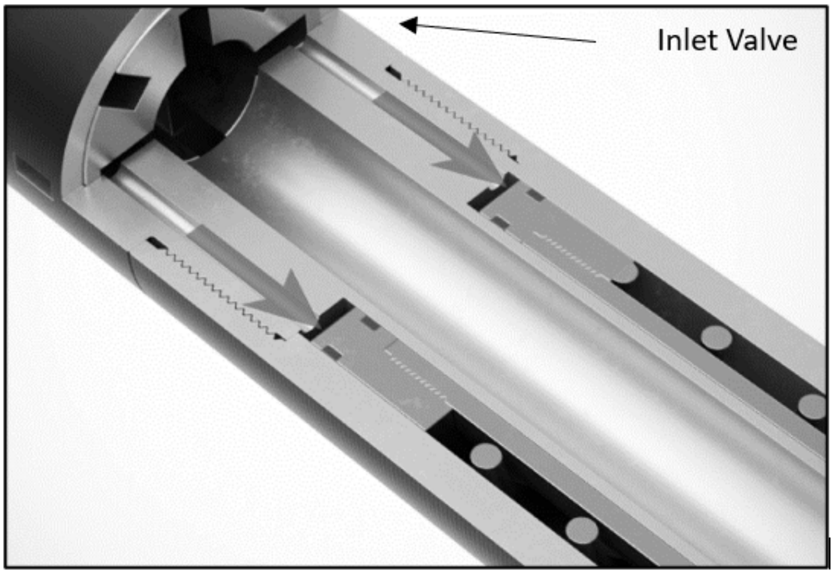


Figure 2: Power Stroke. Inlet Valve aligned to pressurised bore.

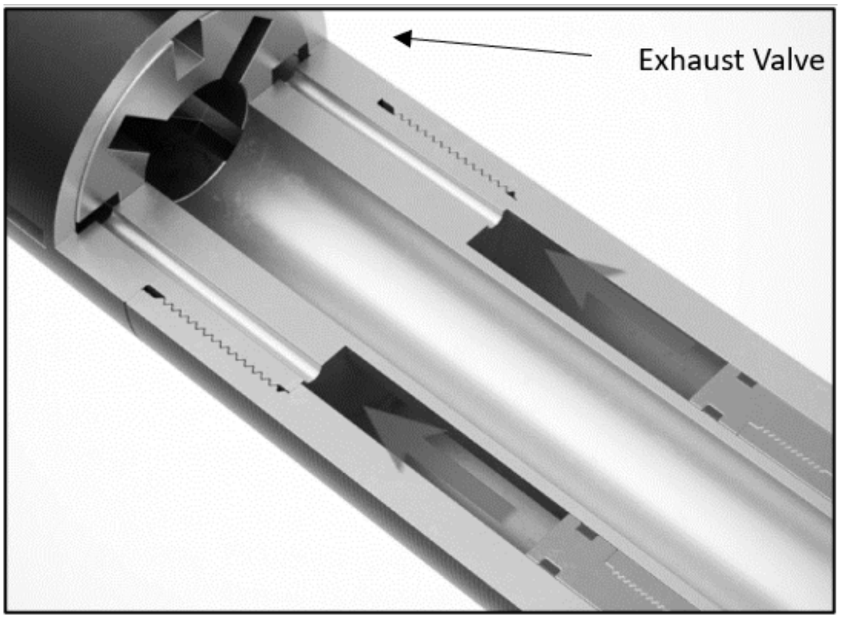


Figure 3: Exhaust stroke. exhaust valve aligned to de-pressurised annulus.

Within the system, the engine is coupled to an impulse generator to deliver controlled axial impulse force to the drill bit.

The complete system can be configured to be elastomer free and entirely metal-to-metal, allowing operation at ultra-high temperatures without concern for degradation of elastomeric seal material.

6.0 Design of the Percussion-Enhanced PDC Drill Bit

In order to maximise the performance and durability of the percussion-enhanced drilling system, ZerdaLab were engaged to analyse the system's axial impulse load signature and using that performance data, design and develop a bespoke PDC bit.

