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Vacuumized Pipe-in-Pipe Solution for Efficient Geothermal Heat Extraction Everywhere for District Cooling and Heating and Industrial Usage

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ABSTRACT

A Closed Loop Horizontal Geothermal (CLHG) co-axial well completed with a vacuumized pipe-in-pipe solution provides efficient heat extraction everywhere for district cooling and heating, industrial usage, and with interesting promises for both heat storage and power generation. Wells with a typical depth of 2-5 km and a 2-5 km horizontal section can be adapted to provide the required heated fluid energy output with virtually no CO_2 emissions.

In the CLHG well, a non-damaging working fluid is circulated in the annulus between the pipe-in-pipe tubing and the outer casing and/or liner sections with contact to the geological formations. In this process, the working fluid will be heated along the horizontal section to the approximate temperature of the subsurface before returning to the surface inside the pipe-in-pipe, ensuring minimum heat loss. The vacuum in the pipe-in-pipe solution is continuous and controlled and nearly eliminates the heat loss as it acts like a thermos flask. In comparison, a standard solution loses 30-40% of the heat during its return to the surface.

Because the CLHG well has no water circulation from geological formations and limited geological requirements, the solution has near-global applications. However, some locations are preferred due to a higher geothermal gradient and/or thermal conductivity of the geological formation for the main part of the horizontal well section.

The CLHG well enables a very diverse application of geothermal heat for +50 years. There is minor corrosion in the well completion, and, as opposed to a doublet hydrothermal well solution, the CLHG well requires no maintenance of downhole equipment or downhole well interventions (i.e., acidizing or fracturing the geological formation) to maintain the flow of working fluid to the surface. Continuous successful project execution is achieved by fully utilizing oilfield services experience, knowhow, and sustained technological development.

1. INTRODUCTION

In order to significantly reduce the geological requirements and mitigate the conventional doublet hydrothermal well issues and location limitations, focus is increasingly changing to closed loop solutions to harvest geothermal energy (International Energy Agency, 2024).

Several new innovative closed loop geothermal well solutions and designs are currently in development. (Law et al., 2014; Think GeoEnergy, 2024). These Advanced Geothermal Systems (AGS) can function without the need for particular geological properties and requirements, providing flexibility when choosing project sites. While conventional doublet hydrothermal wells aim at creating artificial hydrothermal reservoirs, AGS employ a reservoir-independent Closed Loop Geothermal System (CLGS) for direct thermal energy extraction and thus have only few site-specific requirements. This enables their application virtually everywhere and limits development risks related to resource availability (International Energy Agency, 2024).

CLGS can be divided into two main categories, the first being a single well using a co-axial solution with a possible slanted or horizontal section, and the second covering two or more wells connected at several deep intersection points (Maver and Vestavik, 2024).

A key issue with the single well co-axial solution is how the heat loss of the working fluid returning to the surface will be high if not properly thermally insulated. For this purpose, it is proposed to use a pipe-in-pipe solution with a continuous and controlled vacuum to thermally insulate and minimize the heat loss (Maver et al., 2023). This Closed Loop Horizontal Geothermal (CLHG) well solution uses a completely closed loop system for the circulation of working fluid to be heated by the geological formation in the horizontal section and returned to the surface in a vacuumized pipe-in-pipe solution with minimal heat loss.

2. CLOSED LOOP HORIZONTAL GEOTHERMAL WELL SOLUTION

2.1 Well completion

The CLHG well is drilled to a vertical depth of 3-5 km depth (depending on the temperature requirement) with a 2-5 km horizontal (or slanted) section either as a single well or a group of wells, depending on the required thermal energy (Maver et al., 2023). Each well will be completed with the patented pipe-in-pipe solution with a continuous and controlled vacuum between a 4” inner pipe and a 5.5” outer pipe. The geological formation heat is harvested by circulating a working fluid down the well on the outside of the pipe-in-pipe assembly and the inside of the lower completion liner in the horizontal section of the well. The working fluid is returned to the surface inside the 4" pipe-in-pipe assembly with a minimal heat loss as the assembly is working similarly to a thermos flask (Fig 1A).

The individual pipe-in-pipe tubing sections are pre-assembled (Figure 1B, C), and are then assembled on the rig floor and lowered into the well (Figure 2). The vacuum pump is located on the surface for easy maintenance. The process of vacuumization can be initiated as soon as the completion string is hung off the wellhead. The vacuum will be regularly tested during the installation process, and since the tubing completion is made up of gas-tight pipes and connections known from the oil and gas industry, no leakages are expected. However, should a significant leakage in the vacuum occur after installation, it may be necessary to pull out the pipe-in-pipe vacuumized tubing for repair. The pipe-in-pipe vacuumized tubing is designed by experts in the oil service industry specializing in drilling and completing deep horizontal wells with special production tubing and associated smart well services.

