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Fast Hole Making While Steering With Directional Steel Shot Drilling: Technology Overview And Field Performance

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ABSTRACT

In recent years, the start-up Canopus developed the Directional Steel Shot Drilling (DSSD™) technology. DSSD is a unique combination of the latest Polycrystalline Diamond Compact (PDC) bit technology and steel shot erosion. The hybrid PDC-steel shot erosion technology is found to drill faster than a PDC bit on its own while the reduced mechanical forces improve bit longevity and reduce drilling assembly vibrations. Furthermore, the downhole steering sub of DSSD controls the erosion at each hole bottom sector thereby creating an effective directional action and turning DSSD into a Rotary Steerable System. The steering action does not impact the rate of penetration (ROP) and the only energy source required is a commercial down hole battery. The paper describes the DSSD concept, its components, and operational features like the real-time drilling performance optimization, the steel shot circulation control system, and the high steering sub directional accuracy. Next, actual DSSD performance at full scale drill test facilities and in field pilots are presented. Target rock types include sandstone, limestone, and granite. The first field application of DSSD concerned the successful construction of two closed loop borehole heat exchangers including drilling unstable sandy clay as well as ultra-hard chert. Case studies on the impact of DSSD-enabled geothermal structures show an up to tenfold increase of the heat production per borehole heat exchanger and a threefold heat production per DSSD-multilateral doublet. The paper concludes with the field pilot preparations of a high temperature version of DSSD for deep and ultra deep drilling.

1 INTRODUCTION

Canopus recently developed the Directional Steel Shot Drilling technology to enable the cost-effective construction of highly productive geothermal structures. DSSD does not have a depth restriction and can be applied both shallow and (ultra-)deep. DSSD is building on the Abrasive Jet-Drilling Technology described by Fair (1981), who reported on an extensive field test campaign on abrasives jet drilling by Gulf Research and Development in the 60-70s. Fair realized extremely high ROP of abrasive jet-drilling with steel shot particles, but mud property control and other drilling fluid circulation challenges relating to the circulation of an at least 4vol% concentration of steel shot particles were never resolved.

A later industrial development project by Shell focused on resolving the burden of the heavy steel shot particles on the drilling mud density by recirculating the steel shot at the drill bit thereby enhancing the concentration to 4vol% at the bit while the concentration inside the drill pipe and the well annulus could be reduced to less than 1vol%, see Blange (2004). Following successful field pilots, a Shell Technology Ventures start-up DrillStream tried to commercialize the Shell technology as a high rate of penetration solution for unsteered hard rock drilling of slim holes for the tight gas market. DrillStream struggled in the low margin gas market during at that time and their limit to vertical drilling.

Particle Impact Drilling (PID) technology, a development project concerning a combination of polycrystalline Diamond Compact (PDC) bit technology with steel shot erosion, see Pink et al. (2022) and Pink et al. (2023), was recently discontinued. That technology was unsteered like DrillStream's solution and circulated high concentrations of larger steel shot. PID also differs in many other aspects from the directional steel shot drilling technology of Canopus.

The abovementioned development projects were motivated by the energy efficiency of rock removal by steel shot erosion and the, at first sight, straightforward method of aiming a high-pressure solids-laden mud stream at the hole bottom. Conventional rig pumps can be used to circulate the slurry with the steel shot and it was perceived as an effective and straightforward to deploy solution for hard rock drilling challenges. However, drill

bit technology evolution, and in particular the development of the modern high-performance PDC-bits have improved the modern drilling performance a lot. In addition, much better known today than a few decades ago is the importance of drill string vibration mitigation through proper BHA design and rig rotary drive control as well as the impact that the drilling fluid has on ROP and bit longevity. Hence, the focus has shifted from solely high ROP drilling in hard rock towards a combined challenge optimizing ROP, bit longevity, vibration control and reach.