The overarching design features include:

1. tailored bit tip profile design to ensure the nose area is well protected to take continuous cyclic axial oscillations and to transmit the energy to the rock.
2. large bit shoulder radius to ensure its durability as it is exposed to high linear velocities in abrasive rock.
3. radiused cone to allow more space for the extended nose area and lateral stability of the bit.
4. bespoke cutters back rake to account for cyclic axial load while providing sufficient point-loading to fail and shear the rock.
5. bit forces balancing on latest 3-cutter comprehensive model "CHASE".
6. hybrid gauge for enhanced lateral stability of the bit using diamond-impregnated material elements (DIM) in the cutting structure.
7. purposefully oriented conical PDC components behind the primary cutting structure to protect the nose and to aid cyclic axial load generated by the system transferred to the rock and protect the main cutting structure.
8. DIMs behind the shoulder cutters to further enhance lateral stability of the bit.
9. full CFD and re-engineered bit hydraulics from conventional approach to boost cuttings evacuation from the face of the bit and provide a better colling to the shoulder cutters, as well as to facilitate adequate bit pressure drop to drilling system.
10. long gauge to aid more effective axial load transfer to the rock.
11. high-specification PDC cutters across the entire face of the bit, including gauge and back angler, reduce designed-in risks of preferential failure of the cutting structure.
12. diamond enhanced hard facing on both gauge and blade tops of the bit.
13. API steel body, optimal to handle cyclic continuous loads and to resist severe lateral and axial vibrations.

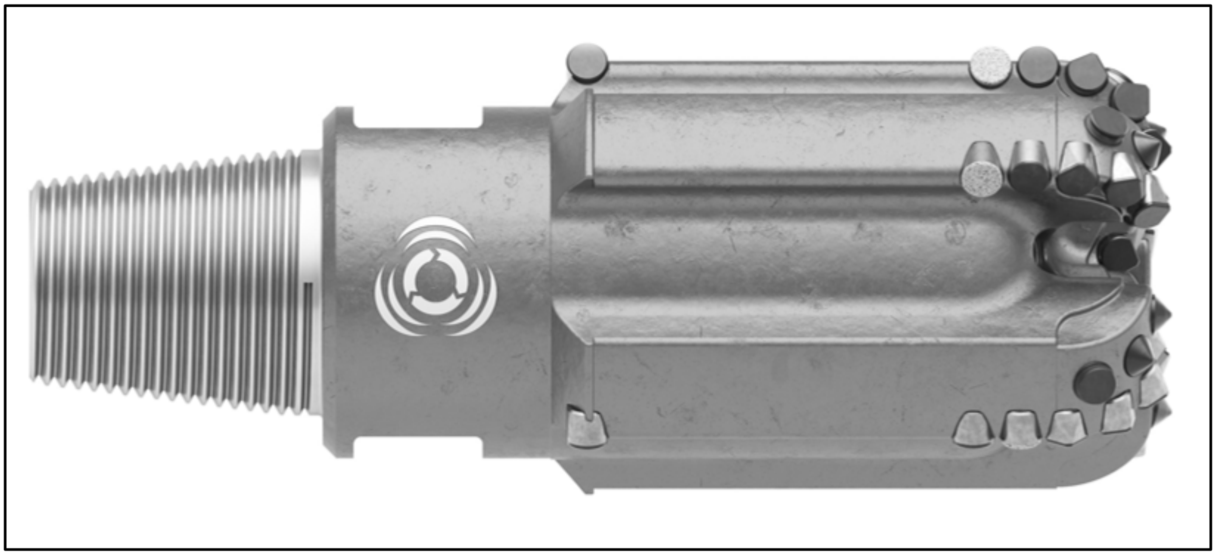


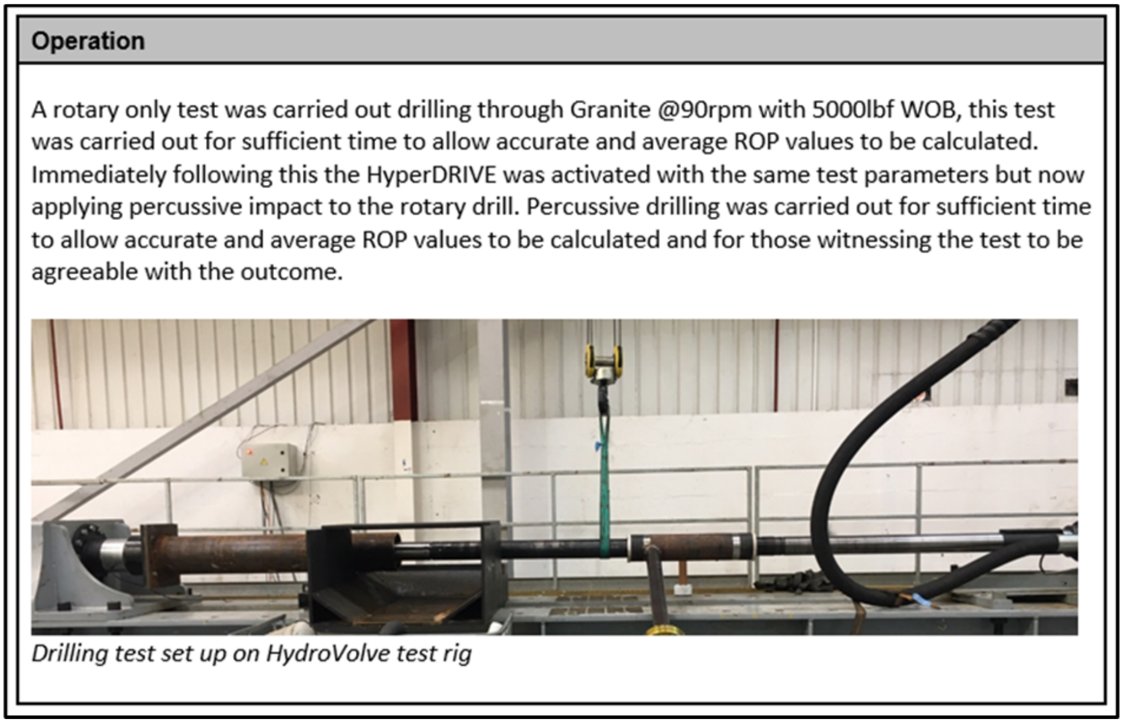
Figure 4: Percussion-enhanced PDC drill bit

