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Deep U-tube heat exchanger breakthrough: combining laser and cryogenics gas for geothermal energy exploitation

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ABSTRACT

The disruptive technology envisioned in the “Deep U-tube heat exchanger breakthrough: combining laser and cryogenics gas for geothermal energy exploitation (DeepU)” Project is expected to revolutionize the deep geothermal energy sector. The ultimate goal is to create a deep (>4 km) closed-loop connection in the shape of a U-tube exchanger by developing a fast and effective drilling technology. A laser drill head is combined with special drill strings sustaining the coupled action of laser and cryogenic gas, responsible for melting, evaporating and cooling even the hardest rocks. The fine particles are transported to the surface in the gas stream via the earth tube required for the geothermal heat exchanger. Specific temperature control analysis and innovative laser lenses, able to convey the heat and sustain multilateral drilling, guarantee liquefaction and vitrification of the rocks from the ground surface to significant depths. The resulting glazed layer on the borehole walls acts as a case so that the heat exchanger is ready immediately after drilling. The technical feasibility of DeepU is demonstrated at the laboratory scale, and the specific objectives of the Project are: (i) select a cryogenic gas able to cool in a controlled manner the rock melted by a laser; (ii) develop an innovative lightweight drill string able to host the gas and the laser at the same time; (iii) develop specific temperature control analysis and innovative laser lenses able to convey the heat and to sustain multilateral drilling, (iv) determine the physical-thermal phenomena affecting different kinds of rocks in order to assess the borehole wall vitrification and integrity. Numerical simulations calibrated by the laboratory data provide references to define the DeepU geothermal exploitation potential, including economic analyses. The legislative aspects and environmental standards related to the proposed solution are also assessed. The high-risk innovation presented in DeepU has the potential to make geothermal energy systems accessible anywhere in a targeted and demand-oriented manner, offering a complementary approach and an alternative solution to traditional energy storage and production, decentralizing the power supply also in areas where this is currently deemed uneconomic.

1. INTRODUCTION

Continuously renewable, CO_2-neutral, clean, affordable, and modern energy for the benefit of all people is the 7th of the United Nations Sustainable Development Goals (SDG). Geothermal energy (GTE), defined as the thermal energy stored in the earth, is considered a critical renewable energy source for the future, as c. 99 % of the earth's mass is hotter than 1000 °C allowing GTE to be tapped through environmentally friendly carbon-neutral energy conversion (Horne 2012, Tester et al. 2006, Gupta and Roy 2006). Today’s installed geothermal capacity accounts for less than 1% of global geothermal resources (Winsloe et al., 2020). The most commonly exploited resources at shallow reservoir depths (1-3km) represent a small fraction of the total recoverable energy that can be exploited at deeper depths. To meet modern society's electricity and heating/cooling demands, innovative and emerging technologies must be developed to fully use the earth’s geothermal potential (SET Plan 2018). GTE production is expected to grow steadily until 2050. Cost reduction and improved system performance, together with a better understanding of the geological conditions in which novel solutions for GTE production can be applied, are key factors in stimulating the uptake of GTE at the European and global levels (EGEC 2022, BP 2022). Understanding heat transfer and fluid flow in deep geologic environments over long periods (>20 years) remains a top priority for research and development (More and Simmons, 2013). Also, a drilling technology that is more efficient than the current one – from an economic and technological point of view, is crucial.

Besides facilitating a rapid transition to renewables, GTE plays a key role as it offers several advantages, e.g. its contribution to reducing the thermal needs of the residential sector thanks to its thermal technologies or its continuous and flexible production that can be switched between electricity and thermal generation in Combined Heat and Power (CHP) applications. Therefore, increasing the share of GTE in the energy mix is fundamental to developing national and European energy policies. Geothermal resources are conventionally divided into near-surface (shallow) and deep (Banks 2012, Huenges and Ledrou 2011). The former reach depths of 400 m and temperatures of c. 20 °C to 60 °C; they are used in combination with heat pumps or directly using geothermal heat in district heating networks. The latter, deep geothermal resources, have a temperature c. >100 °C at > 1km depth and are suitable for direct use of heat and electricity production. However, current deep geothermal technologies suffer limitations and disadvantages, among them: a) depth limitation (4-5km) due to the traditional drilling methods and evaporation temperature of the flushing water;

b) earthquakes risk in case of hydraulic stimulation for permeability enhancement; c) high pumping costs for water circulation; d) risk of contamination in "open" water circuits (Manzella et al., 2019).

