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INNOVATIONS IN THE EXPLOITATION OF GEOTHERMAL ENERGY

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ABSTRACT

While the demand for energy grows worldwide, the world depends on 80% of fossil fuels, which produces greenhouse gases and air pollutants, to generate electricity. Solar and wind energy represent a good opportunity, but these are energies dependent on nature and are not available throughout the day or periods of the year at the same intensity. Geothermal energy is, virtually, infinite, and available, at different depths, anywhere in the world, but it involves a high cost of well construction and production plant. This study, based on a systematic review of the literature, presents innovations ranging from alternatives for reusing oil wells for geothermal exploration to the standardization and automation of the drilling process. These can make geothermal energy economically viable and available.

Keywords: Geothermal energy; Innovation; Energy Transition; Oil Wells.

1 INTRODUCTION

Electrification is a path that allows for greater energy interconnectivity, in addition to reducing emissions and pollution near the user (B. HERRING e H. RASHID, 2023). In the generation of electric energy there are mainly two types of generation: nature-dependent or intermittent, and nature-independent, also known as base generation. Nature-dependent generation, such as wind and solar, relies on specific conditions for energy production and needs to be associated with energy storage forms or immediate consumption, making it less reliable for a region. On the other hand, nature-independent generation supports regional consumption and is a more reliable energy source. This is independent of environmental conditions or the need for storage association, such as fossil, nuclear, and geothermal energy (BARBOSA LIMA, 2023).

Due to political and social pressures, such as environmental concerns and/or suspicions of nuclear proliferation, nuclear energy has been losing prominence in some countries, such as Germany. Else, fossil energy has been linked to global warming due to greenhouse gas emissions (DW, 2023). Thus, geothermal energy, currently limited to some regions of the world and with a high initial installation cost, emerges as a potential alternative (JOLIE, SCOTT, *et al.*, 2021).

Regarding geographical limitations, the main aspect is that drilling near volcanic regions allows access to geothermal energy at shallower depths. It should be noted that it is possible to find viable temperatures for geothermal energy production in any region of the planet. However, the cost aspect is generally not feasible with current technology (KUJBUS, 2007). The challenge for exploring this type of energy in non-volcanic regions lies in the fact that some soil conditions in different regions of the world, such as Brazil, for example, present layers with lower or moderate temperatures. This makes it difficult due to the high associated costs, but does not make it impossible to implement a plant (NETO, 2023).

Considering the desire to search for basic energy alternatives that do not entail pollution impacts or emissions, some companies have been investing in the development of new technologies. They aim for a technological leap in the process of building these geothermal wells at viable costs and generating significant margins (DICK, FREYER, *et al.*, 2011).

In this sense, the research question that supports this study is: What innovations have the potential to enable geothermal energy?

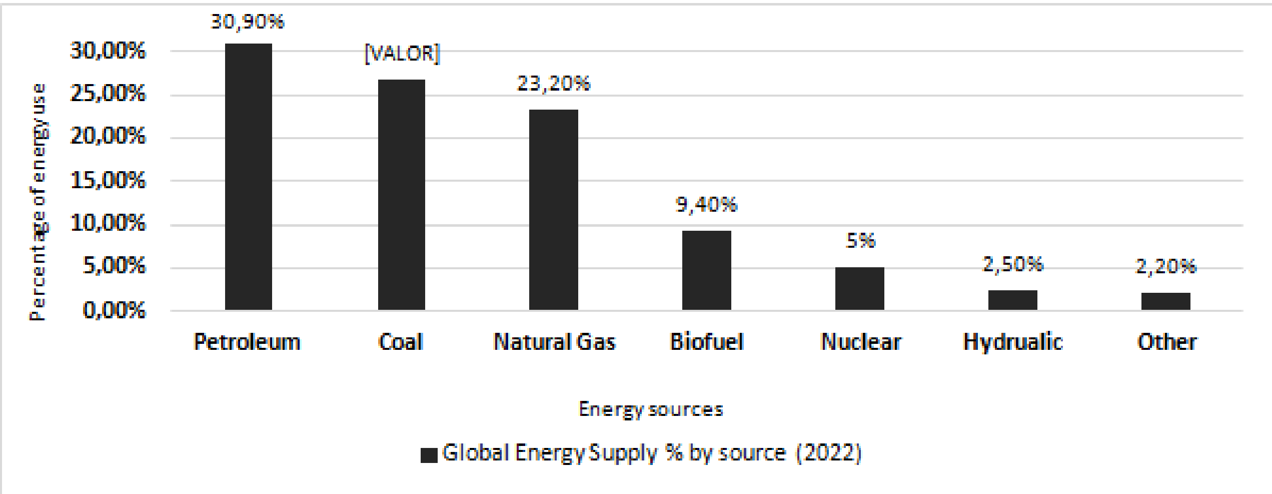
2 LITERATURE REVIEW

2.1 CONTEXTUALIZE GEOTHERMAL ENERGY IN RELATION TO OTHER FORMS OF ENERGY GENERATION

2.1.1 IMPACT OF GEOTHERMAL POWER GENERATION ON THE WORLD

Today, the world depends primarily on fossil energy sources (approximately 80%). The use of fuels from these sources results in the emission of greenhouse gases and atmospheric pollutants, as represented in Figure 1, where Geothermal is part of other sources (B. HERRING e H. RASHID, 2023). A temperature differential of 20°C in hydrothermal resources is already sufficient for electricity production. Na produção de energia geotérmica, essa temperatura é importante pois indica a presença de gradiente de aumento de temperatura em relação à profundidade, o que é imprescindível para a extração eficiente da energia geotérmica. (JAGUSZTYN, 2012).

Fig. 1 | Supply from Energy Global % by source (2022).



While there is a growing demand for energy, there is also an increasing demand for water and food production (JAGUSZTYN, 2012). Geothermal energy is the cleanest form of energy available, due to its reduced environmental footprint. (HE e WANG, 2018). Approximately ninety countries around the world already benefit from the use of geothermal energy. (JOLIE, SCOTT, *et al.*, 2021).

The use of geothermal energy for heating is ancient, with the first evidence dating back to the third century BC by the Romans. The first practical demonstration of electricity production using geothermal energy was in 1904, when steam from a geothermal system was used with a rudimentary generator to power five lamps. In 1913, the first electric plant powered by geothermal energy began operation, and by 1944, it produced 127 MWe (ORAZZINI, KASIRIN, *et al.*, 2011). The recent technology evolution and the current Green House Gases (GHG) reduction needs enabled the expansion of Geothermal generation.