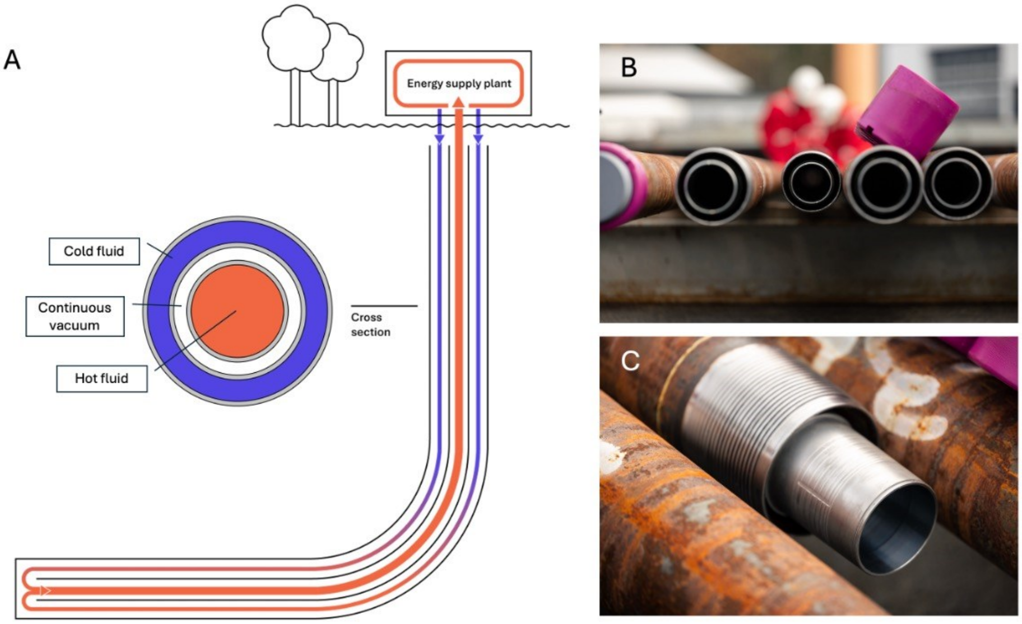

Figure 1: A - CLHG well solution. B - Closed loop co-axial pipes with a continuous controlled vacuum between the two pipes. C – The pin connections of the closed loop coaxial pipe-in-pipes.

The CLHG well completion is not exposed to any oxygen or formation fluids, giving it long-term durability and no maintenance requirements.

Figure 2: Assembly of individual pre-assembled coaxial pipe-in-pipe tubing sections on the rig floor.

2.2 Performance of solution

Without a vacuum to insulate the circulating working fluid, a heat loss of 35-40% can be experienced. Managing this loss of heat is key to making the vacuumized pipe-in-pipe solution unique and the projects economically viable. Using a model from The Institute for Energy Research (IFE), Norway, the heat loss has been found to equate to only a few percent (Figure 3A). This has been further compared and confirmed by various models.

The output temperature of the working fluid at surface level is controlled by the initial temperature which is determined mainly by the depth of the horizontal well section and the working fluid circulation rate (Figure 3B-C). The energy output over time highly depends on the thermal conductivity of the rock containing the horizontal well section (Figure 3D-E). By extending the horizontal well section, the thermal energy output increases linearly.

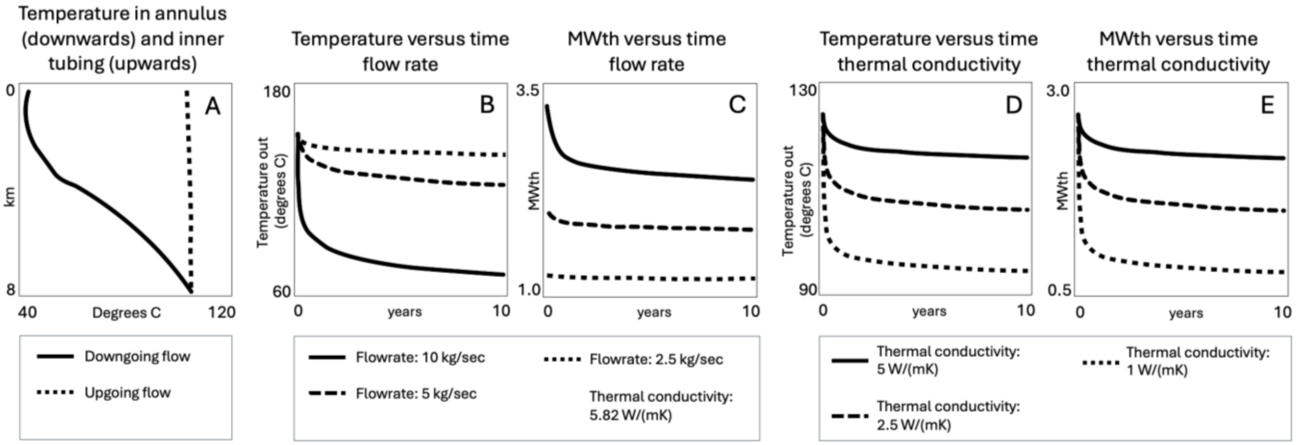

Figure 3: A: The predicted heat loss of the returning working fluid due to the vacuumized pipe-in-pipe. B and C: The temperature and MWth output over time as a function of the flow rate in the CLHG well solution. D and E: The temperature and MWth output over time as a function of the thermal conductivity represented by a very loosely compacted sedimentary rock (1 W/(mK)), a compact, good quality sandstone (2.5 W/(mK)) and halite (5.0 W/(mK)) in the CLHG well solution.

The geological formation around the borehole will cool down quickly after circulation start-up. After just a few months, the geological formation 10 m from the borehole begins to cool. However, this "cold front" slows down. After 10 years, it will have moved away to approximately 40 m from the borehole. With stable production, this process will continue with a logarithmic reduction of the speed of the "cold front." The formation cool-down could be reduced in some wells if there is an active water movement present in the geological formation.

After 50 years of production, the "cold front" will have moved approximately 100 m away from the borehole. If the horizontal well section is at a depth of 4 km, the variation in temperature in the surroundings will still be limited and have a small impact on the heat produced.

If 2 MWth are produced for 50 years, the average cooling of a cylinder of the geological formation around the well is approximately 8.2 degrees C. The cooling at the borehole wall is more at the heal and less at the toe of the horizontal section.