To overcome these limits and make projects economically viable, the DeepU technology focuses on demonstrating at the lab scale a U-shaped closed-loop system, i.e. physically isolated from the surrounding environment, through the temperature management of a combined laser/cryogenic gas drilling action. With a new, revolutionary, intelligent temperature management control system tested in the laboratory, the project will use a laser-beam propulsion drilling method and a cryogenic gaseous flushing medium to realize a heat exchanger consisting of two vertical and one horizontal tube section (U-shape). The tubes will be connected at a right angle by re-directing the vertical laser beam by 90°. The use of laser & cryogenic gas will form a glazed layer on the borehole walls, allowing an underground closed-loop system to immediately develop after drilling without requiring further casing activities. This technical solution will also favor the gravity pump effect during geothermal exploitation. If successful, the DeepU technological solution will contribute to realizing ultra-deep geothermal heat exchangers at >4km depth.

2. ABOUT THE PROJECT

The DeepU project started in March 2022 and will run for three years. It involves six participants coordinated by the University of Padua, Italy. The project structure is based on seven work packages (WPs) (Fig. 1). Five of these (WP1 to WP5) address the technological and scientific development of the project and are assisted by two WPs devoted to dissemination and communication (WP6) and management (WP7). DeepU is expected to achieve technical and environmental/standardization innovation goals. The former focuses on developing a lightweight drill string to transport the cryogenic gas and sheath the laser beam (WP1) and creating a scaled U-tube heat exchanger model by deflecting the laser beam using a special mirror optics (WP2). The latter aims to assess the thermal effects of the laser beam and cryogenic gas on hard/soft rocks in terms of borehole wall vitrification (WP2-WP3), to characterize the drilling residues generated by the laser (WP3), to define the regulatory aspects and the environmental, health and safety (EHS) evaluation of the DeepU technology (WP4), to assess the commercial attractiveness of DeepU (WP5).