The DSSD technology combines the latest PDC bit technology with steel shot erosion while mitigating the challenges revealed by the abovementioned abrasive jet drilling projects. Figure 1 shows a set of 6 inch diameter Canopus DSSD drill bits. The circulated concentration of steel shot is only 0.5 vol% and the Canopus proprietary bit design enables the combination of PDC-cutting action and steel shot erosion all over the drill bit face. High rates of penetration have been measured at the test facilities of the Rijswijk Centre of Sustainable Geo-Energy (RCSG) of TNO in the Netherlands in granite and limestone, see Reinicke et al. (2025). The drilling performance requires less weight and torque on the bit which increases bit life and reduce vibrations of the drilling assembly.



Figure 1. Three 6 inch diameter DSSD drill bits. The nozzle distribution is such that the jets cover all radii of the hole bottom.

Zikovic et al. (2022) discusses the wellbore transport properties and circulation rates for the steel shot particles used for DSSD. Figure 2 shows the typical steel shot particles and the solids transport test facility of RCSG. With this set-up the borehole inclination as well as the importance of drill pipe rotation on the hole cleaning were studied. The particle size for DSSD is in the range of 0.5 to 1.0 mm, much smaller than for instance the particle size for used by Particle Impact Drilling and hence, easier to transport.



Figure 2. On the left two types of steel shot particles with 0.5 to 1.0 mm. On the right the well bore transport test facility at RCSG

Zikovic et al (2022) showed the sudden transition from bed forming to full wellbore transport depending on drill pipe rotational speed, drilling fluid rheology, and particle size. Figure 3 gives an impression of the various flow regimes evolving from flow rate variations and rheology settings.

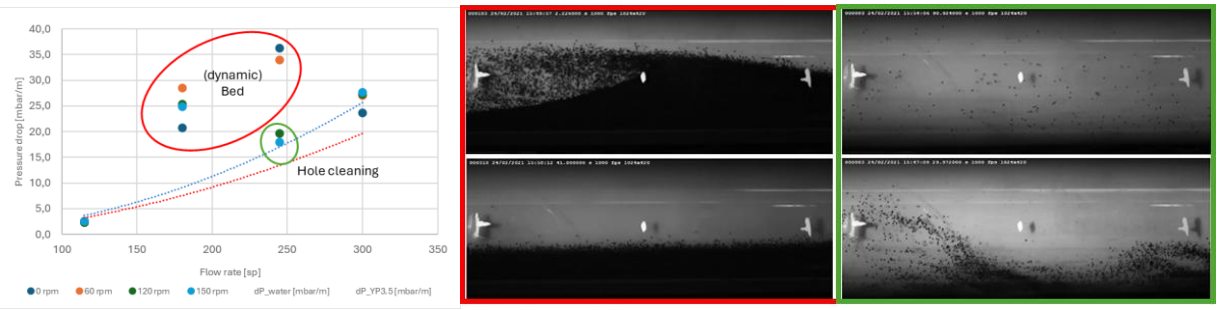


Figure 3. Investigation of hole cleaning conditions for wellbore transport of steel shot particles depending on particle size, rheology, flow rate, drill pipe rotation and well bore inclination. (Zikovic et al. 2022). The photos on the right hand side show bad transport (red frame) and good transport (green frame) and the transport regimes. The bad transport is reflected by an increased pump pressure (figure left hand side), in particular at pump start-up.

The Directional Steel Shot Drilling (DSSD) technology of Canopus is much more than just a high ROP solution for hard rock. Even more important than a high instantaneous ROP is that cutter wear is minimized, and the bit survives ideally till the end of a complete hole section. The borehole should also stay in gauge, and, most important, the hole making technology should enable wellbore construction that deliver high productivity. Given the much lower energy content of hot water compared to oil, high productivity through excellent reservoir contact is key for geothermal. This implies drilling technology realizing long reach reservoir sections and/or multi-laterals at economical drilling cost.