7.0 Testing of the Hydraulic Percussion Drive System

A program of testing was conducted at the HydroVolve Drilling Test Centre. The test rig featured a 60ft horizontal test bed equipped with a 1,200klbf push/pull capability, a 120RPM, 15,000ft.lb rotary drive system and a 600GPM, 5000psi flow loop. The test rig was full instrumented to record WOB, axial impulse load, pressure, ROP, RPM and torque at a data capture rate of 10,000hz

Figure 5: HydroVolve Drilling Test Centre, Aberdeen

A 6” percussion-enhanced drilling system was fitted with a 6” custom designed PDC bit and a series of test programs were performed drilling in high UCS blue Rubislaw granite to determine the performance characteristics and to define the optimal operating parameters



Operation

A rotary only test was carried out drilling through Granite @90rpm with 5000lbf WOB, this test was carried out for sufficient time to allow accurate and average ROP values to be calculated. Immediately following this the HyperDRIVE was activated with the same test parameters but now applying percussive impact to the rotary drill. Percussive drilling was carried out for sufficient time to allow accurate and average ROP values to be calculated and for those witnessing the test to be agreeable with the outcome.

Drilling test set up on HydroVolve test rig

Figure 6: Test Program Excerpt

Figure 7: -The Complete System with PDC bits - 6” (top), 8-1/2” (middle), 12-1/4” (bottom)

The results presented below in Figures 8, 9 and 10 conclusively demonstrated that the percussion-enhanced drilling system directly attributed to a gain in ROP by a factor of 2.6 over conventional rotary drilling with identical parameters.

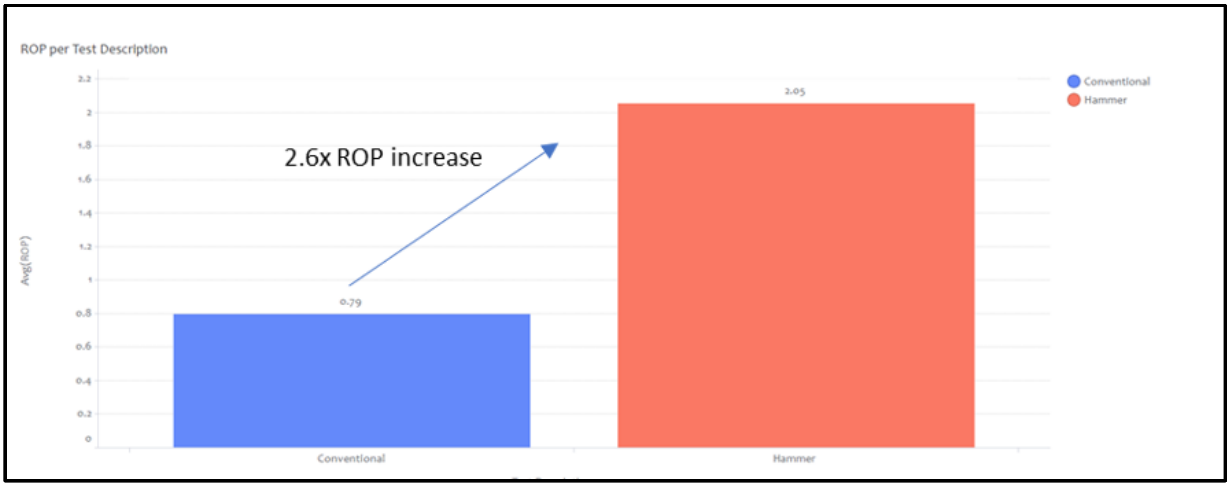


Figure 8: ROP increase - conventional rotary drilling vs percussion-enhanced drilling.