The CLHG well solution is flexible in its heat provision. This is a benefit in cases where the heat demand is a subject of seasonality. The flexibility is realized by either changing the flow rate (Figure 3B-C) or completely stopping the working fluid flow for a period of time. This allows the subsurface to reheat for over-extracting heat during other periods or even reversing the working fluid flow to use excess energy and heat the subsurface for heat storage.

In some cases, the flow of the circulation working fluid in the well can sustain itself by the natural phenomenon of the thermos siphon effect due to the heated fluid in the inner pipe being less dense than the cold water in the outer pipe. However, the circulation of working fluid at various flow rates requires a circulation pump of up to 40 KW.

2.3 Three key attributes significantly impacting project commerciality

There are three key commerciality attributes of the CLHG well solution. First attribute is the geothermal gradient and thereby the depth at which a certain temperature is reached. The second attribute is the thermal conductivity of the geological formation controlling the heat flow, especially in the horizontal section. The third attribute is the drilling and completion performance, determining the number of days it takes to drill and complete a well. These key attributes are related to three main geological settings in order to review the energy production and well construction cost (Table 1). The geological settings are distinct categories relating to the commercial execution of the CLHG well solution only enabling an initial geographical assessment.

2.3.1 Geothermal gradient

The geothermal gradient varies with geographical location and is typically determined by measuring the bottom-hole temperature after drilling. Temperature logs obtained immediately after drilling can also be used but are in general affected by the drilling and fluid circulation.

Table 1: Three geological settings applicable for a CLHG well.

Geological setting	Geothermal gradient (degrees C/km)	Thermal conductivity (W/(mK))	ROP (m/hour)
Sedimentary rocks	Geothermal gradients exhibit non-linear, systematic relationships with continental crustal thickness and lithosphere thickness in sedimentary basins. 'Normal' gradient for continental settings is found to be only valid in regions with 1.5–2.5-km thick sedimentary cover. In areas with > 12-km thick sediment cover, gradients show a significant rise, indicating the influence of relatively thinned lithosphere along passive margins (Kolawole and Evenick, 2023). For a higher-than-average geothermal gradient like a narrow graben, the Rhine Graben in Germany and France is an example. It is 30-40 km wide and 300 km long, and the Rhine river flows through it. It has a geothermal gradient of 50-58 degrees C/km (Dezayes et al., 2008).	Low thermal conductivity values are characteristic for dry, non-consolidated sedimentary rocks such as gravels and sands. Higher thermal conductivity values are characteristic for the most sedimentary rocks. Rocks with high quartz content like sandstone and water-saturated rocks are good thermal conductors (Schön, 2015). Sedimentary rocks, especially shales, tend to be highly anisotropic which is why the direction of the thermal conductivity measurement is critical with an anisotropy factor from 0.12 to 6.07, measured perpendicular versus parallel to the bedding (Čermák and Rybach, 1982), and for shale rocks has been shown to vary from 1.5 to 3.8 (Labus and Labus, 2018).	ROP is very dependent on the formation properties, the drill string design including the downhole drilling equipment technology, the drilling fluids properties and fluid circulation hydraulics, the bit design, and the drilling rig and crew capability. The ROP will therefore exhibit large variations. ROP of 5 to 30 m/hour is common.
Basement (volcanic, igneous and metamorphic) rocks	Areas with, for example, a Precambrian shield have a lower temperature gradient. Fennoscandian Shield constitutes the northwestern part of the East European Craton and dominates in Sweden, Norway, Finland and Western most Russia (Pedersen et al, 2013). Due to the very thick lithosphere, all the Fennoscandian Shield is a low enthalpy area and an example of a geothermal gradient of 8-15 degrees C/km (Kallio, 2019). Ring-of-fire consists of oceanic trenches, volcanic arcs, and volcanic belts and/or plate movements with an elevated geothermal gradient due to convergent plate boundaries and having 75% of the world´s volcanoes.	The mean thermal conductivity for 20 crustal rock types range from 1.8-4.2 W/(mK). Because a single rock type can exhibit a broad range of thermal conductivities under different conditions, it is not possible to assign a thermal conductivity to each rock type; it is not the rock type but the percentage of constituent minerals which is the key influence on the thermal conductivity (Han, 1983).	Deep geothermal wells drilled in crystalline granite has ROP values at depths of 2,000 and 3,500 m of 3 to 6 m/hour and at greater depths of 2 to 5 m/hour (Baujard et al., 2017). In a high-temperature, deep granite well an average ROP of 20 m/hour was achieved (Fervo, 2024).
Rock salt (Halite)	Rock salt deposited especially in deeper basins will generally show a higher geothermal gradient due to a thinner crust. Extensive rock salt deposits in sedimentary basins activated by halokinesis creating various salt features locally influence the geothermal gradient due to properties of rock salt (Raymond et al., 2022). The thermal conductivity of rock salt is 2-4 times higher than that of non-evaporitic sediments, and heat is preferentially channeled through the salt, creating positive temperature anomalies around the top of a dome and negative ones at its base (Daniilidis and Herber, 2017).	Rock salt is characterized by a predictable and high thermal conductivity compared to sedimentary, igneous and metamorphic rocks with a high thermal conductivity of >6 W/(mK) at 20 degrees C changing to slightly less than 5 W/(mK) at 160 degrees C (Raymond et al., 2022).	Typical ROP in salt is 15 to 40 m/hour with a PDC bit (Dusseault et al., 2015). The risk of drilling horizontally increases significantly at the top of a salt structure and at the bottom. However, these drilling and completion challenges in salt deposits can be mitigated with the right well planning. A study of the effect of drilling fluid on penetration rate and hole size drilling reports of a ROP of up 18 m/hour (Whitfill et al., 2002). Examples of up to 75 m/hour has been reported through a salt section in Gulf of Mexico deepwater field (Halliburton, 2023).