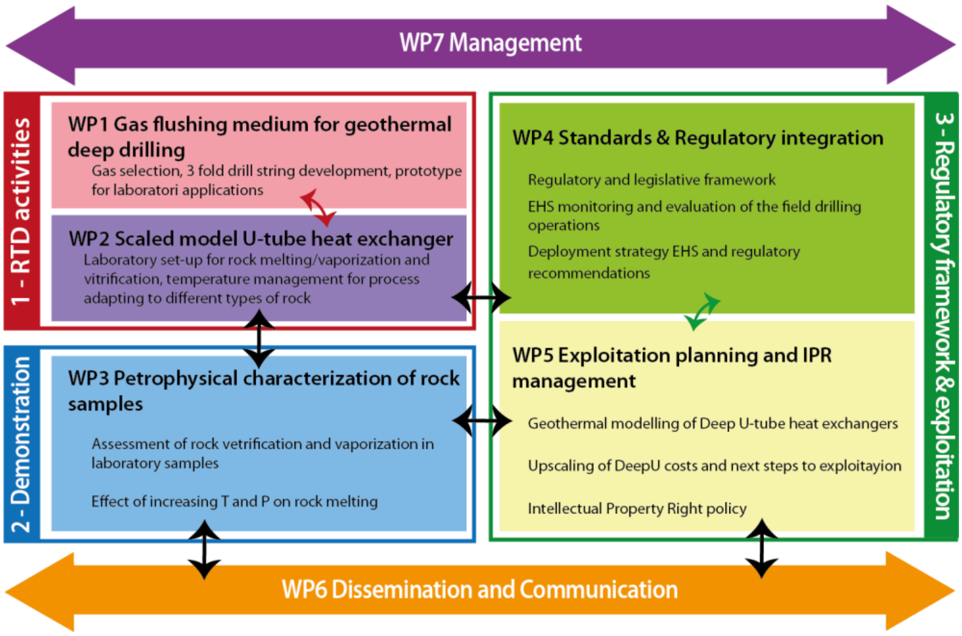

Figure 1: DeepU project organization

3. METHODOLOGICAL APPROACH

The project's methodology includes research and laboratory testing. The U-tube heat exchanger will be realised in a lab facility with consolidated rock materials to validate the technology in a relevant environment. The lab tests will provide scientific and operational data for upscaling DeepU. Finally, regulatory framework analysis and exploitation planning will provide insights for possible field operations respecting the existing regulations and the scalability potential of the U-tube heat exchangers. The foreseen activity of each work package and the preliminary results achieved in DeepU from the start of the project up to the time of this writing can be summarized as follow.

3.1 WP1 – Gas flushing medium for geothermal deep drilling

Various trials and tests are foreseen in order to achieve the main target of a lightweight drill string while keeping the cryogenic gas in the liquid state over a long distance within a drill string, to cool the laser drill head in the borehole where temperatures of over 1000°C prevail. This innovative drill string will also have to guide a laser beam in the middle of the drill string to the bottom of the borehole. The extensive experience of Prevent GmbH in developing and producing complex and highly innovative drill strings will be a main advantage for drill string production. The trials will test different gases and materials and also different ambient temperatures. Conclusions and findings from each trial and test will be used in further developing a modified drill string. In total, it is planned that at least three different drill strings will be designed and manufactured within the project.

We have investigated four different gases that could be used in the DeepU project, i.e., three noble gases (argon, krypton, helium) and nitrogen, which is abundant (78%) in the atmosphere. To consider a gas for this project, it must remain in the liquid phase for a very long distance under a great range of temperature and pressure conditions.

Gases can be converted to liquids by compressing them at a suitable temperature. However, when the temperatures rise, maintaining liquefaction becomes more and more difficult as the kinetic energy of the particles that make up the gas also increases. Beyond the critical temperature (specific for each gas), the liquid state is impossible. Therefore, every effort must be made to ensure that the liquid gas in the cryogenic pipes heats up very, very slowly (Fig. 2). The critical temperature (CT), the critical pressure (CP) and the triple point (TrPo) for each gas (Table 1) play a major role. The CT is the temperature at and above which a gas cannot exists as a liquid, no matter how much pressure is applied; the CP is the pressure required to liquify a gas at its critical temperature; the TrPo is the temperature and pressure at which the three phases (solid, liquid, and gas) of a pure substance can coexist in thermodynamic equilibrium.

In addition, the temperature difference (ΔT) between CT and the boiling temperature of each gas is a key factor in assessing the best temperature range for its use in the liquefied condition. For example, the ΔT value for krypton, argon, nitrogen and helium is 90 °C, 64 °C, 49 °C and 3 °C, respectively. Only if each liquid gas is kept within its specific temperature range, then can sufficient cooling volume prevent the DeepU drill head from melting in the borehole bottom.