Because of its unique features, DSSD is able to drill these highly productive borehole structures at low cost. DSSD includes a unique rotary steerable solution based on manipulation of the steel shot erosion at the bit. The steering action does not interfere with the hole making and the ROP is not impacted by the directional control. DSSD directional action can realize rapid built rates with a 90° degree turn within 3 m. The maximum dog leg severity (DLS) is limited by the stiffness of the drilling assembly or drill pipe, usually to flexible enough for such an extreme curvature. Details of the concept are described in Blangé et al. (2022), and the results of a field pilot of the DSSD technology, including directional performance in two horizontal laterals, are discussed by Knebel et al. (2023).

1.1 Focus of this paper

This paper discusses the first commercial application of the DSSD technology. DSSD does not have any depth restrictions and can be applied for many drilling challenges, but Canopus identified the construction of near surface closed loop borehole heat exchangers (BHE) as the fastest first DSSD product to market. In May 2025 Canopus drilled two closed loop BHEs to over 400m vertical depth for heating and cooling of an office building in Delft (NL) with a ultra-light truck mounted drilling machine (15 ton lifting capacity).

In chapter 2, the DSSD technology is described. The chapter includes – in addition to the summary above - a more elaborate discussion of drill tests conducted in 2025 and also the importance of real time rig performance monitoring for DSSD.

The BHEs that DSSD drills differ from the standard 100 to 200m vertical, unsteered BHE designs usually constructed for domestic heating. The directional control of DSSD allows curved BHE installations and BHE collisions when drilled from one pad. Canopus' curved BHE design starts vertically, but as soon as a sufficiently consolidated formations are encountered, the BHEs are drilled away from each other. With an ultra-light drilling machine and without blow out preventer (BOP) and requirement for a cased hole, BHEs can be drilled to 500 m vertical depth in The Netherlands. The utilized small drilling machine is low cost, is very mobile, and requires only a small footprint. With the DSSD technology, the operational envelope of such drilling machine can be extended, enabling vertical depth of 500 m (and more), realizing curved designs with up to 700m along-hole length. Soft to very hard rock can be intersected while low weight on bit (WOB) is maintained. In short, the DSSD technology drills deeper and much longer BHEs than conventional and therefore, produce much more heating and cooling per BHE. Canopus novel BHE production concept clusters 8-12 of these deep, curved BHE's in one heating & cooling solution, the so-called Canoctopus™ system. The Canoctopus BHE cluster must be modelled differently than a single BHE and Chapter 3 discusses these differences.

Finally, chapter 4 covers the results of the DSSD performance for the BHE construction in Delft, and the paper concludes with a forward look and describes the further DSSD development by Canopus.

2 THE DSSD TECHNOLOGY

Figure 4 provides an overview of a DSSD unit. A DSSD unit comprises five components: 1) spherical steel shot particles smaller than 1mm; 2) a steel shot injection unit (SIU) that adds the steel shot to the pressurized drilling fluid; and a downhole drilling assembly including 3) a steering sub that converts the supplied steel shot into concentration pulses synchronized with the steering action, 4) a PDC drill bit design for DSSD, and 5) the real time well construction monitoring system supporting the operator in optimizing the DSSD performance and well construction. The DSSD system can be retrofitted on any drilling rig.

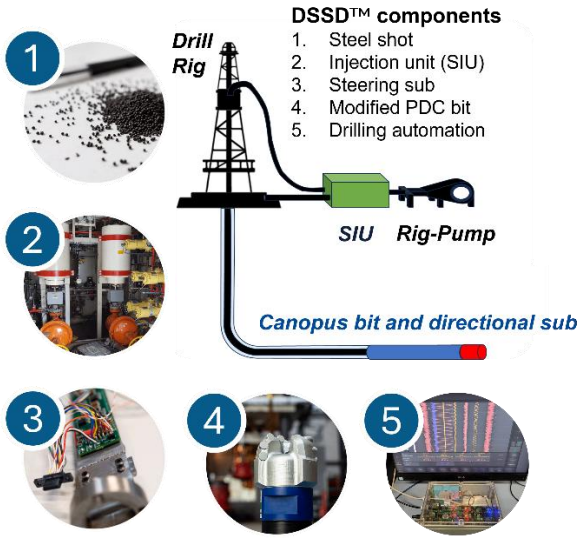


Figure 4. The DSSD technology comprises five components and is deployed as a drilling service. The equipment can be retrofitted on any drilling rig: Horizontal drilling machines, truck-mounted rigs, as well as large rigs for (ultra) deep drilling beyond 6 km vertical depth.