Shallow heat flux data can also give a direct indication of the existence and magnitude of anomalous heat sources within the crust and is therefore able to provide a firm basis from which to predict the increase in temperature with depth as well as showing a correlation in regional mapping (Limberger et al., 2018). However, high heat flux does not always translate into a high geothermal gradient

(Beardsmore and Cooper, 2009). Furthermore, geothermal gradients from continents show no clear relationships with crustal age but decrease with increasing crustal and lithospheric thicknesses (Kolawole and Evenic, 2023).

HeatFlow.org is a repository for data and models related to thermal studies of the earth and includes the global variation in geothermal gradient for individual countries. The thermal gradient from the continental crust has a median gradient of 34 degrees C/km (Thermoglobe, 2023).

Three onshore geological settings are reviewed in Table 1, and each setting show significant variations in the geothermal gradient. Rifts and back-arc basins especially have a high to very high geothermal gradient, whereas cratons and fold belts have a very low geothermal gradient (Thermoglobe, 2023).

The geothermal gradient at the horizontal part of the CLHG well is key to achieving a desired temperature and MWth output at the surface. As a minimum, the virgin geological formation temperature has to be higher than the required working fluid temperature to be delivered at the surface.

2.3.2 Thermal conductivity

Conduction within a solid, liquid, or gas is the principal mode of heat transfer in the earth and a principal thermal property. Thermal conductivity varies with the composition of the rock and is controlled primarily by the relative effectiveness of heat transport through grain-to-grain paths of the rock. The presence of pores in the rock will therefore limit the heat transport. A rock type has a large range of heat conductivities, depending on the grain size, grain composition, material between the grains, pore fluid composition, pore size, and porosity (Robertson, 1988).

The thermal conductivity of rocks generally decreases with increasing temperature and increases with increasing pressure. The effects of temperature and pressure generally counteract each other with depth. This can be deduced using available data from existing wells such as core samples, cuttings analyzed in a laboratory with lithological descriptions, and geophysical well logs. The result of correlating thermal conductivity from core data with well log data can be used to infer thermal conductivity for boreholes without appropriate core data that are drilled in a similar geological setting (Hartman et al., 2005).

Laboratory tests have shown a correlation between thermal conductivity and compressional wave velocity (Piementa et al., 2014). There are examples of how this correlation has been used to predict thermal conductivity from seismic interval velocities, including a simple linear relationship between thermal conductivity and seismic interval velocity for clastic sedimentary rocks (Duffaut et al., 2018). The application will depend on the quality of the seismic data, including frequency content, to gain thermal conductivity data at a usable level. However, in many cases, the degree of detail is probably insufficient for geothermal well planning.

Summarized observed thermal conductivity and mechanical properties from 70 best published papers show coal having the lowest thermal conductivity of 0.2 W/(mK) and sandstone having the highest thermal conductivity of 7.1 W/(mK) (Lee et al., 2015).

Optimizing the stratigraphic level of the geothermal well is important to achieve thermal conductivity to an extent that can ensure an adequate MWth output over time. Due to the significant variation in rocks' thermal conductivity, assessing the actual thermal conductivity of the subsurface requires mapping the individual layers of the stratigraphic column and, if possible, using sample measurements from nearby analog wells. If additional thermal conductivity information is required for the final well placement, this may be gathered from the cuttings while drilling the geothermal well using a needle probe method to provide information for the development of a thermal model.

2.3.3 Drilling and completion performance

The drilling rate of penetration (ROP) is dependent on drill bit type and condition, formation properties, drilling mud properties, weight on bit, rotary speed, and hole cleaning efficiency. The ROP exhibits a large variation with examples of 2 m/h in granite and 75 m/h through a salt structure (Table 1).

The drilling rig design, tubular running, and cementing technology are also critical in reducing the time and cost of drilling and completing a well.

Drilling in basement rocks is more difficult and more expensive than drilling in sedimentary rocks. In contrast, rock salt can be easy to drill but more difficult to complete. Salt is commonly two to three times faster than drilling in sedimentary rocks and even faster than drilling in basement rocks.

Promising new drilling technologies with a geothermal focus that could further significantly increase the ROP in basement rocks are currently being developed (GA Drilling, 2024).

3. GEOTHERMAL HEAT OPPORTUNITIES

3.1 Geological overview

With minimal geothermal reservoir requirements for a well to produce heat, the CLHG well has a near global application. However, some geological settings are economically more attractive. Using the three geological settings described in Table 1, it is possible to provide a global overview of the well completion requirements and geothermal heat extraction potential (Figure 4).