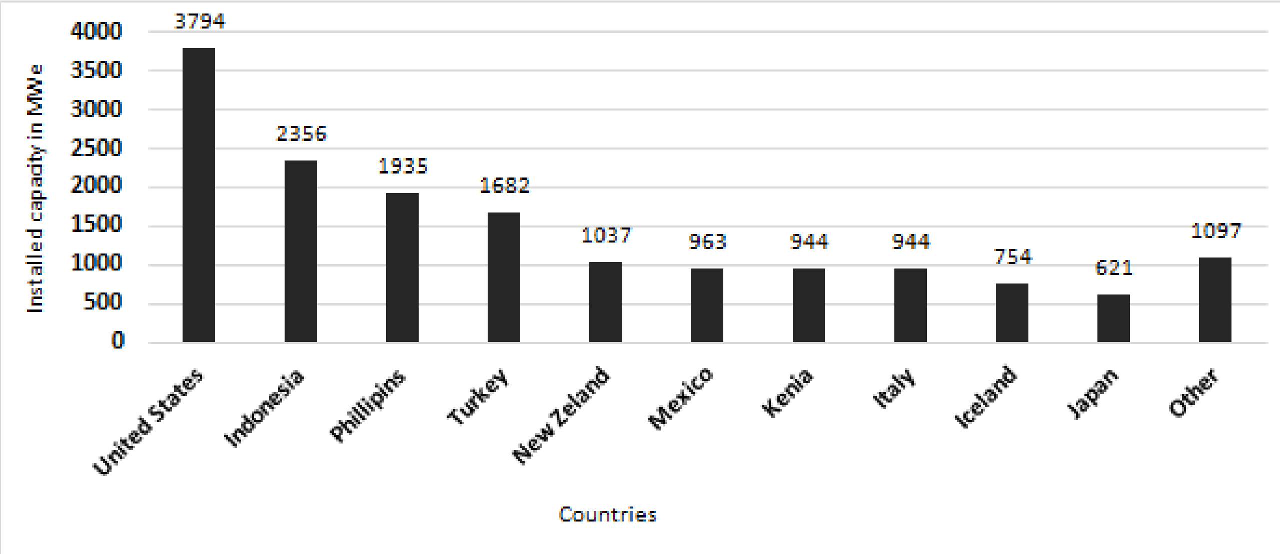
The cost of electricity produced by geothermal energy is competitive with other sources. Unlike wind and solar energy, geothermal energy can operate uninterrupted. Additionally, compared to nuclear energy, geothermal energy requires less area for installation (JONES, SCHULENBURG e WRIGHT, 2010).

Geothermal energy has significant potential for energy production worldwide, especially in regions with favorable geological conditions. This type of energy does not produce greenhouse gases and has shown promising results in Iceland, a European country with numerous geothermal projects (HAMMONS e GUNNARSSON, 2010).

Geothermal energy is a virtually unlimited and uninterrupted resource. Additionally, there is enough thermal energy at a depth of ten kilometers to exceed the current fossil fuel resources by 50,000 times (B. HERRING e H. RASHID, 2023). HE e WANG (2018) claims suggest that the efficiency of geothermal energy ranges from 85% to 95%. It is also reported to be 3.6 times more available than wind energy and 5.4 times more available than solar energy.

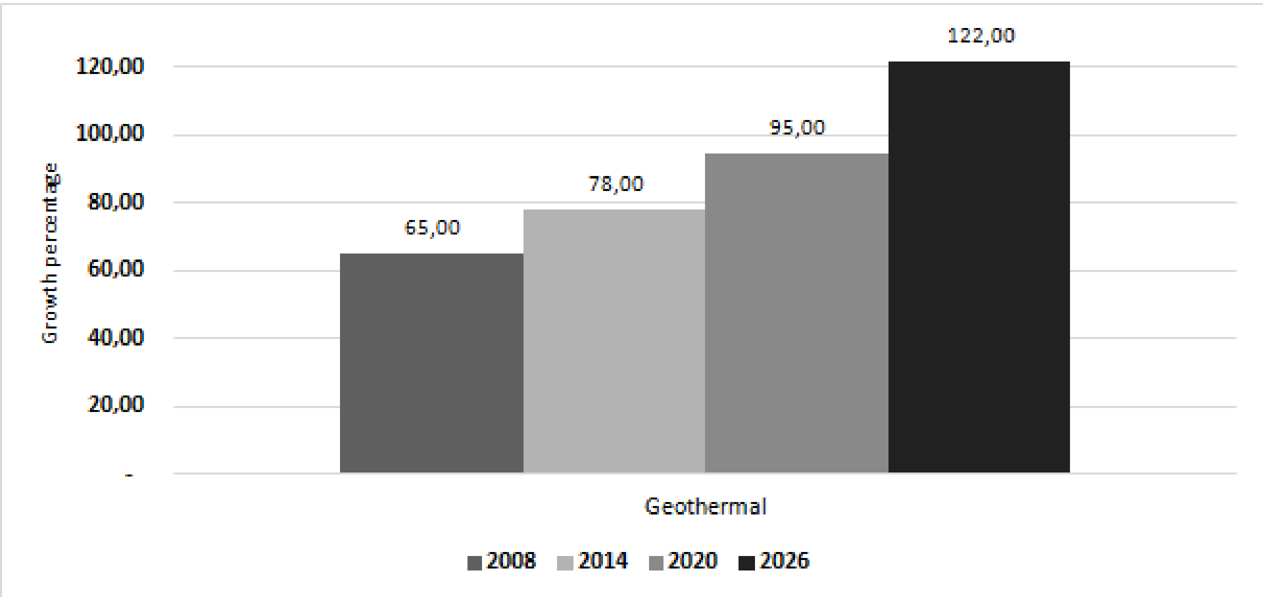
Geothermal energy accounts for 3.2% of the energy generation in Türkiye, approximately 1700 MW. This makes Türkiye the 4th largest producer of geothermal energy in the world, behind the United States, Indonesia, and the Philippines. One of the reasons for this success is the significant collaboration among operating companies, well owners, and service companies in developing these projects (PEDROSA, OCHOA, *et al.*, 2023). The installed capacity of geothermal energy worldwide is 16,127 MW, and the largest producers are shown in Figure 2 (THINKGEOENERGY RESEARCH, 2023).

Fig. 2 | Largest Geothermal Energy Producers in the World 2022 – Installed Geothermal Capacity in MWe



Geothermal Energy is showing a steady increase in generation. At the same time, the rate of growth is also increasing period after period, as observed in Figure 3 (INTERNATIONAL ENERGY AGENCY, 2021).

Fig. 3 | Growing on Geothermal Energy production (TWh).



To place the Geothermal in context with other Renewable sources, Table 1 shows the amount of TWh generated. Although Geothermal Energy works during day and night or cloud days, independently of changes like rain regime, lower winds, which could be resulted from Climate Change, there are some important considerations. The generation volume is not at levels that could offer better electrical grid stability, without the need for energy storage systems (INTERNATIONAL ENERGY AGENCY, 2021).

Table 1 | Renewable electricity generation by technology, 2008-2026 (TWh).