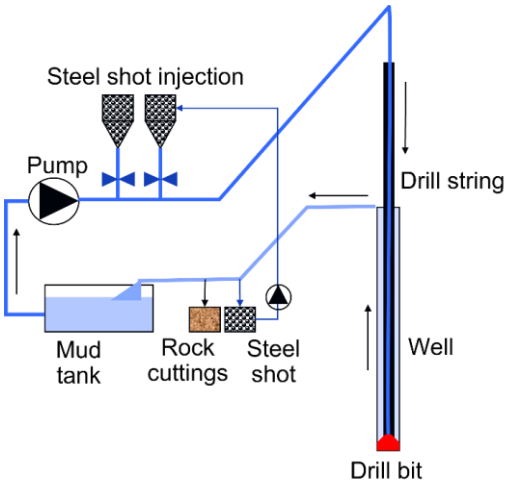


Figure 5. Schematic of the well hydraulics system for DSSD. Normal drilling mud is used as required for bore hole stability and well bore transport. The steel shot is injected into the mud downstream of the rig pump and removed from the mud before the mud reaches the mud tanks. Hence, the pump and the tanks do not see the steel shot particles and the steel shot is only used while making hole.

The steel shot particles are injected into the drilling mud downstream of the rig pump, as shown in Figure 5. Spherical particles, as opposed to edged ones, are used to avoid wear of the drill conduits and pipes. As a rule of thumb, shot velocity is maintained below 10 m/s everywhere except the high abrasion resistant drill bit nozzles. To date, the steel shot circulation did not cause any wear of the DSSD equipment or other drilling equipment in tests and field pilots.

The rig pumps are to provide at least 50 bar bit pressure for steering at 0.5 vol% steel shot. For other drilling purposes the steel shot concentration, the flow rate, and the bit pressure can be increased as desired. For instance, for drilling a hard rock streak the concentration can be increased temporarily to 2 vol% and for ultra deep drilling through hard rock an increased concentration of steel shot can be combined with an increased bit

pressure of 250 bar. For ultra deep drilling, usually through compact and hard crystalline formations, rate of penetration and bit longevity is a challenge whereas the equivalent circulation density (ECD) of the mud is less of an issue. For those applications higher concentrations up to 4 vol% and bit pressures exceeding 250 bar can be considered.

For shallow drilling with the light drilling machines as used for the first DSSD field pilots, see Figure 6, it also might be worthwhile to increase the pump pressure and/or the circulated steel shot concentration in the case of hard rock drilling. For the pilot in Delft, discussed later, the 50 bar and 0.5 vol% concentration worked well.

The steel shot particles are separated from the returns by shale shakers and a magnetic drum separator and reused during the drilling process. To date and within the measurement accuracy, all particles returned to surface and no damage of steel shot has been recorded as the impact force of shot hitting the hole bottom does not exceed the elastic limit of the steel. At 0.5 vol% only a 5 liter steel shot per 1000 liter drilling fluid is required to 'charge' the mud system.