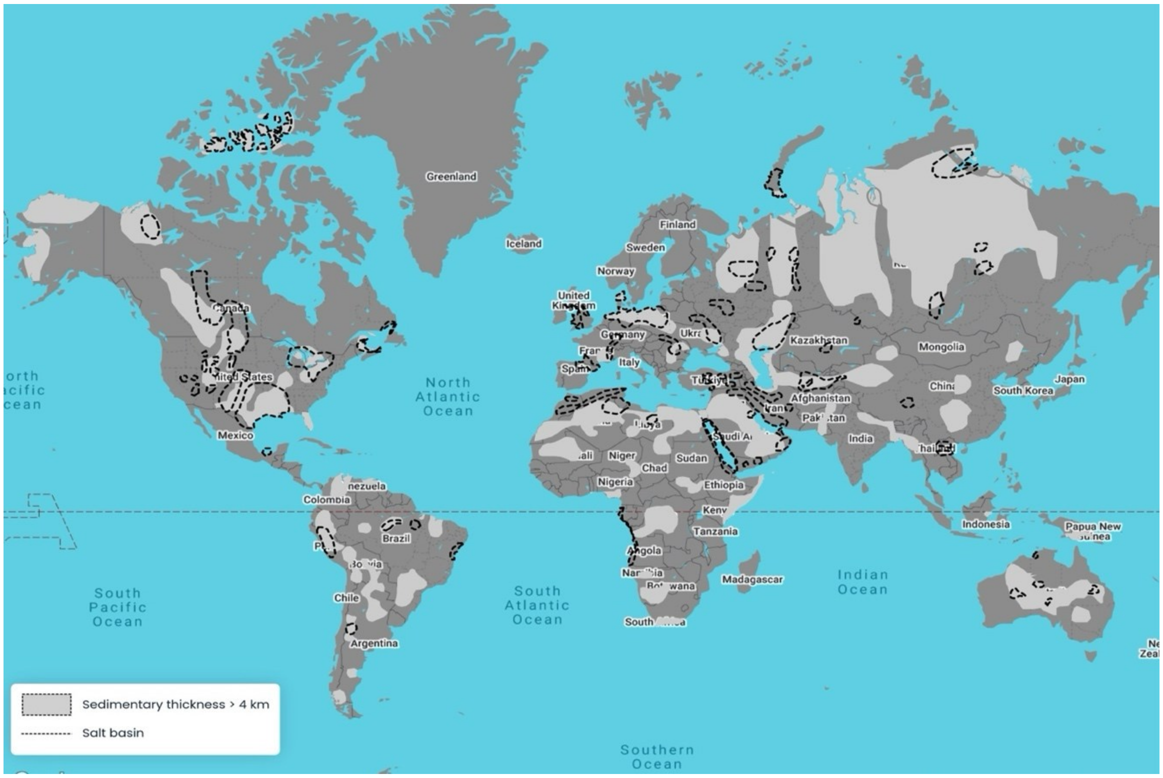

Figure 4: The global distribution of sedimentary rocks, basement rocks, and rock salt, as defined in Table 1, for a CLHG well solution. The map is a simplification compiled from different publications to provide a generalized overview (Evenick, 2021; Folle, 2008, Laske and Masters, 1997).

A substantial part of continents has a sediment cover which is less than four km thick. At places where the sediment cover is more than 4 km thick, it will in many cases be possible to complete a commercial CLHG well with the horizontal section in sedimentary formations (if the geothermal gradient is sufficiently high). If the sedimentary section is less than 4 km thick, it is likely that the horizontal section of a CLHG well needs to be completed in basement rocks. There are areas where parts of or the entire vertical CLHG well section also must be completed in basement rocks due to a limited sedimentary cover.

Commercially, the most attractive places for a CLHG well are areas with sufficiently thick rock salt deposits and salt structures at an adequate depth to achieve a high temperature for the horizontal part of the CLHG well. This is due to rock salt's high thermal conductivity. For the mapped rock salt (Figure 4), neither the thickness nor depositional depth, and therefore the temperature, have been considered.

As more than 10% of oil production worldwide comes from reservoirs at +4 km (International Energy Agency, 2024), technology and know-how are available for completing a geothermal well at these depths.

3.2 Project scope for a 10 MW thermal plant

Different geological settings and heat applications will require different well completions. Table 2 presents examples of different well completions for a 10-well plant with 20 MWth output. The long term temperature of the working fluid on the surface can have industrial applications. The long term temperature of 85 degrees C is furthermore applicable for district cooling using an absorption chiller and 3rd generation district heating. Finally, a long term produced temperature of 70 degrees C is applicable for 4th generation district heating, which is becoming more common.

4. GEOTHERMAL HEAT APPLICATIONS

It is possible to achieve a 1-3 MWth output per well depending on the depth of the horizontal section and associated temperature, the length of the horizontal section, and the thermal conductivity of the rock at the horizontal section (Table 3).

Table 2: Example of well completion requirements for a 10-well solution with a total of 20 MWth output for three geological settings assuming an initial 150 degrees C virgin formation temperature at the horizontal section at a 4.5 km vertical depth.

	Temperature	Well length	Temperatures	Well length
Sedimentary rocks: 2.5 W/(mk)	Long term produced temperature: 85 degrees C Return temperature: 45 degrees C	Horizontal: 6,150 km Total: 10,650 km	Long term produced temperature: 70 degrees C Return temperature: 38 degrees C	Horizontal: 5,000 km Total: 9,500 km
Basement (igneous and metamorphic rocks): 3.5 W/(mk)		Horizontal: 4.400 km Total: 8,900 km		Horizontal: 3,600 km Total: 8,100 km
Rock salt: 5.0 W/(mk)		Horizontal: 3,100 km Total: 7,600 km		Horizontal: 2,500 km Total: 7,000 km

4.1 District heating

The temperature and MWth energy output makes the CLHG well ideal for direct use in district heating (Table 3). The top-side installation circulates the working fluid in the CLHG well to heat it up. When the working fluid returns to the surface, the heat is extracted through a heat exchanger, without using a heat pump, delivering heat directly to the end user.

Table 3: Geothermal heat usage.