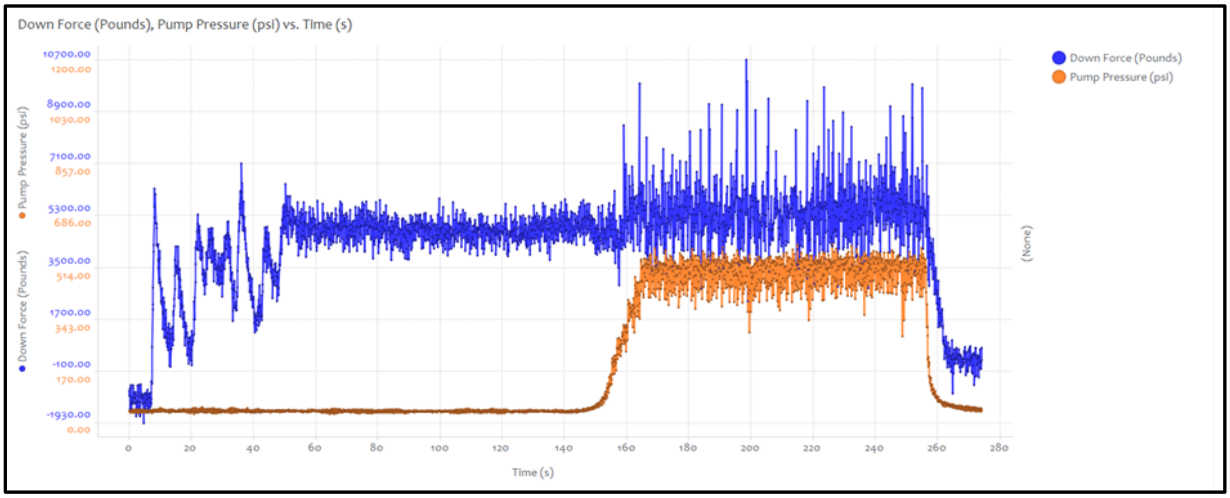


Figure 9: Reactive down force on granite and pump pressure vs time.

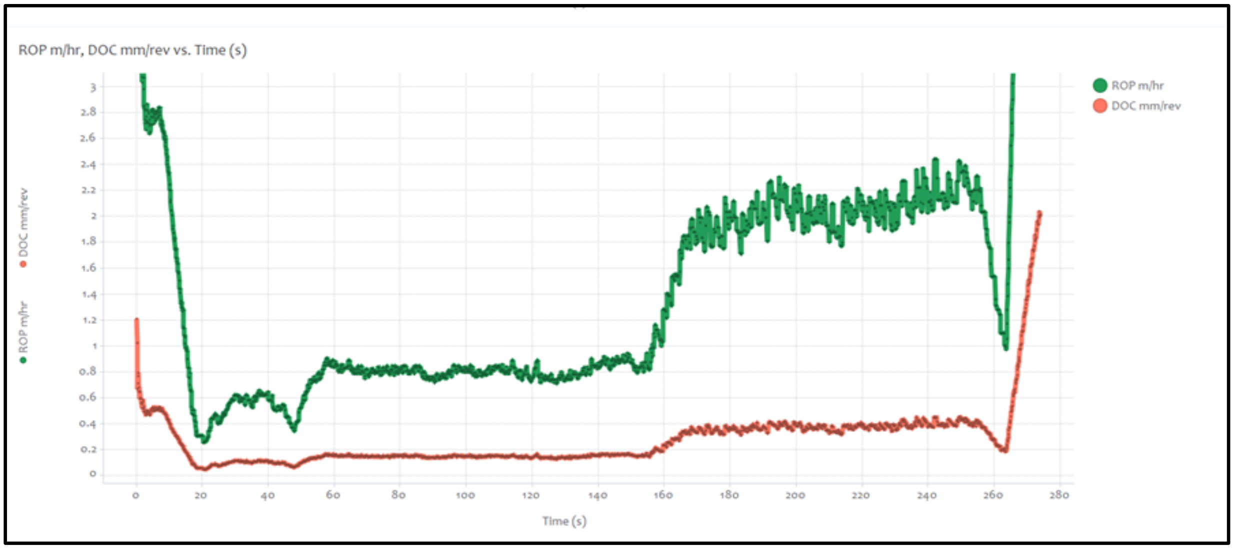


Figure 10: Rate of penetration (ROP) and depth of cut (DOC) vs time.