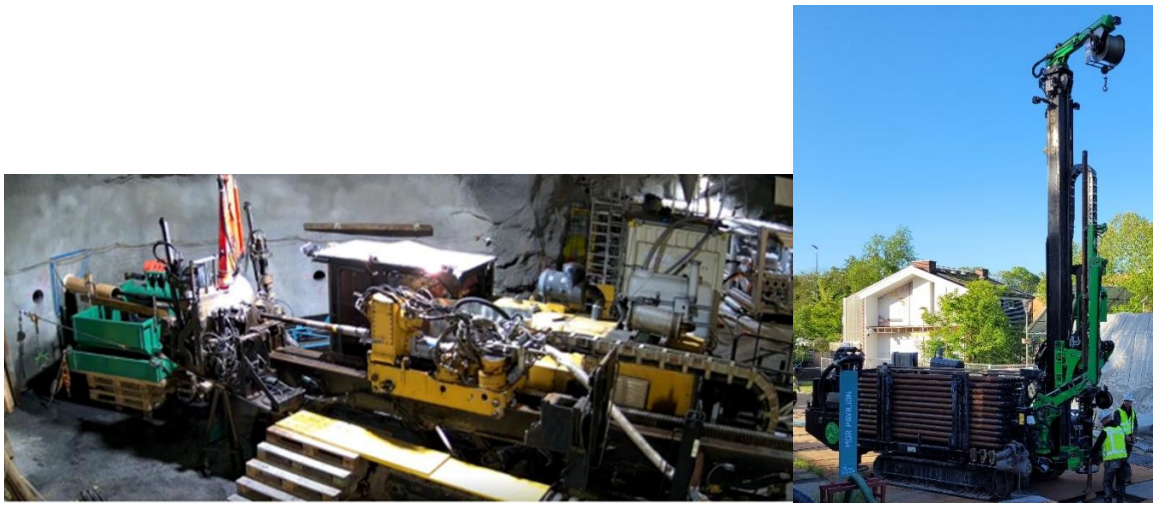


Figure 6. Two drilling machine with which the DSSD technology has been piloted: A Vermeer horizontal drilling machine (left) for a pilot at VersuchsStollen Hagerbach in Switzerland, and a Conrad 15 ton drilling machine of Remborg for the construction of two borehole heat exchangers beyond 400 m vertical depth in The Green Village, University Delft, The Netherlands.

2.1 The DSSD drilling performance

The current DSSD assembly is 10m long and includes the steering sub, the directional module, and the battery pack. It is important that the steering sub is close to the drill bit as the directional sensors should measure the drilling direction accurately and the created steel shot concentration pulses must reach the bit in short distance to mitigate pulse broadening. The steering sub measures the flow rate down hole so that it can accurately calculate the travel time of a steel shot concentration pulse to the bit. This is important for correlating the pulse arrival-time at the bit with the (rotating) bit nozzle orientation for an accurate steering action.

The drill bit combines the mechanical PDC-cutter action with steel shot erosion action. A common method for evaluating the PDC bit-rock interaction is based on the mechanical specific energy (MSE), i.e. the amount of mechanical energy required to remove a unit of target formation volume. Similarly, for erosion, the material removal rate is almost proportional to the kinetic energy in the erosive particles. While both mechanisms remove rock, the simultaneous mechanical and erosive action results in a synergetic effect boosting the ROP. Effectively, a hole bottom profile with erosion damage is easier for the PDC-cutters to break down further. Hence, the synergetic effect is more than the addition of both removal mechanisms.

Figure 7 shows test samples of various rock types exposed to a straight erosive jet. The groove depth gives the specific rock erosivity factor, a parameter similar to the mechanical specific energy. At the same erosive energy, a larger volume of soft rock is removed than of hard rock. The specific rock erosivity is nearly proportional to the unconfined compressive strength of the target rock and, hence, is largely independent of the drilling depth and mud column while drilling. In contrast, the MSE is proportional to the confined compressive strength and does depend on drilling depth and mud column weight.



Figure 7. Steel shot erosion tests in various rock types, including granite, limestone, slate, and various sandstones.

Figure 8 shows two boreholes drilled with the DSSD bit. The hole bottom on the right-hand side was drilled solely with steel shot and without mechanical drilling action. The hole bottom on the left was produced with only the PDC bit. The different hole bottom profiles illustrate the mechanism of combined bit-rock interaction where the PDC cutters bite into a different hole bottom profile of an erosively pre-damaged rock as described previously.



Figure 8. Hole bottom profile for a PDC bit with steel shot (right) and without (left). The steel shot erosion damages the hole bottom such that the PDC-cutters require less energy to break down the rock matrix.