	Description	**Use cases**
District heating	Most district heating systems are categorized as 3rd generation, requiring an input temperature of approximately 90 degrees C. However, to improve the cost efficiency, a transition has started to 4th generation district heating systems, requiring an input temperature of 50-70 degrees C.	District heating offers great potential for efficient, cost-effective and flexible large-scale use of geothermal energy. At present, global district heat production is nearly 17EJ, up 30% from 2000 level, representing 9% of the global heating need (Energy Post, 2022). The European geothermal heating market is set to experience significant growth in the coming years as governments try to find an affordable alternative to expensive gas-fired heating (Rystad, 2022).
District cooling	For cooling using geothermal heat, a single-effect absorption chiller is used. This is designed for 80-120 degrees C water input and typically has a Coefficient Of Performance (COP) of 0.65-0.75 to produce 6-7 degrees C chilled water (Al-Tahaineh et al., 2013).	Recently, ADNOC and the National Central Cooling Company PJSC (Tabreed), announced the first project in the Gulf region to harness energy from two geothermal wells using an absorption cooling system to produce chilled water. This will supply Tabreed’s district cooling network at Masdar City, Abu Dhabi, accounting for 10% of its cooling needs (ADNOC, 2023).
Industrial usage	The temperature ranges for district heating and cooling also have direct usage in many industrial processes as presented in a Lindal diagram (World Bank, 2022; International Energy Agency, 2024).	For industrial usage, the whole geothermal temperature range can be utilized for recreational usage, greenhouse heating. The lower temperature range can e.g. be used for pasteurization, milk evaporation and concrete curing. The higher temperature range e.g. for cement drying and sterilization.

The CLHG well top-side unit is fitted into a 20-foot container consisting of a heat exchanger, circulation pump, vacuum pump, district heating circulation pump, expansion tank, make-up fluid tank, power and control system, and instrumentation incl. flowmeters, temperature sensors, and pressure sensors.

4.2 District cooling

District cooling works according to the same principles as district heating by circulating a cold fluid in a district grid to buildings using an absorption chiller (Table 3). It provides better energy efficiency than existing cooling solutions, frees up much-needed space in urban areas, and provides easier operation of cooling systems for end users (DI Energy, 2022).

The market for district cooling is currently smaller than for district heating even though the demand for cooling is far higher than for heating on a global scale. In the Gulf Region (GCC), investments in district cooling are increasing annually, leading to widespread adoption in the UAE and Saudi Arabia (DBDH, 2023). Hence, the district cooling market is already growing rapidly and is expected to keep growing in the future, both in temperate countries and even faster in warmer countries which have the strongest growth in population, building mass, and income levels (DI Energy, 2022).

4.3 Industrial usage

Direct use of geothermal energy has enormous potential to supply heat for recreational usage, in the agriculture industry, and for industrial processes (World Bank, 2022; International Energy Agency, 2024), (Table 3).

The heat consumption in industrial processes is more than five times the heat used in the district heating grids. Heat accounts for 74% of the global industrial energy demand, representing 85EJ consumption (International Energy Agency, 2017).

Table 4: Societal benefits of the CLHG well solution.

ENERGY ACCESS	
Virtually free energy forever	The main electricity requirement is a circulation pump of only up to 40 KW (depending on the flow rate).
Constant energy source	It is an uninterrupted and constant energy source available 24/7, for billions of years.
Secure	The whole well completion is below ground and not directly accessible. Even the surface installation with the size of a 20-foot container can be placed underground.
ENVIRONMENTAL IMPACT	
Limited transport of energy	With limited geological requirements, the geothermal well solution can theoretically be located anywhere close to the end user, eliminating the need to use energy for distribution.
No rare minerals and metals requirement	Standard pipes and equipment are used for a geothermal well completion and does not require any rare earth minerals and metals.
Minor surface footprint	The surface installation for one well can fit into a 20-foot container that can be noise-free.
Near zero CO2 emissions (Energy efficiency)	The main power requirement is a circulation pump of up to 40 KW. This means that for a 2 MWth, the COP is 1:50. This power requirement can be covered by windmills or solar panels.
Water usage	Very limited working fluid usage as it is a closed loop system with no circulation in geological formations.
PROJECT COST	
Predictable and low operational cost	Following the installation of the geothermal well completion, which requires no downhole equipment for operation, only maintenance of the limited surface installation is required. This minimizes the maintenance cost and results in a low operation cost which will mainly consist of the cost of power for the circulation pump.
Efficient and safe execution	The utilization of original oil and gas industry technology, know-how, and vast experience including recent USA onshore unconventional drilling will ensure an efficient and safe well execution.
No failed wells	With no requirement of an active hydrothermal aquifer with specific flow characteristics, the well will always produce heat but with potential uncertainty relating to temperature and MWth output.
SUBSURFACE IMPACT	
No fracturing of the subsurface	As it is a completely closed loop solution, and no enhancement of the subsurface is done, there is no requirement for fracturing the subsurface to create hydrologic connectivity.
No induced micro-seismicity	With no stimulation of a hydrothermal aquifer required, no seismicity is induced.
No ground water pollution	With no fracturing, there is also no risk of interfering with and polluting groundwater aquifers.

4.4 Energy storage

An additional application not reviewed in Table 3 reverses the working fluid flow in the CLHG well. If energy is available to heat the working fluid to a significantly higher temperature than the existing temperature along the horizontal well section, it would be possible during part of the year, when there is no application for the heat, to reverse the flow to reheat the subsurface for later harvesting like Underground Thermal Energy Storage (UTES).

4.5 Power generation

With flow rates of 5-15 l/s and subsurface temperature target, the CLHG well is more suitable for thermal production than power production. However, power production would be possible in some high temperature regimes and as a possible supplement to the primary thermal application.

5. DISCUSSION

Geothermal energy is abundantly available with 15,000,000 ZJ which is approximately 25.000 times more than oil and gas (Beard and Jones, 2023). Hence, the question is not access but how to extract the geothermal heat both efficiently and cost effectively. The CLHG well solution, with its unique attributes and with significant and exclusively positive societal benefits, can meet these objectives (Table 4).