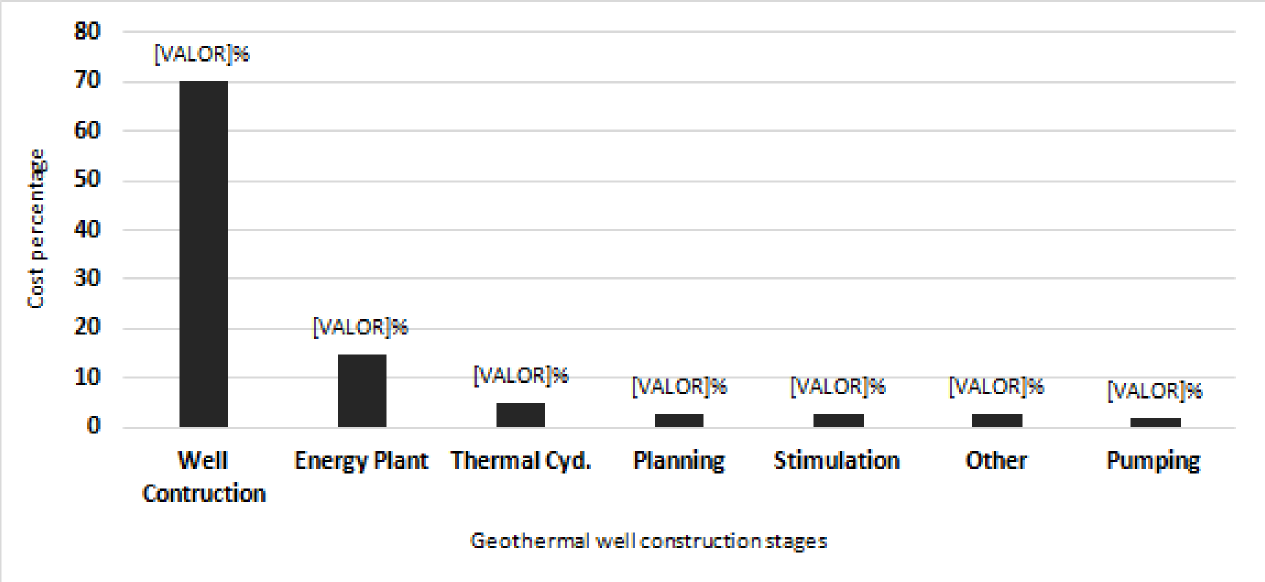
TWh	2008	2014	2020	2026
Hydropower	3,208.00	3,888.00	4,312.00	4,854.00
Bioenergy	246.00	421.00	601.00	865.00
Onshore Wind	217.00	697.00	1,489.00	2,835.00
Offshore Wind	5.00	25.00	110.00	470.00
Solar	12.00	185.00	827.00	2,300.00
Concentrated Solar	1.00	8.00	13.00	26.00
Geothermal	65.00	78.00	95.00	122.00
Ocean	Not Available	1.00	1.00	2.00

2.1.2 GEOTHERMAL ENERGY MARKET AND ITS COST

From 1990 to 2018, there was a stagnation followed by a decline in geothermal energy generation in the United States. However, in recent years, this market has been growing at a rate of 10.9% per year, especially due to the existence of incentives for new forms of energy (SANTOS, DAHI TALEGHANI e ELSWORTH, 2022). The continuation of these incentives might enable more investment in geothermal energy.

The main factor that hinders investments in the construction of geothermal energy installations is the high initial costs and consequently the return on investment (ROI) (DICK, FREYER, *et al.*, 2011). For instance, the well construction represents the highest cost given the complexity of the operation and the required equipment, per Figure 4.

Fig. 4 | Decomposition Percentage of the Cost from Construction from one plant Geothermal (depth 3962 to 4877m).



On the other side, an abandoned well represents both a risk and a responsibility for the operator. Repurposing an oil well with geothermal potential can be an economically interesting solution, as is being studied in Indonesia (SYARIFUDIN, OCTAVIUS e MAURICE, 2016). If there is already an existing oil well to be tapped, the costs are lower, reducing from $0.98/kWh for a new development to $0.87/kWh in reused wells, Table 2 (SANTOS, DAHI TALEGHANI e ELSWORTH, 2022).

Table 2 | Comparison from Prices between Well new and Refurbished.

Category	New Well	Well Reengineering
Total Cost (M$)	116	83
Well Drilling	21,7	0
Plant Development	5,8	0
Well Development	0,67	0
Pumps	10,5	10,5
Tubing	7,2	0
Well Reconditioning	0	15
Torque Cycle Equipment	40	40
Connection to the mains	12	12
Fees and Approvals	13	5
Capacity (MW)	15	12
Electricity Production (GWh/year)	118	95

For example, the implementation of reengineering wells in Hungary has the potential to double the current 1,000 MW of geothermal energy (SZUCS, TURAI, *et al.*, 2022). Furthermore, the electricity generation is not the only possible use of geothermal energy. Direct use in heating buildings is an alternative, and a model in Greece uses geothermal energy directly for heating greenhouses used in food production (FIRFIRIS, KOUGIAS, *et al.*, 2012).

One way to enable this growth is to promote the development of geothermal energy through risk-sharing between public and private institutions. Both the United States and Germany have been significantly investing in the development of high-risk technologies with the goal of reducing the cost of energy production. Companies and universities have contributed by sharing their experiences and knowledge (DICK, FREYER, *et al.*, 2011).

Beyond these countries, Iceland has also made significant investments in developing projects for drilling at greater depths. The goal is to improve the economic viability and efficiency of geothermal energy. These projects aim to reach temperatures of 450°C (HAMMONS e GUNNARSSON, 2010).

There is also an agreement between the European Union and Mexico to develop technologies for modeling, exploitation, and production of high-temperature fields (BRUHN, JOLIE e HUENGES, 2018).

There has been exponential growth in lessons learned from the development, operation, and research associated with geothermal energy. However, access to much of this data is restricted. This is related not only because it is protected by institutions but also because it is not centralized or compatible, as there are no guidelines on how to insert this data. The Department of Energy has been working to facilitate access to this data (WEERS, PORSE, *et al.*, 2021).

Wells with a single diameter have the potential to reduce the construction cost of geothermal wells by 10 to 30%. Additionally, automating the drilling process with real-time decision-making for drilling parameters can further reduce construction costs by another 10%. Moreover, a 10% cost reduction can be achieved if non-productive drilling time is reduced by 50% (DICK, FREYER, *et al.*, 2011).

2.2 GEOTHERMAL ENERGY AND THE PROCESS OF BUILDING A GEOTHERMAL WELL

2.2.1 CLASSIFYING GEOTHERMAL ENERGY

Geothermal wells can be classified according to their temperature: low temperature wells are below 150ºC, medium temperature wells range between 150ºC and 200ºC, and high temperature wells are above 200ºC (MOHAMED, SALEHI e AHMED, 2021).

There are different forms of geothermal energy exploitation: conventional, deep, which tends to explore areas with higher enthalpy and low permeability, and Enhanced Geothermal Systems (EGS) (PEDROSA, OCHOA, *et al.*, 2023) to better understand, the systems can be conventional or unconventional. In conventional systems, geothermal energy is used directly, such as in the heating of buildings. This application is limited to regions that have access to natural thermal brine reservoirs. Unconventional systems are divided into Advanced Geothermal Systems (AGS) and Enhanced Geothermal Systems (EGS) (B. HERRING e H. RASHID, 2023)

It is important to highlight that the production of geothermal energy in conventional hydrothermal systems uses a water cycle that permeates formations. Sequentially, warms by convection with thermal rocks, and produces steam in areas near the surface where it can be used (ORAZZINI, KASIRIN, *et al.*, 2012).

The EGS system is highly dependent on the knowledge of the rock from which heat is to be exchanged because the permeability of these types of rocks tends to be low and requires hydraulic fracturing. For example, to allow the fluid to move from the injection well to the production well. AGS systems operate in a closed circuit, meaning the fluid does not have direct contact with the formation. This can occur through two wells, injection and production, similar to the EGS system. Furthermore, can operate in a single well mode where the fluid is injected through the annulus of a coated well and returns heated through the interior of a production tubing (HAMMONS e GUNNARSSON, 2010).