Figure 9 shows the DSSD bit for the drill tests mounted in the drill test facility of RCSG. The target rock sample is located underneath the visible steel tray. The photo illustrates that at a certain rotational angle of the bit the jets dominantly hit one side of the hole bottom. This is key for the steering action.



Figure 9. The Canopus drill bit in the drill test facility of the Rijswijk Centre for Sustainable Geo-Energy of TNO (NL). Note the asymmetric jets that enable the differential hole bottom erosion that causes the steering action.

The bit-rock interaction for hybrid rock removal is illustrated by Figure 10. The curve for PDC drilling without steel shot shows the typical dependence of the rate of penetration as a function of the weight on bit (WOB) for constant bit rotational speed, ambient pressure and bit hydraulics. For effective hole making, a PDC bit has to

be pushed into the rockface deeper than the chamfer on the cutters. Steel shot erosion damages the hole bottom such that less cutters are engaged, and as a result less cutters 'carry' the WOB. This gives that the chamfer of those cutters are completely pressed into the rock face at a lower WOB and the efficient WOB range starts at a lower WOB. As less cutters are engaged to the rock face the driller should reduce the maximum acceptable WOB to some extent.

Note that in the case of drilling hard rock the cutters will not be fully pushed into the hole bottom as this would require WOB values that would damage the cutters. Effectively the WOB for best performance in hard rock will be in the steep part of the curve, and by adding steel shot erosion that steep curve section moves to lower WOB values while the ROP is increased substantially and the cutter wear reduced.

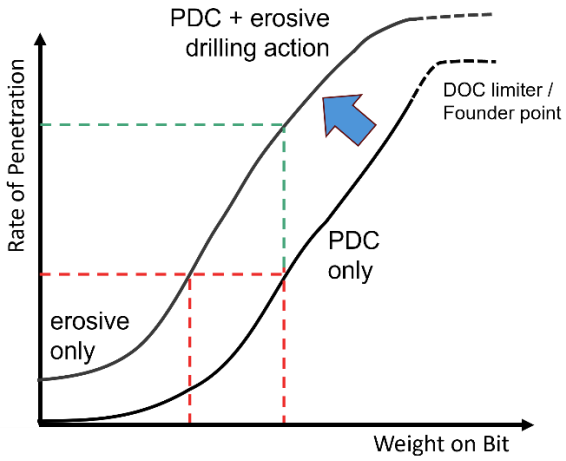


Figure 10. Rate of penetration impact of steel shot erosion on PDC bit performance. In hard rock the maximum depth of cut (DOC limiter) is not reached as this would exceed the maximum loading specification of the cutters. The combined mechanical cutting and the steel shot erosion result in a positive synergy delivering more than the sum of the two hole making methods. The optimum is determined by bit pressure differential, steel shot concentration, down hole pressure, weight on bit and bit RPM.

The Figure 11 below shows drill test results illustrating the relation discussed above. The bar chart on the left compares the ROP increase when adding steel shot erosion while keeping the WOB and bit RPM constant. That ROP increase can be very large, especially for higher steel shot concentration (2 vol% for this drill test) and high bit pressures exceeding 150 bar. The chart also highlights the benefits of the hybrid method with increased drilling depth mitigating the effect of downhole pressure on ROP.

The graph on the right-hand side of Figure 11 shows the impact of adding only 0.3 vol% of steel shot to the drilling fluid at about 100 bar bit pressure. These values are more than sufficient for directional control, even in hard rock like granite and tight limestone. And despite the much lower erosive energy in these low concentration drill tests, the ROP increase by adding the steel shot is significant. As stated above, the bit-rock interaction of a PDC bit not only depends on the mechanical loading, bit design and cutter selection, but also on the ambient pressure and the mud rheology. Newtonian drilling fluids drill much faster than fluids with non-Newtonian rheology. Furthermore, instantaneous ROP is not important, the time required to drill a full hole section is important. Hence, a balance of ROB and bit longevity must be realized to reduce the time for tripping the drill bit in and out of the hole.