To technically and economically successfully complete the CLHG well with a long horizontal section to harvest heat, best practices and improved well designs especially from the USA onshore unconventional oil and gas industry are used. The designs have demonstrated that it is possible to drive the major production increase in oil and gas production since 2010. This evolution was possible due to new technology and developments for deep horizontal drilling and completion leading to reduced drilling and completion times, lower total well costs, and increased well performance in the period 2006 to 2015 (Energy Information Administration, 2016). By planning campaigns of hundreds or even thousands of wells at a time with a high degree of repeatability, the operators adopted the factory production mentality to field development, impacting efficiency and cost significantly. There are examples of rig moves where the operators have been able to reduce rig move times by 40%. For an unconventional oil and gas well campaign, the first three wells took 73 days to drill. The next three wells were 20% faster, and three further wells were 37% faster than the first wells (Latimer and Meier, 2017). This learning curve phenomenon has also been observed for larger European geothermal projects (Latimer & Meier, 2017) and lately drilling operations at Fervo's Cape Station are showing a 70% year-over-year reduction in drilling times (Fervo Energy, 2024).

Horizontal wells have become the predominant method when drilling for oil and gas in onshore USA. In 2019, 75% of all newly drilled wells were drilled vertically with a horizontal section that averaged 5.5 km (Energy Information Administration, 2020).

It is predicted that the oil and gas industry could be instrumental in encouraging future geothermal developments as up to 80% of the investment required in a geothermal project involves capacity and skills that are common in the oil and gas industry. With the engagement from policymakers and the oil and gas industry, it is estimated that costs for next-generation geothermal wells could decrease by up to 80% by 2035 (International Energy Agency, 2024).

Hence, by developing the geothermal industry, utilizing all aspects of the oil and gas industry, and industrializing the drilling, the CLHG wells will enable an economically and technically feasible project execution.

6. CONCLUSIONS

The CLHG well solution can be part of solving the energy trilemma of being Affordable and Available (Competitive), Green and Clean (Sustainable), and Secure and Reliable (Resilient).

A closed loop horizontal well solution with a vacuumized pipe-in-pipe tubing completion that utilizes oilfield technology and expertise for drilling and completion can expand the use of geothermal energy worldwide, creating a demand for many tens of thousands of wells if not more.

As there is no need for a geological formation with certain petrophysical properties for flowing water between wells, the closed loop horizontal geothermal well solution has a near global application.

There is no maintenance of downhole equipment and limited and easy maintenance of the surface equipment as the working fluid is not exposed to damaging formation water. The closed loop solution ensures limited corrosion and no plugging of the geological formation enabling it to produce heat for more than 50 years.

A completely secure, reliable and constant production of a heated fluid is possible. The solution can be connected to district heating and cooling grids as well as to industrial plants. The solution is environmentally very friendly with practically zero CO_2 emissions and producing energy almost free of charge as the heat inflow from the earth's interior is nearly infinite.

Of the three parts of the energy trilemma, only affordability needs to be further improved. This can be done by increasing rig availability and reducing drilling costs, which does seem to show significant promise.

Given the abundant availability across the world, the CLHG well solution makes geothermal energy readily available, giving access to this truly democratic energy source for the benefit of mankind and the planet.

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REFERENCES

ADNOC: ADNOC and Tabreed advance the first project in the region to harness geothermal energy. Press Release, 14 August. https://www.adnoc.ae/en/News-and-Media/Press-Releases (2023).

Al-Tahaineh, H., Frihat, M., and Al-Rashdan, M.: Exergy analysis of a single-effect water-lithium bromide absorption chiller powered by waste energy source for different cooling capacities. Energy and Power 3 (6), p. 106-118. http://dx.doi.org/10.5923/j.ep.20130306.02 (2013).

Baujard, C., Hehn, R. Genter A., Teza, D., Bau, J., Guinot, F., Martin A., and Steinlechner, S.: Rate of penetration of geothermal wells: A key challenge in hard rocks. Proceedings, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, SGP-TR-212 1 (2017).

Beard, J. C., and Jones, B. A.: The future of geothermal in Texas. The coming century of growth and prosperity in the lone star state, 359 pp. (2023).

Beardsmore, G. R., and Cooper, G. T.: Geothermal systems assessment – identification and mitigation of EGS exploration risk. Thirty-Fourth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, Feb 9-11, Proceedings, SGP-TR-187 (2009).

Cermak. V., and Rybach L.: Thermal conductivity and specific heat of minerals and rocks. In: Angenheister G, editor. Landolt-Börnstein: Numerical data and functional relationships in science and technology. Berlin, Springer, Vol 1a, p. 305–343 (1982)

Daniilidis, A., and Herber, R.: Salt intrusions providing a new geothermal exploration target for higher energy recovery at shallower depths. Energy, Vol 118 (1), p. 658-670 (2017).

DBDH: District cooling. Danish Board of District Heating (DBDH). https://dbdh.dk/all-about-district-heating/cooling/ (2023).

Dezayes, C., Genter, A., Thinon, I., Courrioux, G., and Tourlière, B.: Geothermal potential assessment of clastic Triasssic reservoirs (Upper Rhine Graben, France), Proceedings, Thirty-Second Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 28-30, SGP-TR-185 (2008).

DI Energy: The future of district energy. The Danish Energy Industries Federation (2022).

Duffaut, K., Hokstad, K., Kyrkjebø, R., and Wiik, T.: A simple relationship between thermal conductivity and seismic interval velocity. Leading Edge, Vol 37 (5), p. 322–400 (2018).

Dusseault, M. B., Maury, V., Sanfilippo, F. and Santarelli, F. J.: Drilling through salt: Constitutive behavoir and drilling strategies. ResearchGate, 12 pp. (2015).

Energy Information Administration: Trends in U.S. Oil and Natural Gas Upstream Costs. US Energy Information Administration, Report, March (2016).