Production cycles can be direct, utilizing high enthalpy fluids, where steam produced in the well is directly used in turbines for energy production. This system is highly efficient, simple to operate, and has lower capital costs compared to others. Single/Dual Flash systems operate with medium-high enthalpy fluids, using a mixture of water and steam. The heated water from the well is pumped into a cooler water tank, generating steam that feeds the turbine (B. HERRING e H. RASHID, 2023).

Binary or Organic cycles operate with low enthalpy fluids. In this the heated water from the well passes through a heat exchanger, warming a secondary circuit with an organic fluid with a low boiling point, generating energy through the turbine (B. HERRING e H. RASHID, 2023).

Conventional systems use back pressure turbines to relieve steam after energy production, or they use condensing steam turbines that utilize a cooling tower to condense the water (HAMMONS e GUNNARSSON, 2010).

Organic Rankine Cycle (ORC) or binary cycles generally operate with isobutane, isopentane, R-134A, and ammonia. Additionally, there is a cycle called the Kalina Cycle (KC), where ammonia and water are mixed in the primary circuit (SANTOS, DAHI TALEGHANI e ELSWORTH, 2022).

2.2.2 FINDING GEOTHERMAL ZONES

Geothermal wells are more productive and healthier when found in areas with volcanic activity from the Tertiary period or older, or in systems with well-developed fracture networks. In volcanic domains, three types of systems are observed: andesitic arc, silicic volcanic, and mafic volcanic (JOLIE, SCOTT, *et al.*, 2021).

Beyond the observation of zones with tectonic and volcanic activity, it is possible to explore the existence of zones with geothermal energy potential using satellites (GeoVision). In a second stage, an evaluation of the area is conducted with a helicopter to confirm the extent of anomalies. Finally, a report is presented with recommendations for geothermal drilling zones (COMBS e DRIZIN, 2012).

The presence of certain minerals can determine the presence of a hydrothermal system. The spectral signature of deposits of opal and chalcedony can determine if they come from an active system or a former epithermal system. The main minerals are cinnabar (HgS), tuff, travertine ($CaCO_3$), opal (SiO_2 *nH_2O), chalcedony (SiO_2), and quartz (SiO_2). These are the main evidence that can be found from space and later confirmed through area evaluations (JONES, SCHULENBURG e WRIGHT, 2010).

There are still several zones of potential geothermal exploitation in the world that have not yet been exploited. One of them is the volcanic province of Snake River in the United States (SHERVAIS, EVANS, *et al.*, 2011).

2.2.3 CONSTRUCTION OF THE GEOTHERMAL WELL

Geothermal energy harnesses the Earth's temperature to generate steam, which is then used to produce energy through a turbine. Regions with higher volcanic and tectonic activity are better positioned for geothermal energy production due to the shallower depths required to reach high temperatures (B. HERRING e H. RASHID, 2023).

Building a geothermal well typically takes an average of 45 days, but this duration can vary significantly, ranging from 25 to 100 days. The cost of constructing a geothermal well also varies widely. The cheapest wells can cost around $1 million, while the most expensive ones can exceed $15 million. However, the approximate cost for constructing a geothermal well generally ranges from $4 to $6 million (SANTOS, DAHI TALEGHANI e ELSWORTH, 2022).

Modern exploitation methods have allowed the discovery of steam at depths of up to 1,000 meters in regions predominantly composed of sedimentary rocks. However, to find deep geothermal areas, it is necessary to drill through thick layers of highly abrasive metamorphic rock to reach the granite basement. Generally, reservoirs of heated rocks are composed of metamorphic rocks with intrusions of igneous rocks (ORAZZINI, KASIRIN, *et al.*, 2012).

The development of geothermal wells can be advantageous for companies in the oil supply chain. Technologies and projects from petroleum wells can be easily adapted for geothermal drilling. For example, experiences from the development of wells in the South China Sea, where the drilling temperature ranges from 200 to 260ºC and the pressure exceeds 138 MPa, demonstrate the feasibility of such adaptations (LI, XIE, *et al.*, 2021).

Ideally, geothermal wells should have temperatures above 180ºC. However, existing petroleum wells with temperatures above 120ºC can be reused for geothermal production, contributing to the reduction of carbon footprint (SANTOS, DAHI TALEGHANI e ELSWORTH, 2022). Beyond the lessons learned in perforations, these wells can be easily translated to geothermal wells (MOHAMED, SALEHI e AHMED, 2021).

The well is built in phases with different diameters, progressing in a telescopic manner from the largest diameter, 26 inches, to 17.5 inches, 12.25 inches, and finally to 8.5 inches. The final phase targets the rock formation where the highest temperature advantage can be obtained (PEDROSA, OCHOA, *et al.*, 2023).

One alternative for geothermal wells is constructing wells with the same diameter. This approach allows for a reduction in the volume of material to be perforated, as well as a decrease in the consumption of materials such as cement and coating, compared to the traditional well pattern. The consumption of coating and fluid can be reduced by 60%, and the production of training cuts can also be reduced. Additionally, the consumption of cement can be reduced by 75%. However, the challenges for constructing wells with a single diameter lie in the ability to countersink (ream) and enlarge wells with previously coated phases (DICK, FREYER, *et al.*, 2011).

The drilling is done through a rotary drilling platform, which rotates a drilling column. In a simplified way, is composed of drilling pipes, stabilizers, directional measurement equipment, directional control equipment, and a drill bit. The drilling pipes are connected in groups of three until the desired depth is reached (THOMAS, 2004).

There are diverse types of drill bits available in the market, each for a specific application. The most notable ones are tricone bits, PDC bits, and impregnated bits. Each type of bit works with a different cutting mechanism. Tricone bits cut and tear rocks and have a movable mechanism. PDC bits operate with a shearing mechanism using industrial diamonds. Impregnated bits use natural diamonds in a grinding mechanism, usually associated with high rotation speeds of the drill string (THOMAS, 2004).

To cut granite, the best options are using tricone or impregnated drill bit. However, impregnated bits are very expensive, while tricone bits, which are more commonly used, have a shorter lifespan due to their reliance on moving parts, grease, and seals (ORAZZINI, KASIRIN, *et al.*, 2012).

A fluid is pumped inside the drilling column with several functions to highlight cooling the drill, lubrication, loading clippings from drilling to the surface, stabilization of the perforated rock wall, cooling the column, and reducing friction. The fluid returns through the annulus of the column and is treated and recycled at the surface. For the fluid to accomplish its function, it is essential that its rheological properties remain stable (MOHAMED, SALEHI e AHMED, 2021).

For use in mud motors that replace elastomers with metallic stamps, a special fluid that ensures optimal lubrication is necessary. This fluid can include added water. For fluids used in geothermal perforations, thermal stability is required. Tests were successful with the use of bentonite stabilized with a low molecular weight copolymer. The use of additives to reduce wear showed the expected findings (CHATTERJEE, DICK, *et al.*, 2014).

At the end of the drilling process, a circulation of fluids is performed to clean the well. A steel tube, called a casing, is then lowered to maintain the stability of the column, and isolate the perforated formations. Once installed, the casing is cemented by pumping cement inside the column, with the return flow through the annulus, so that the tube is cemented between the rock and the casing, keeping the interior clean (THOMAS, 2004).