Given all those practical factors impacting the economic bit performance, Canopus is developing a real time rig monitoring system with which bit performance, including bit longevity can be optimized while drilling. As the borehole should also be drilled to the desired target and with minimal tortuosity to mitigate various other well construction challenges the accurate directional control, well bore hydraulics and torque and drag are also to be addressed. However, this is beyond the scope of this paper.

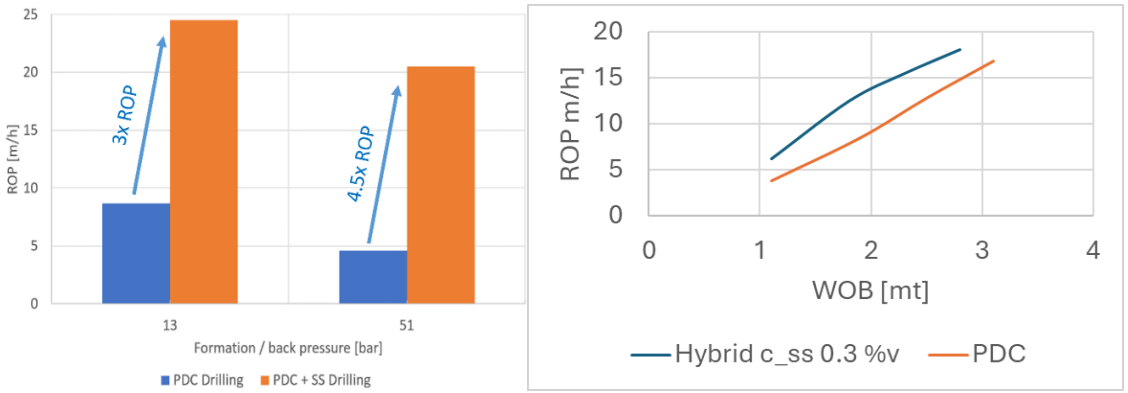


Figure 11. ROP increase as a result of adding steel shot erosion to the PDC-mechanical rock removal. On the left hand side the impact of 2.0 vol% steel shot in the drilling mud when drilling limestone with the PDC-bit. The graph on the right-hand side shows the ROP improvement at steel shot concentration as low as 0.3 vol% required for steering. Without steel shot the PDC-bit produced by Canopus, Zerdalab and GPS has already an impressive performance in the 110 MPa UCS limestone.

3 DSSD FOR CLOSED LOOP BOREHOLE HEAT EXCHANGERS: THE CANOCTOPUS™ CONCEPT

Closed loop borehole heat exchangers for Borehole Thermal Energy Storage (BTES) transfer heat from a building to the subsurface in the summer. In the winter the process is reversed by transferring heat from the subsurface to the building. Per annual cycle the energy required for the circulation pumps and the heat pump is a factor 5 smaller than the energy directly used for heating and cooling. BHEs are closed loop systems and work better the higher the thermal gradient in the subsurface and the better the formation conductivity. Deeper BHEs usually produce more heat per meter borehole because of the increase of the subsurface temperature with depth and because subsurface conductivity increases with depths.

In 2024, about 20,000 bore hole heat exchangers (BHEs) were drilled in The Netherlands. These are vertical and have typically a depth of 100 to 200 m. Subsurface is soft formation with occasionally hard streaks. Utilized drilling machines are small, have usually less than 25 ton hook load capacity and can operate in densely populated areas from a small site like a parking lot. Installations provide domestic heating and cooling and may entirely remove the need for hydrocarbon-based heating.

A case study by Wawoe et al. (2025) showed that deep and curved BHEs produce up to ten times more heating per BHE than the typical 150m deep vertical BHEs. DSSD can construct clusters of curved BHE (like Figure 12) with a small drilling machine within a month (office hours), including the placement and grouting of the U-tubes. The DSSD-drilled BHEs access deeper and higher temperature formations, are longer, target subsurface with higher heat conductivity, and are steered away from each other. See Figure 12 for a schematic of a cluster of 7 curved BHEs. A single cluster, a so-called Canoctopus™, produces up to 1000 MWh heat per year (Dutch case, heat modelling by GHEtool) and a BHE-spacing at surface of 8 m suffices. After installation the closed loop BHE's operate for at least 30 years and do not have to accessed for maintenance.