8.0 System Field Trials

In April and May of 2023, three successive field trials were conducted from land operations in continental Europe deploying one each of three sizes of the percussion-enhanced drilling system: 12-1/4”, 8-1/2” and 6”, demonstrating highly successful performance capability.

As the systems were deployed in ‘tight well’ drilling operations, data and observations reported here are restricted due to confidentiality.

Key highlights from the three percussion-enhanced drilling system deployments can be summarised as follows.

1) Delivered fastest ROP ever recorded in an extensively drilled basin.
2) Achieved the longest drilled interval ever recorded in an extensively drilled basin.
3) Achieved ROP three times the minimum pre-deployment success criteria.
4) Achieved a drilled distance more than double the minimum pre-deployment success criteria.
5) Demonstrated doubling of field average ROP across multiple bit providers.
6) Demonstrated near-triple distance achieved over field average across multiple bit providers.
7) Demonstrated flow durability with over 350hrs circulating with 2.1Sg mud in a single deployment.
8) demonstrated thermal stability with over 28days on bottom at > 220degreesC.
9) Demonstrated mechanical reliability with >250hrs drilling time in one run at >220degres C.
10) Drilled >600m interval, shoe-to-shoe in one run, against best offset well of 220m interval.
11) Successfully drilled out a shoe track.
12) Proved design integrity and reliability of the PDC bit.

These field trials conclusively prove that the percussion-enhanced drilling method delivers significant ROP and durability gains over conventional drilling; in line with the test results obtained.

9.0 Case History: 6” Percussion-enhanced Drilling System Deployment.

The percussion-enhanced drilling system with 6” custom designed PDC was deployed in a challenging application: a deep S-shaped profile well with inclination below 20deg and total depths in excess of 6000m, with a high contrast in lithologies varying between 5-8 kpsi shale and 22-25 kpsi sandstone reservoir and limestone stringers. Historically, it was taking from 5 to 15 drill bit runs to drill the 6” section with average ROP of 1 m/hr. Due to high depths and long drill strings, the low-frequency torsional oscillation (well known as stick-slip) was commonly present while drilling, reducing performance of the drill bits and accelerating cutter wear. Due to the slim hole size, small diameter drill pipes were used (3.5in pipe body diameter) therefor limiting the hydraulic capabilities of the system and further limiting cooling of the drill bit cutting structure and inhibiting cuttings evacuation from the bit face. The main objective of the trial run was to exceed a drilling distance of 100m in a single run, with the historical average being ~80m, therefore the focus was to ensure the bit survived as long as possible. From the ROP perspective, the customer had set an objective of more than 0.7 m/hr.

The field trial was conducted in May 2023 and was considered to be a huge success with the system drilling a total depth of 229m at an averaged ROP of ~2m/hr more than double the expected drilled distance and triple the ROP expected.

Figure 11 below shows the distance versus ROP performance for the system against all other bit runs deployed in the basin, clearly demonstrating the record-breaking performance of the system.