This process is repeated at every perforated phase until the desired depth is reached. At this point, an operation involving a cannonade is performed, shooting a plasma beam for drilling or coating, cementing, and training. This allows for the connection between the interior of the well and the formation (THOMAS, 2004).

2.3 DESCRIBE THE MAIN CHALLENGES IN BUILDING A GEOTHERMAL WELL

2.3.1 SUSTAINABILITY CHALLENGES

Generally, healthy drilling of several wells in the region is aimed at maximizing the use of geothermal potential. This process requires the movement of the drilling platform, which is a large structure that occupies a significant amount of space and can damage the landscape. To avoid these movements, using a block drilling technique is a satisfactory solution. This technique allows for the drilling of several wells from a single region (ZHANG, NJEE, *et al.*, 2012).

Initially, in Türkiye, several vertical wells were drilled. Moving the platform and the benefit of drilling directional wells from the same block were also considered. The wells that were imagined to be vertical, drilled without directional control, ended up being diverted. This happened because geothermal drilling areas tend to present extremely hard geological formations, failures, and merges (PEDROSA, OCHOA, *et al.*, 2023).

2.3.2 CHALLENGES REGARDING DRILLING DYNAMICS

In the construction of geothermal wells in Kenya, the lithology found was very fractured, abrasive, and had problems with circulation losses. There was damage to drilling equipment due to high discharge temperatures, a low rate of penetration (ROP), loss of cement, and the breakdown of drilling foam structures at high temperatures (ZHANG, NJEE, *et al.*, 2012).

The same phenomenon also happens in Türkiye. It presents in two phases: first, in formations with high sand content, and second, in abrasive formations. In the last phase, problems such as temperature, accentuated vibrations, fluid losses, detour trends, high torque and friction, and strong reactive torque are observed (PEDROSA, OCHOA, *et al.*, 2023). Beyond abrasiveness, these rocks also have high hardness (MOHAMED, SALEHI e AHMED, 2021).

Drilling in this type of rock has an impact on the weight of the fluid of 15 to 30%, as well as the apparent viscosity which changes from 50 to 139%. The plastic viscosity which increases from 20 to 113%, the point of flow that changes from 50 to 161%, and the gel strength (10min) that changes from 1 to 26% (PEDROSA, OCHOA, *et al.*, 2023).

Given that the drilling column is long, the depth of the well, and the rotation is at the top, it is expected that vibrations will occur. However, excessive vibrations can damage the equipment used for measurements or even break the column. Due to the particularities of a geothermal well, attention to the design of the drilling column must take into consideration the lessons learned from wells in the same area, which should be well-studied and correlated with the depths where problems were found (PEDROSA, OCHOA, *et al.*, 2023).

Also due to the type of interspersed formation, the use of tricone bits has the advantage of providing greater directional control in relation to the axis of the tool. This advantage is also combined with the advantage of crushing and excavating the rock, which is also compatible with this formation (PEDROSA, OCHOA, *et al.*, 2023).

Tricone bits also had problems drilling this formation. One of the problems, temperature, can be improved with new seal technologies. Durability, due to the abrasiveness and hardness of the formation, required a new cutting structure and a new type of tungsten carbide to reduce wear (ORAZZINI, KASIRIN, *et al.*, 2012).

2.3.3 PROBLEMS WITH DRILLING FLUIDS

In China, the reverse circulation technique using air (Airlift) has been successful in preventing fluid loss problems. However, this technique had a learning curve that included improvements in the drill bit, such as increasing the TFA (Total Flow Area), using a reduced-size nozzle in the center of the drill bit, and protectors between the cones of the drill bit. Additionally, there were learnings in compressor selection and the use of an improved mixer that better mixes the gas with water, allowing for better solid carrying. Other solutions to reduce air leaks included better alignment in the piping, improvements in seal installation, and the use of a greater number of seals (ZHANG e ZHANG, 2014).

Water-based mud has been successfully used in formations up to 280ºC. The use of water, instead of other fluids like oil-based or synthetic, has the advantage of preventing formation damage. In southern Australia, the use of high-weight water-based fluid in combination with Managed Pressure Drilling (MPD) technique in formations with high-pressure fracture systems (DICK, FREYER, *et al.*, 2011).

The physicochemical stability is crucial in well drilling. Chemical stability is related to how the fluid can interact with other contaminant substances. The physical stability is connected to the fluid's resistance to temperature, pressure, and excessive shear (MOHAMED, SALEHI e AHMED, 2021).

The drilling fluid (mud) is also affected by temperature, which has the potential to alter its rheological properties. Bentonite muds experience an increase in yield strength due to the exchange of sodium ions, clay swelling, and flocculation. Polymeric additives are also affected by temperature, lowering their viscosity. Pressure does not significantly affect the properties of the fluids, especially under certain temperature conditions (MOHAMED, SALEHI e AHMED, 2021).

The fluid can also become unstable due to the separation of weight elements, such as barite, which leads to density instability and can even cause a pressure imbalance in the well (Mohamed, Salehi, & Ahmed, 2021). This occurs because the weight of the drilling fluid works to prevent formation fluids from invading the well, a phenomenon known as a kick (THOMAS, 2004).

One of the functions of the fluid is to clean the well. As drilling progresses, some formation cuttings tend to accumulate at the lowest part of the bottom and drag along as the drill string advances. This accumulation is more common in wells with an inclination above 35º, and good well cleaning is required. For this, the rheological properties of the fluid need to be closely monitored in high-temperature and large-diameter wells, as is the case in geothermal well scenarios (MOHAMED, SALEHI e AHMED, 2021).

One of the ways to monitor the properties of the drilling fluid is through the Equivalent Circulating Density (ECD). When the ECD is too low, a kick can occur, but if it is too high, a formation fracture can occur. Monitoring the ECD is an effective way to understand well cleaning (MOHAMED, SALEHI e AHMED, 2021).

Oil-based fluids are generally more effective, but they have a higher cost and lead to greater environmental concerns, so the use of water-based fluid is more common in geothermal drilling. The use of water-based fluids with clay was the first option, however, clay causes formation damage and reduces reservoir permeability. Nowadays, a generation of water-based fluids with other additives and better performance has shown satisfactory results (bentonite, high-temperature deflocculant, lignite, caustic lignite, polymeric loss control fluid, NaOH, sodium polyacrylate). More modern polymeric fluids are more expensive and have a higher filtrate, but they are better in lubrication and rheology (MOHAMED, SALEHI e AHMED, 2021).

2.3.4 TEMPERATURE PROBLEMS

Some geothermal wells in China can reach depths of up to 4200 meters (ZHANG e ZHANG, 2014). In Turkey, the drilling temperature range is from 220 to 295º C at depths varying from 2500 to 4800 meters, with the enthalpy range considered medium-high, that is, from 120 to 240º C. (PEDROSA, OCHOA, *et al.*, 2023) In Germany, the depth range is from 4572 to 6400 meters, with static temperatures from 160 to 216º C (DICK, FREYER, *et al.*, 2011). Geothermal zones with temperatures of 450º C (supercritical fluids) can have their energy production capacity multiplied by ten (HAMMONS e GUNNARSSON, 2010).