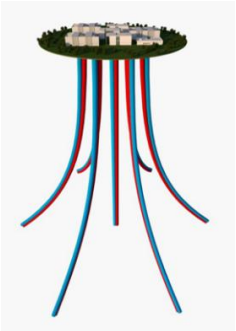


Figure 12. The DSSD technology enables the cost-effective construction of clusters of closed-loop bore hole heat exchangers for heating and cooling. The clusters are deeper and longer than conventional BHE's thereby producing much more thermal energy per BHE. Drilling them away from each other reduces their interference and improves the yield per BHE further. Case studies show that a factor ten higher heat production compared to conventional vertical BHE's of 150m depth is realized (Wawoe et al. 2025). Less BHE's for similar heating and cooling supply reduces the surface area and simplify the heating network.

4 DSSD FIELD PILOT

In May 2025, Canopus drilled two BHEs to over 400m vertical depth at The Green Village of the Technical University of Delft, The Netherlands. The BHEs were constructed in the middle of a street between two office buildings. At 400m the bit ran into a chert layer (4 times harder than granite) which could not be drilled with the 15 ton rated drilling machine delivering only 1 ton WOB on the DSSD bit in pure PDC-mode. After circulating steel shot for 10 minutes at only 50 bar pump pressure the bit could pass through this ultra-hart rock. Figure 13 shows the retrieved bit after drilling the chert. The bit did not exhibit any wear. The figure also shows the steel shot retrieval at the shaker. All steel shot was retrieved.



Figure 13. Left, the DSSD drill bit retrieved after drilling a chert layer. WOB on the 6 inch diameter bit was only 1 ton. The bit was not damaged by the chert nor by the steel shot laden jets. The photo on the right hand side shows the steel shot retrieved at the shaker. The typical ROP was 70 m/hr.

5 OUTLOOK 2026+

A pilot testing DSSD at 1500 m vertical depth is expected to be executed in the second half of 2026. In parallel, cost effective DSSD units are built for drilling curved BHE installations up to 500 m vertical depth. Given the expected impact on the heat transition and reduction of the dependence on gas and power in Europe, the scope for DSSD is 10,000s of curved BHEs in the upcoming years.

DSSD is also perceived to be an attractive option for the cost-effective construction of deep and ultradeep multilateral or radiator-like geothermal structures. This requires a DSSD version suitable for 175 °C down hole operating (circulation) temperature. Usually, the formation temperature can be at least 50 °C higher than that, depending on down hole temperature control. These deep and ultra-deep applications also require optimization of DSSD for hard rock drilling and enhancement of the directional control by geo-steering and/or magnetic ranging. These developments are on the way.

6 CONCLUSION

DSSD is found to be an easy to retrofit drilling tool which provides low-cost rotary steerable control while increasing rate of penetration in the case of hard rock. Lab results and the first field results demonstrated that the combination of steel shot erosion with the Canopus PDC-bit achieves this performance at reduced mechanical loading of the bit cutters and thereby improving bit longevity and drilling reach per bit run.

Drilling automation is key for getting the most out of DSSD. It enables the optimization of rate of penetration, the reach, and the trajectory control all at the same time. It also enables the real time comparison of the actual completion, casing or probe running loads with their specific load limits.

DSSD is a strong candidate for improving deep and ultra deep drilling performance and reduction of well construction costs. But DSSD is also a very attractive, and market-ready, drilling solution for the construction of bore hole heat exchangers up to 500 m vertical depth with low cost, light drilling machines. Two BHE's in Delft (NL) were completely constructed within six 12-hr working days, including conductor placement, U-tube probe

placement and grouting. Projects for high volume domestic heating and cooling are very attractive in Europe and at the same time allow for fast field hardening of DSSD to be ready for deep and ultradeep geothermal development projects in the coming years.

Acknowledgements

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