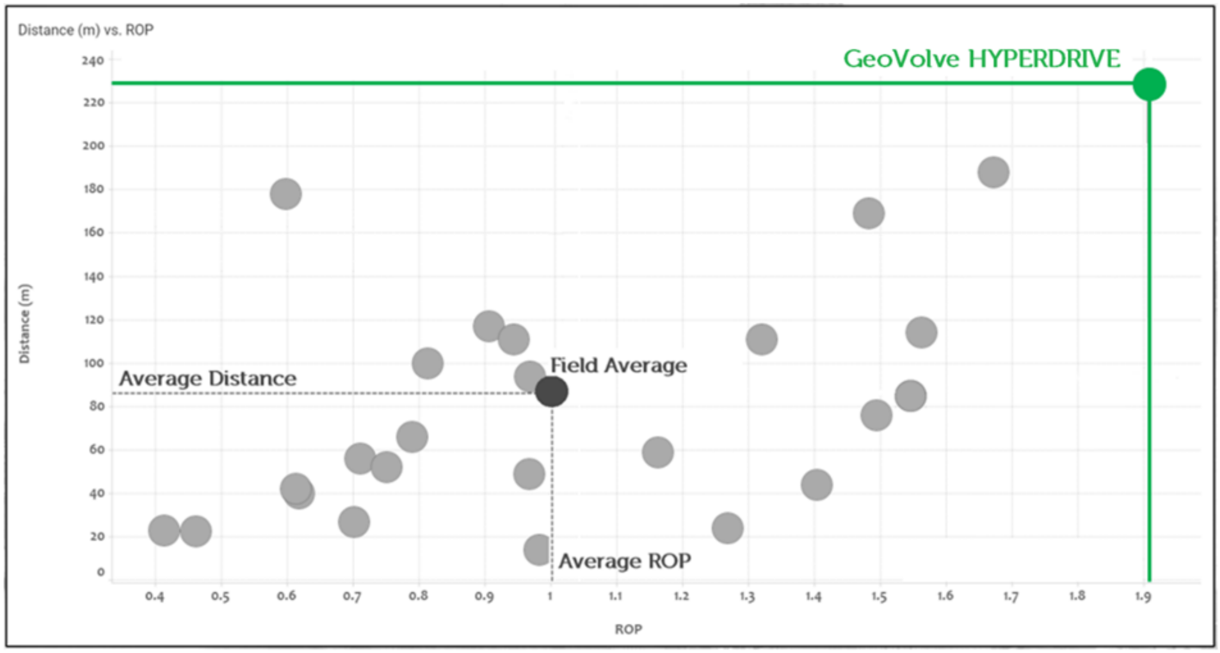


Figure 11: Distance vs ROP for all bit runs in basin, highlighting both average and percussion-enhanced drilling values.

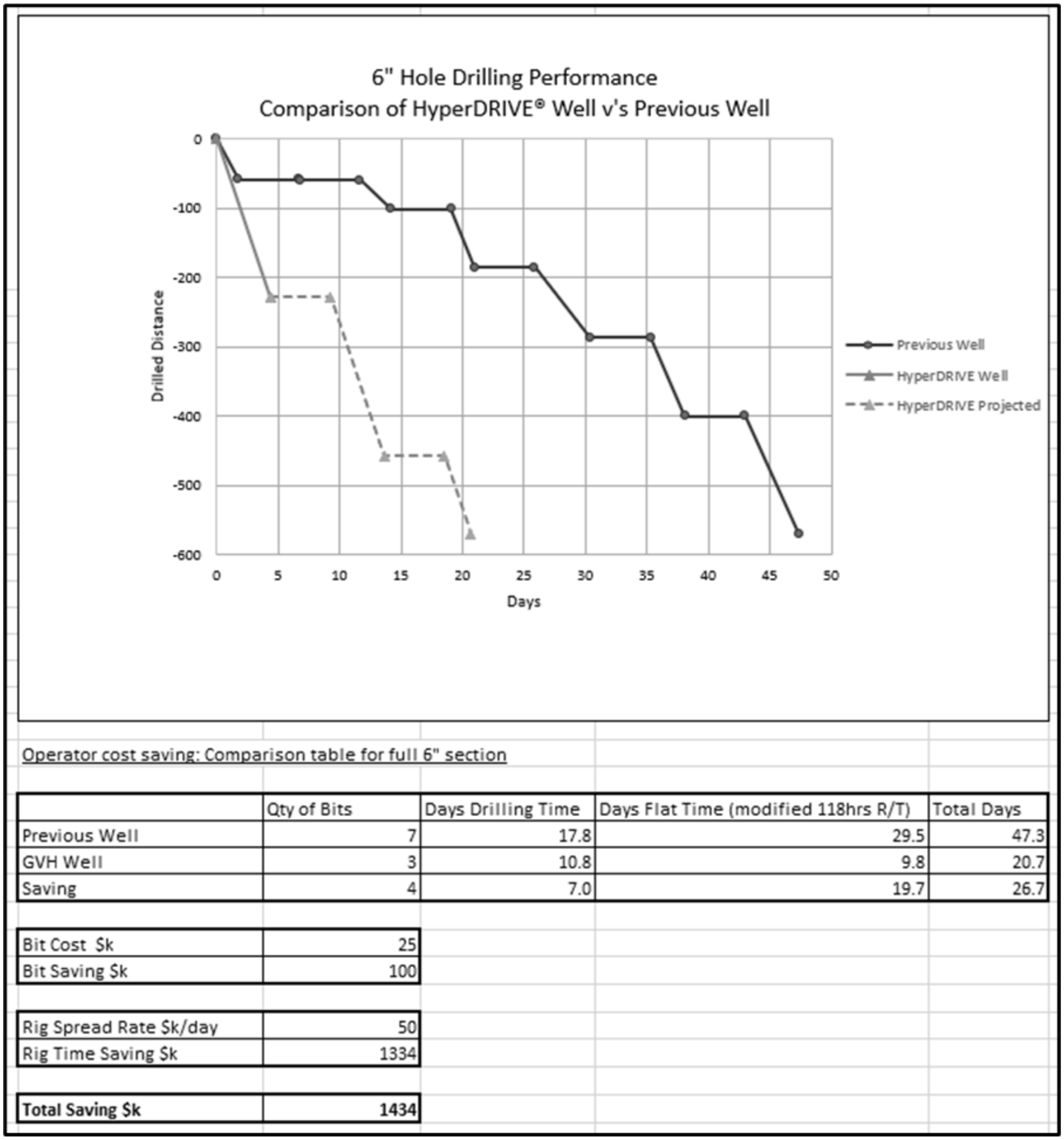
Figure 12 below shows the time-depth curve of the run drilled with the percussion-enhanced system against the nearest actual offset well drilled in the same basin. The graph shows the initial actual deployment of the system and projects the final time-depth based upon repeat performance in successive runs. The flat time has been averaged from the offset well data to give and accurate flat time estimate for the projection. The time depth comparison clearly shows three significant cost saving functions:

1) drilling rig time and cost savings due to drilling with increased ROP.

2) drilling rig flat time cost savings due to avoidance of tripping to change failed drill bits and.

3) replacement cost of the failed drill bits.

Had the percussion-enhanced drilling system been deployed for the full 6” hole section, the estimated cost savings for this 600m hole section alone are in excess of $1,400,000.



Operator cost saving: Comparison table for full 6" section

	Qty of Bits	Days Drilling Time	Days Flat Time (modified 118hrs R/T)	Total Days
Previous Well	7	17.8	29.5	47.3
GVH Well	3	10.8	9.8	20.7
Saving	4	7.0	19.7	26.7

Bit Cost $k	25
Bit Saving $k	100

Rig Spread Rate $k/day	50
Rig Time Saving $k	1334

Total Saving $k	**1434**

Figure 12: Time-Depth curve for offset well vs percussion-enhanced drilling.

10.0 Conclusion

The development of the percussion-enhanced drilling system in combination with the bespoke PDC bit has proven that the addition of controlled axial impulse to PDC rotary drill bits delivers significant gains in both Rate of Penetration (ROP) and bit durability.

The benefits therefore are that wells can be drilled more quickly and more cost effectively using HydroVolve's percussion-enhanced drilling method. This therefore reduces overall capital burden on geothermal project development and equally reduces the LCOE significantly – particularly important for globalising the opportunity for enhanced geothermal (EGS) and advanced geothermal systems and delivering geothermal everywhere.

Acknowledgements

Adam Ubhi, Vasiliy Zbaraskiy and the respective engineers at both HydroVolve and Zerdalab

REFERENCES

Bouabba, Y., 2016. FluidHammer Performance Drilling Tool Increases Drilling Efficiency, Cost Savings in Africa. [online] Linkedin.com. Available at: <https://www.linkedin.com/pulse/fluidhammer-performance-drilling-tool-increases-cost-savings-bouaba/> [Accessed 27 September 2021].

Dumas, P., Antics, M. and Ungemach, P. (2013) 'Report on Geothermal Drilling', *GEOELEC*, pp. 1–36.

Flowers, S. (2021) Future energy – geothermal power, Wood Mackenzie. Available at: https://www.woodmac.com/news/the-edge/future-energy--geothermal-power/#:~:text=It's%20an%20'always%20on'%20power,as%20hot%20as%20the%20sun. (Accessed: 17 July 2023).

Hamrick, T., 2011. Optimization of Operating Parameters for Minimum Mechanical Specific Energy in Drilling. U.S. Department of Energy Office of Scientific and Technical Information,.

Huang, X., Hu, G., Meng, Q. and Zheng, X., 2016. Development Status of Hydraulic Hammers and Development Trends of Hydraulic hammers Used in Oil and Gas Well Drilling. Research Institute of Petroleum Exploration and Development,, 21(16), pp.5453-5464.

Lazard, 2023, 2023 levelized cost of energy+ (2023) https://www.lazard.com. Available at: https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/ (Accessed: 17 July 2023).

Li, B., Aljohar, A., Zhan, G., Sehsah, O., Otaibi, A. and Suo, Z., 2020. ROP Enhancement in High Mud Weight Applications Using Rotary Percussion Drilling. International Petroleum Exhibition & Conference,.