In addition to the high temperature of the formations, the friction temperature of the drilling pipe and the friction of the drill bit cutting through the rock further increase the temperature, which can reach 350ºC. In this environment, it is common to experience failures in seals, metallic materials, and electronic components of the drilling equipment and the drill bit (ZHANG, NJEE, *et al.*, 2012).

Another factor that also affects the temperature is the loss of circulation, which can cause the temperature at the drill bit to vary from 100 to 280ºC, leading to overheating. One of the effects of this overheating is the failure of seals and grease, which can cause a drill bit to fail after drilling only 68 meters or 15 hours (ORAZZINI, KASIRIN, *et al.*, 2012).

To make the tricone bit capable of drilling wells up to 300ºC, it was necessary to replace the elastomers with metallic seals and pressure compensators, as well as to find the most appropriate type of grease for these temperatures (CHATTERJEE, DICK, *et al.*, 2014).

To manage the effects of temperature, it is necessary to use special electronics technologies and manage the cooling of the equipment. This includes the use of staged cooling, drilling fluid (mud) coolers, and continuous fluid circulation (PEDROSA, OCHOA, *et al.*, 2023).

The downhole motor, used to convert hydraulic energy into mechanical energy, operates on the Moineau principle, utilizing a rotor that spins like an endless screw within a stator that uses an elastomer to seal the chambers of the rotor. The rotor's movement is then transmitted to the drill bit (CHATTERJEE, MACPHERSON, *et al.*, 2016).

In a geothermal well, the elastomer becomes more vulnerable to temperature and presents premature failures. An alternative is the use of drilling turbines that do not have elastomers or elements affected by the same temperature range, but they have other limitations, such as the need for more powerful surface pumps (HERBERT, 1982).

Currently, there are special elastomers that are more resistant to temperature and allow for greater drilling efficiency with tricone or hybrid bits, which operate better at low rotation, something that cannot be achieved with a turbine (PEDROSA, OCHOA, *et al.*, 2023).

Motors that use metallic seals instead of elastomeric seals were also developed, requiring the complete development of a coating technology for the rotors. Furthermore, employing three-dimensional scanner technology to ensure a homogeneous thickness (CHATTERJEE, DICK, *et al.*, 2014).

To minimize friction, it is also possible to adopt the use of undergauge stabilizers. Reducing friction has positive results in both lowering the temperature of the drill string and increasing the rate of penetration (ROP). To maximize the durability of the drill bit, it is possible to use metallic seals and reamers to expand the drilled well (ZHANG, NJEE, *et al.*, 2012). Some types of special coatings can be used on drilling column tools to reduce the impact of premature wear (PEDROSA, OCHOA, *et al.*, 2023).

2.3.5 DIRECTIONAL CONTROL AND ROP ISSUES

The positioning of a geothermal well has a significant impact on its energy production capacity, as it depends on the heat exchange between the fluid and the formation. Therefore, the use of directional control and measurement systems is especially important (CHATTERJEE, DICK, *et al.*, 2014).

As an alternative to the use of turbines or drilling motors, there is drilling with advanced drilling systems, also known as Rotary Drilling Systems. The use of these systems has shown superior results in terms of drilling rate, reduction of tortuosity, and cost reduction by up to 30%. (PEDROSA, OCHOA, *et al.*, 2023).

Just as it happens with directional control on the column axis (toolface), due to intercalations and fault crossings, it is important to minimize the directional orientation of the equipment, as the formation may tend to pull or push the column in one direction (PEDROSA, OCHOA, *et al.*, 2023).

Another technology under development that could enable a notable change in geothermal well drilling is pulsed plasma drilling. This technology uses short pulses of high-energy plasma to disintegrate rocks without melting them. The prototype uses about 200kW, but the commercial model is expected to operate at 500kW, or 50kWh for each meter drilled at a rate of 10m/h (33ft/h) (GAJDOS, KOCIS e KRISTOFIC, 2021).

Coiled Tubing fluid and drilling fluid (mud) are also required at rates of 1 l/min and 3000 l/min, respectively. The drilling column for the use of this technology uses a bottom tool called PLASMABIT, a fluid and energy transmission line to the PLASMABIT (the technique uses Coiled Tubing equipment) and the surface equipment that remains on the platform (GAJDOS, KOCIS e KRISTOFIC, 2021).

For a good application of the technique, the superficial parts where conventional rotary drilling presents good drilling rates would be done through rotary drilling. The final phase where the greatest challenges in drilling dynamics and temperature are would be done with the use of Coiled Tubing and plasma pulse (GAJDOS, KOCIS e KRISTOFIC, 2021).

Laser technologies have also been evaluated alongside PDC drill bit technology and have achieved satisfactory results in basalt rock with a compressive strength of 45ksi and a laser power of 15 kW. These technologies are also employed with the use of Coiled Tubing (ZEDIKER, 2014).

2.3.6 PROBLEMS IN WELL COMPLETION

During the well completion phase, after the casing is set, water entrapment can occur behind the casing. To prevent this phenomenon, the technique of cleaning the annulus with a known volume of water and filling it with cement reduces this risk, which can lead to casing collapse when exposed to heat exchanges. Due to the fractured formation and to prevent losses, the use of additives in the cement is important, including retarders, dispersants, loss control additives, LCM (Loss Circulation Material), and defoamers (ZHANG, NJEE, *et al.*, 2012).

Due to thermal expansion and contraction, the casing of a geothermal well can have its load capacity reduced by 60%, which must be considered during the planning phase. Additionally, this casing must be made of a material that can withstand operating with high saline concentration fluids, which can lead to corrosion (DICK, FREYER, *et al.*, 2011).

The saline fluids present in a geothermal well contain CO2 and H2S, which increase corrosiveness. One way to prevent damage caused by this corrosive environment is the use of noble materials such as stainless steel. This includes super-duplex alloys, which can also lead to surface damage due to the use of different materials, called galvanic corrosion. These can cause a serious problem in well cementing, leading to regions with insufficient cement quantity. To solve this problem, a ceramic composite technology has been developed (HERNÁNDEZ, CHANDARJIT e LEVIE, 2010).

The use of Electrical Submersible Pumps (ESP) can allow for greater efficiency in energy production by improving water flow in formations with low permeability. These pumps should generally operate at temperatures of 200 to 225ºC, ideally 275ºC, with a flow rate of 60 liters per second (950gpm), 300psi. With a hydraulic power to required energy ratio of 95%, which is chemically stable, supporting saline and corrosive environments, in addition to having an availability of 95% and a cost limited to the range of 750 thousand to 1 million dollars. (MOLLOY, LINDSAY e MALONEY, 2009).

2.3.7 INCREASING THE EFFICIENCY OF ENERGY PRODUCTION

The greater the depth, the higher the temperature, enthalpy, and energy production capacity. However, another key factor is the formation's permeability, as the intention is to inject water through an injector well and withdraw water/steam through the producer well. Thus, the higher the permeability, the greater the heat exchange between the water and the formation. To evaluate permeability, a geothermal ultrasonic imaging technique can be used, which can be performed with a wireline logging tool, lowered into the well after drilling for geophysical studies (DICK, FREYER, *et al.*, 2011).

An aspect of significant importance in geothermal production is the strategy adopted for injecting water towards the production well. It is necessary to conduct studies to understand the geological configuration to determine the best injection points before the project begins, as well as to monitor the water produced in the production well and seismic activities in the region. These models derived from the studies need to be analyzed from both pessimistic and optimistic perspectives to determine the best action plan for the project (ACUÑA, STIMAC, *et al.*, 2008).