Energy Information Administration: U.S. crude oil and natural gas production in 2019 hit records with fewer rigs and wells. Today in Energy, June 25 (2020).

Energy Post: District heating policies for cutting emissions need work says IEA. https://energypost.eu/district-heating-policies-for-cutting-emissions-need-work-says-iea/ (2022).

Evenick, J. C.: Glimpses into Earth's history using a revised global sedimentary basin map. Earth-Science Reviews, 215 (2021).

Fervo Energy: Fervo Energy Drilling Results Show Rapid Advancement of Geothermal Performance. https://fervoenergy.com/fervo-energy-drilling-results-show-rapid-advancement-of-geothermal-performance/ (2024).

Folle, S.: Salt Structures - Exploration and Limits of Interpretation. DGG anual meeting, Szcecin (Poland) Vol: Z. geol. Wiss., Vol. 36 (4-5), p. 321-333 (2008).

GA Drilling: www.gadrilling.com (2024).

Halliburton: Gulf of Mexico operator drills longest and fastest 16-1/2" x 19" salt section in deepwater field. Case study flyer. www.Halliburton.com (2023).

Han, U.: A study on the heat generation and thermal conductivity of crustal rocks. Journal Korean Institute, Mining Geology. Vol 26 (3), p. 371-382 (1983).

Hartmann, A., Rath, V., and Clauser, C.: Thermal conductivity from core and well log data. International Journal of Rock Mechanics and Mining Sciences, Vol 42 (7–8), p. 1042-1055 (2005).

International Energy Agency: Renewable energy for industry from green energy to green materials and fuels. Insights Series: Renewable energy for industry from green energy to green materials and fuels (2017).

International Energy Agency: The future of geothermal energy, 129 pp. (2024).

Kallio, J.: Geothermal energy use, country update for Finland. European Geothermal Congress, Den Haag, 11-14 Jun (2019).

Kolawole, F., and Evenick, J. C.: Global distribution of geothermal gradients in sedimentary basins. Geoscience Frontiers, Vol 14 (6), 101685 (2023).

Labus, M., and Labus, K.: Thermal conductivity and diffusivity of fine-grained sedimentary rocks. Journal of Thermal Analysis and Calorimetry, 132, p. 1669–1676 (2018).

Laske, G., and Masters, G.: A global digital map of sediment thickness, EOS Trans. AGU, 78, F483 (1997).

Latimer, T., and Meier, P.: Use of the Experience Curve to Understand Economics for At-Scale EGS Projects. Proceedings, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, SGP-TR-212 (2017).

Law, R., Bridgeland, D. Nicholson, D., and Chendorain, M.: Heat extraction from deep single wells. Thirty-Ninth workshop on geothermal reservoir engineering, Stanford University, Stanford, California, Feb 24-26, Proceedings, SGP-TR-202 (2014).

Lee, C., Park, J., Park, C., and Park, E.: Current status of research on thermal and mechanical properties of rock under high-temperature condition. Journal of Korean Society for Rock Mechanics, 25 (1), p. 1-23 (2015).

Limberger, J., Boxem, T., Pluymaekers, M., Bruhn, D., Manzella, A., Calcagno, P., Beekman, F., Cloetingh, S., and van Wees, J.-D.: Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization. Renewable and Sustainable Energy Reviews 82, p. 961–975 (2018).

Maver, K. G., Vestavik, O. M., Rasmussen, J. P., and Larsen, C-E.: Closed loop single well geothermal solution. First Break, vol 41 (9), p 83-86 (2023).

Maver, K. G., and Vestavik, O. M.: Geothermal reservoir requirements for closed-loop well solutions to harvest geothermal energy. First Break, vol 42 (10), p. 75-80 (2024).

Pedersen, H. A., Debayle, E., and Maupind, V.: Strong lateral variations of lithospheric mantle beneath cratons – Example from the Baltic Shield. Earth and Planetary Science Letters 383, p.164–172 (2013).

Pimienta, L., Sarout, J., Esteban, L., and Piane, C.D.: Prediction of rocks thermal conductivity from elastic wave velocities, mineralogy and microstructure. Geophysical Journal International, Vol 197 (2), p. 860–874 (2014).

Raymond, J., Langevin, H., Comeau, F.-A., and Malo, M.: Temperature dependence of rock salt thermal conductivity: Implications for geothermal exploration. Renewable Energy 184, p 26-36 (2022).

Robertson, E. C.: Thermal properties of rocks, Open-File Report 88-441, US Department of the interior Geological Survey (1988).

Rystad Energy: Full steam ahead: Europe to spend $7.4 billion on geothermal heating, capacity to reach 6.2 GWt by 2030. Press Release. https://www.rystadenergy.com/news/full-steam-ahead-europe-to-spend-7-4-billion-on-geothermal-heating-capacity-to-re (2022).

Schön, J. H.: Physical properties of rocks: fundamentals and principles of petrophysics (2nd ed). Elsevier, Handbook of Petroleum Exploration and Production, Vol 8, 494 pp (2015).

Thermoglobe: A repository for data and models related to thermal studies of the Earth. http://heatflow.org/ (2023).

Think GeoEnergy: An Overview of Geothermal Resources. https://www.thinkgeoenergy.com/geothermal/an-overview-of-geothermal-resources/ (2024).

Whitfill, D., Rachal, G., Lawson, J. and Armagost, K.: Drilling Salt – Effect of Drilling Fluid on Penetration Rate and Hole Size. IADC/SPE Drilling Conference, Dallas, Texas, 26–28 Feb, IADC/SPE 74546 (2002).

World Bank: Direct utilization of geothermal resources (2022).