Li, B., Tu, Y., Zhan, G., Ajohar, A. and Sehsah, O., 2021. Parameter Optimization and Application Evaluation of Rotary Percussion Drilling. International Petroleum Technology Conference, pp 1-13

Liu, S., Ni, H., Wang, X., Wang, Y. and Wang, P., 2018. Rock-Breaking Mechanism Study of Axial and Torsional Impact Hammer and its Application in Deep Wells. IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, pp.1-9.

Merchant, D., 2016. FluidHammer Drilling Tool and Agitator™PLUS Combination Sets Records in Mexico. [online] Linkedin.com. Available at: <https://www.linkedin.com/pulse/fluidhammer-drilling-tool-agitatorplus-combination-sets-dan-merchant/> [Accessed 27 September 2021].

Nov.com. 2021. NOV Technology-driven solutions. [online] Available at: <https://www.nov.com/> [Accessed 24 September 2021].

Nov.com. 2021. (2) FluidHammer. [online] Available at: <https://www.nov.com/products/fluidhammer> [Accessed 27 September 2021].

Patel, A. (2019) Geotechnical Investigations and Improvement of Ground Conditions. Woodhead Publishing.

Paknejad Amir et al. (2012) ‘Flow Drilling: Underbalance Drilling with Liquid Single-Phase Systems’, in Underbalanced Drilling - Limits and Extremes. Gulf Publishing Company.

Powell, Scott W., and Ertai Hu. "Hydraulic Percussion Drilling System with PDC Bit Increases ROP and Lowers Drilling Costs." Paper presented at the SPE Middle East Unconventional Resources Conference and Exhibition, Muscat, Oman, January 2015. doi:

Powell, Scott , Garcia, Alexis , Barocio, Hector , and Alvaro Alonso. "Percussion Drilling System Combined with Hybrid PDC Bit Increases ROP and Interval Drilled on Taoudenni Basin Well in Mauritania." Paper presented at the SPE/IADC Drilling Conference and Exhibition, London, England, UK, March 2015. doi: https://doi.org/10.2118/173007-MS

Robins, J.C. et al. (2022) ‘2022 GETEM Geothermal Drilling Cost Curve Update’, Presented at the 2022 Geothermal Rising Conference.

Rogers, Clint , Jangani, Reza , Spedale, Angelo , and Sagar Sadawarte. "Exporting USA Percussion Tools and Techniques to Australia: Underbalanced Hammer Drilling Significantly Increases ROP On First Attempt Drilling Ultra-Hard/Abrasive Formations." Paper presented at the SPE Asia Pacific Unconventional Resources Conference and Exhibition, Brisbane, Australia, November 2015. doi: https://doi.org/10.2118/176868-MS

Santos, H., Placido, J., Oliveira, J. and Gamboa, L., 2000. Overcoming Hard Rock Drilling Challenges. Society of Petroleum Engineers, [online] pp.1-6. Available at:

https://onepetro.org/SPEDC/proceedings-abstract/00DC/All-00DC/SPE-59182-MS/132816 [Accessed 4 October 2021].

Scott W., Powell and Ertai Hu. "Hydraulic Percussion Drilling System with PDC Bit Increases ROP and Lowers Drilling Costs." Paper presented at the SPE Middle East Unconventional Resources Conference and Exhibition, Muscat, Oman, January 2015. doi: https://doi.org/10.2118/SPE-172935-MS

Timilsina, G.R. (2020) 'Demystifying the costs of Electricity Generation Technologies', World Bank Group, pp. 1–37. doi:10.1596/1813-9450-9303.

US Energy Information Agency (2022) 'Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022', EIA, pp. 1–26.

Vante, P., 2012. US20140174779A1 - High frequency fluid driven drill hammer percussion drilling in hard formations - Google Patents. [online] Patents.google.com. Available at: <https://patents.google.com/patent/US20140174779A1/en> [Accessed 27 September 2021].

Xu, Z., Jin, Y., Hou, B., Don, J., Pang, H. and Lu, Y., 2016. Rock Breaking Model Under Dynamic Load with the Application of Torsional and Axial Percussion Hammer. International Petroleum Technlology Conference,.

Xuan, L., Guan, Z., Hu, H., Li, J. and Zhang, B., 2016. The Principle and Application of a Novel Rotary Percussion Drilling Tool Drived by Positive Displacement Motor. ADC/SPE Asia Pacific Drilling Technology Conference,.

Ziani, S., Fetayah, S., Boudebza, A., Bendoudou, M. and Fatah, M., 2018. Percussion Performance Drilling Motor Delivered Extreme Cost Saving In Hard and Abrasive Formation in Ahnet Basin, Algeria. Society of Petroleum Engineering, pp.1-10.