Of the 9,000 MW of geothermal plants installed worldwide, only 1,000 MW use the Organic/ Binary Rankine Cycle or a Hybrid Rankine Cycle, while the remaining plants operate with dry steam turbines or steam produced by single or double flash (B. HERRING e H. RASHID, 2023). In the United States, approximately 44% of geothermal plants are 30 years old or older, which accounts for 64% of the generation (SANTOS, DAHI TALEGHANI e ELSWORTH, 2022).

The Organic Rankine Cycle uses an organic fluid that has a lower evaporation temperature than water. This fluid is maintained in a secondary system heated by the water that comes from the well and passes through a heat exchanger. Thus, low enthalpy wells also have the potential for generation, but this technology is not limited to these wells and can also be used for high enthalpy wells, further increasing the potential for energy generation (B. HERRING e H. RASHID, 2023).

Re-entering geothermal wells and updating systems can yield meaningful results in energy production capacity. For example, in Steamboat Hills, intervention and modernization increased energy production by 19MW with the addition of one well and by 84MW upon completion of the entire modernization (AKERLEY, EILAN, *et al.*, 2021).

3 METHODOLOGY

The methodology adopted for the development of the research includes conducting a systematic literature review. In order to guide the scope of the research, the following review questions were defined: how geothermal energy is contextualized compared to other forms of energy generation, what is the process of constructing a geothermal well, what are the main challenges in constructing a geothermal well, and how the innovation management process can contribute to the advancement of this technology.

Therefore, to achieve the proposed objectives, the research conducted is classified in terms of its nature as applied, whose generation of knowledge allows applicability in strategies to optimize the construction of geothermal wells and their economic improvement. Likewise, it is characterized as exploratory, regarding the novelty of the topic in relation to new markets and, at the same time, descriptive, as it relies on data found in the available literature to establish relationships regarding the solution of the study question.

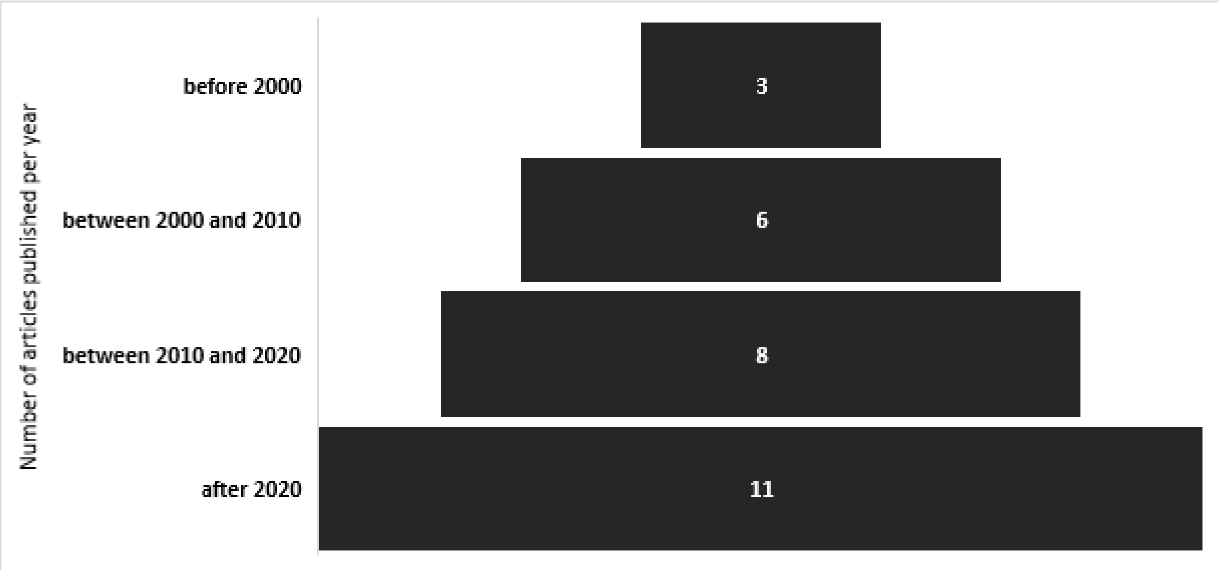
Searches were conducted for terms in the CAPES Periodicals – Scopus Database, and based on the abstracts of the articles, they were classified as: Relevant and Irrelevant, based on their potential to answer the research questions.

The words: "Geothermal AND Energy AND Innovation" were searched, with sixty-three articles found, of which forty-six were considered relevant to the research based on the evaluation made in the abstract, 12 were discarded for not being accessible, and 12 were defined as irrelevant in a more in-depth reading.

One of the articles was found as presented in a Conference and as a Journal article, and here it was counted only once. The article "Innovation Process: Which process for which project" served as the basis for the evaluation of innovation processes.

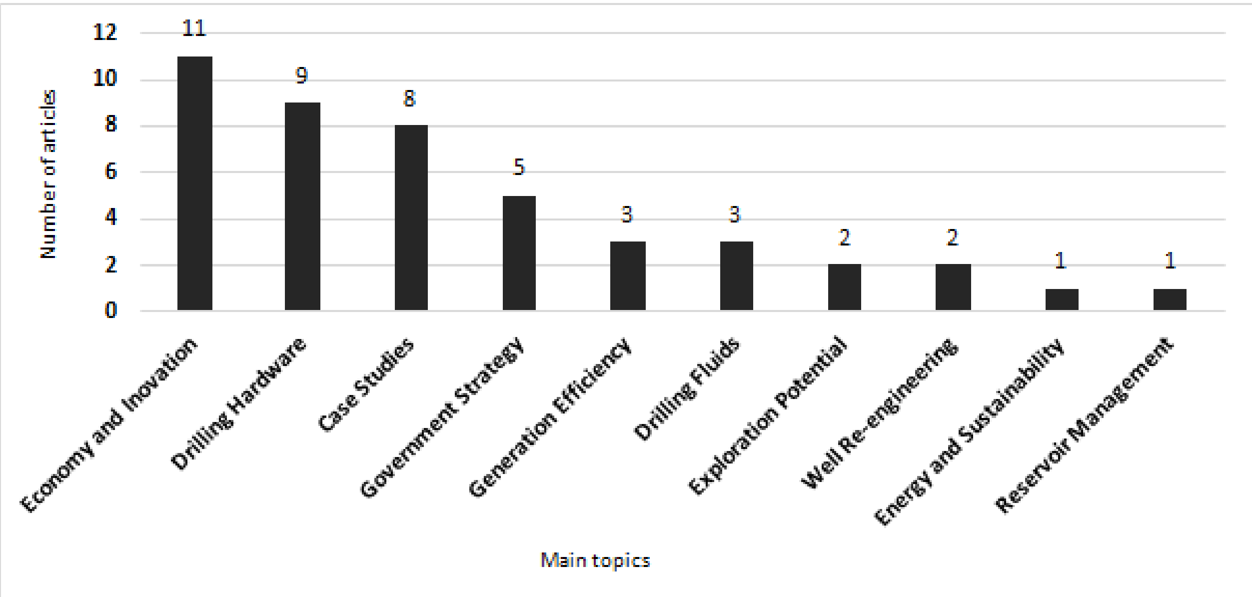
Figure 5. shows the increase in publications on the subject in the Scopus database, it is possible to observe and confirm the increasing relevance of the topic.

Fig. 5 | Year of the Articles Publication found in Scopus



In the top three areas covered by the articles are Economy and Innovation, Drilling Hardware, and Case Studies, per Figure 6, which brings field collected information to this study.

Fig. 6 | Main topics covered by the articles



4 RESULTS AND DISCUSSION

There is a significant global dependence on fossil fuels, while at the same time these are related to greenhouse gases and air pollution. The demand for energy continues to grow worldwide, and conventional forms of renewable energy (wind and solar) do not have a growth rate sufficient to meet the demand. They also don't have the possibility of being available throughout the day or year.

Although less known, Geothermal Energy is cleaner and has a low environmental footprint. But its exploitation is complex and depends on technological advances to be exploited to its maximum potential at a competitive cost. About 70% of the cost of building a geothermal plant is in the cost of constructing the geothermal well. One of the great opportunities is to take advantage of already drilled oil wells in hot zones, many abandoned, to exploit this form of energy.

Various models of innovation management processes in geothermal development are observed, highlighting the process with public or private calls as done by the governments of the United States and Germany. The aim of reducing the cost of geothermal energy exploitation and achieving drilling at temperatures of 300º C.

According to data from Mordor Intelligence, in 2024, the number of installed geothermal bases is expected to grow from 15.68 gigawatts to 17.91 gigawatts by 2029, with a compound annual growth rate of 2.69% during the forecast period (2024-2029).

The process of stopping by technology in the case of the turbine, which was eventually replaced by a bottom motor with a metal seal, where the concept already existed, but there was no technology for a precision coating with uniform thickness. The process of waiting for the market, as in the case of studies conducted in partnership with the European and Mexican governments for studies and technologies in regions with geothermal potential.

Each model serves its purpose, allowing innovation to develop in the most appropriate way for the type of solution and resource available at the time. Giving rise to various lessons learned that can be applied in the market, thereby enabling a safe, sustainable, and accessible energy source for humanity. From the literature review it was possible to build a table compiling some of the main challenges and the potential solutions, per Table 3.

Table 3 | Solutions for the main problems in geothermal well construction.

Area		Problem	Solution
Drilling	Fluids	Loss of Circulation and Well Cleaning	Use of foam and air as drilling fluid Consider losses in the planning of fluid supply with a larger tank
		High Torque and Drag	Use of foam fluid
		High sand content	Strict control of solids and sand on the surface, and constant attention to fluid conditions
		Problems with the Airlift	Increase in TFA (Total Flow Area) Utilization of a smaller diameter hole in the center of the bit Utilization of protectors between the cones of the bit Increase in the number of seals and their diameter. New type of mixer and better compressor selection
		Stuck Pipe	Establish a process for monitoring ECD and fluid rheological parameters
		Rheology Issues	Prior tests of physicochemical stability Use of polymer base fluids or polymer additives
		Reservoir damage or plugging	Reduce the use of clays as additives
	Electronics	Failure of Measurement While Drilling (MWD) Tools	Utilization of single-shot tools, simpler in electronics and temperature-resistant Utilization of mud cooling systems on the surface. Continuous circulation. Staged cooling.
	Column	Rate of Penetration (ROP)	Utilization of undergauge stabilizers Utilization of tricone bits that are more compatible with formations found in geothermal wells, providing a crushing, and excavating effect on the rock.
		Directional control	Utilization of directional measurement equipment (MWD) in conjunction with downhole motor for directional control. Utilization of Rotary Steerable System to improve well quality, avoid tortuosity, and reduce construction time.
		Excessive vibration	Management of drilling parameters and risk mitigation actions. Detailed planning of the drilling column.
		Elastomer failures	Use of drill turbines that do not have elastomers as a seal, or in cases where the use of turbines is not feasible due to torque and weight requirements, the use of other Directional control systems may be an option. Use of more modern elastomers that have a higher temperature resistance.
		BHA and tool wear	Use of special coatings to reduce wear.
	Well collision	Directional trends	Plan the well with little demand for orientation
		When drilling several wells in the same block, the risk of collision increases	To prevent this problem, the recommendation is to start the trajectory (KOP) from a shallower point.
	Bit	Bit durability, wear, seal and bearing failure	Drill bits with gauge protection and metal seal. Planning shorter runs. Use of special greases for high temperature. Use of reamers to expand the well
		Directional control	Use of tricone drills allows for better control of the *tool face*
		Difficulties in cutting granite	Use of tricone drills (more economical) or impregnated drills (more expensive)

Cementation	Damage to the casing	Water trapping behind the casing	Cleaning the annular of the casing with a known volume of water and filling the annular with cement.
	Poor Cementing	Cement losses, premature set	Use of additives such as retardants, dispersants, additives, and additives Loss Combat, LCM (*Loss Circulation Material*) and Deformer
Completion	Artificial Lifting	Artificial Lifting system Failure	Definition of a series of specifications to allow an increase in the service life of submerged centrifugal pumps.
Sustainability	Occupied area	Occupation of areas, deforestation	Grouping wells in the same block
COST Drilling time, use of materials (cement and casing), disposal of well cutouts		Drilling new wells	Exploiting depleted oil wells in areas with geothermal potential
		Single-diameter well drilling	

In the world of oil, the rocks drilled are sedimentary. Although the methods are the same, except for ongoing studies with laser or plasma drilling, a whole technological development. This is necessary to justify the investment in these new materials that can withstand drilling in more abrasive, hard, intercalated rocks, full of faults, and at much higher temperatures.

5 FINAL CONSIDERATIONS

Although only one article identified on this research was more focused on the sustainability aspect, per Graph 6, Geothermal exploration is a significant opportunity for the development of a sustainable global electric matrix. It is considered the form of renewable energy with the smallest spatial and environmental footprint, in addition to having the highest technical generation potential among renewable energies. It is virtually inexhaustible and has potential in any region of the world.

The operational cost of a geothermal plant is low, but the construction cost of the well and the geothermal plant is still high and involves many risks, especially when moving away from areas where geothermal systems are found at shallow depths. There are several challenges in well construction, from the drilling of the well itself, given the specific type of formation, to identify drilling equipment that can be reliable on hot, deeper and longer wells. This work summarizes the main ones and its alternative solutions in Table 3.

Geothermal Energy is the number six in generation (TWh) among the renewable sources, but it is showing constant growth year over year. Numerous projects are underway worldwide to reduce geothermal costs and choosing the best innovation management model can represent a strategic advantage for success.

Many countries have already initiated partnerships, both between nations and public-private, to achieve faster results and accelerate the energy transition process. From the cases revised, these partnership, the investment and the risk taking are the enablers to mature this technology. Furthermore, untap a renewable non-nature dependent form of energy, which can represent a solution to the electrical grid reliability and availability, as many of the other sources of energy are more susceptible to climate change or seasons, day-night cycle.

For future studies, it is suggested that issues related to lower-cost drilling technologies be explored in greater depth, which could enhance the implementation of geothermal plants in different regions of the world.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS:

During the preparation of this work the author used Microsoft Copilot to fix some translation from Portuguese to English. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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