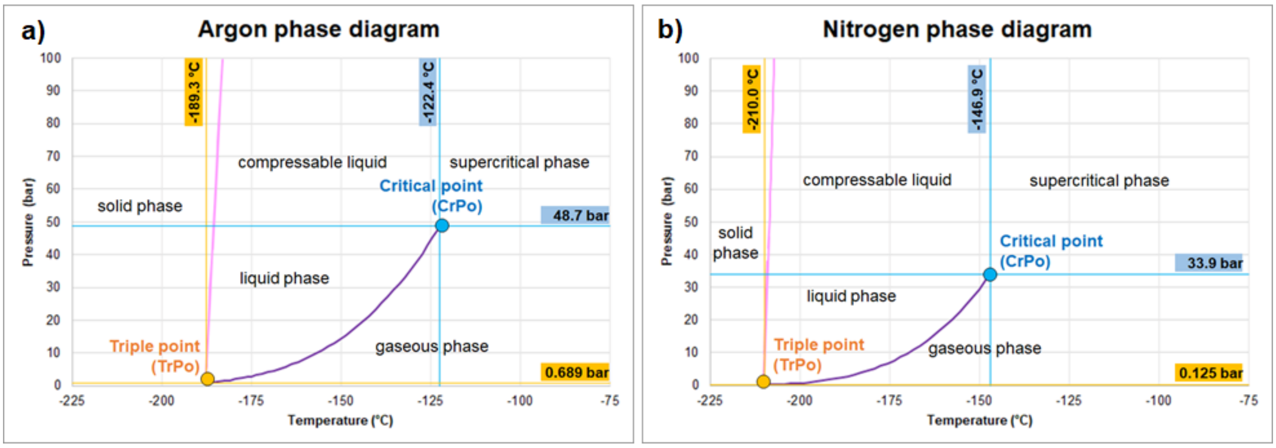

Figure 2: Phases diagram for argon (a) and nitrogen gases (b). CrPo = critical point, the point on a phase diagram at which both the liquid and gas phases of a substance can coexist, and the phase boundaries vanish; TrPo = triple point, where the three phases (solid, liquid, and gas) of a pure substance coexist in thermodynamic equilibrium.

Table 1: Critical temperature, triple point temperature, boiling point temperature, melting point temperature and critical pressure values for the four cryogenic gases considered for the DeepU project (modified from Gosman et al 1969; Jefferson Lab, U.S. Department of Energy 2022; Donnelly and Barenghi 1998; -Ziegler et al. 1964; Theeuwes and Bearman 1970; Span et al. 2000).

Gas	Critical temperature (CT)	Triple point temperature	Boiling point temperature	Melting point temperature	Critical pressure (absolute)
Argon (Ar)*	−122.29 °C (150.86 K)	-189.35 °C (83.80 K)	−185.87 °C (87.28 K)	−189.35 °C (83.80 K)	48.34 atm – 48.98 bar (4.898 MPa)
Krypton (Kr)**	−63.8 °C (209.46 K)	-157.39 °C (115.76 K)	−153.37 °C (119.78 K)	−157.4 °C (115.8 K)	54.48 atm – 55.20 bar (5:520MPa)
Helium-4 (He)**	−267.96 °C (5.19 K)	-270.98 °C (2.17 K)	−268.93 °C (4.22 K)	−272.2 °C (0.95 K)	2.244 atm – 2.274 bar (0.2274 MPa)
Nitrogen (N)****	−146.958 °C (126.192 K)	-209.999 °C (63.151 K)	−195.795 °C (77.355 K)	−209.9 °C (63.2 K)	33.514 atm - 33.958 bar (3.3958 MPa)

Another essential factor that must not be ignored is the critical pressure (absolute). As shown in Table 1, the highest critical pressure of 5,500 kPa must be ensured for krypton, while argon, nitrogen and helium require 4,870, 3,390 and 227 kPa, respectively. Very few cryogenic tubes can withstand a pressure of 5,500 kPa, so argon and nitrogen are the two most suitable gases to be used within the drill string conceived in DeepU. In the coming months, further detailed investigations have to be carried out, especially on these two gases, about (i) their compatibility with the laser lenses, (ii) the cryotube materials used to realize the drill strings, such as stainless steel and fibre composites, and especially (iii) the interaction with different types of molten rock.

For the first laboratory tests, a drill string with an outer tube of 100 mm and an inner tube of 60 mm was designed and manufactured (Fig. 3a-b). The outer tube consists of a high-temperature stainless steel tube made of the material 1.4841, which can withstand temperatures of more than 1,000°C, and the inner tube is a low-temperature tube made of the material 1.4301, which can withstand temperatures of -200°C (Bramfitt and Benscoter 2001). Up to 8 cryogenic flexible tubes can be placed between the inner and outer tubes. Depending on the liquid gas required to cool the drill head, between 4 and 8 cryotubes can supply the drill head with liquid gas (Fig. 3b). The flexible cryotubes have a special coupling to prevent warming up the liquid gas in the coupling area and are outstanding at compensating for linear expansion due to temperature differences, making it easy to withstand high-temperature changes (Fig. 3c).

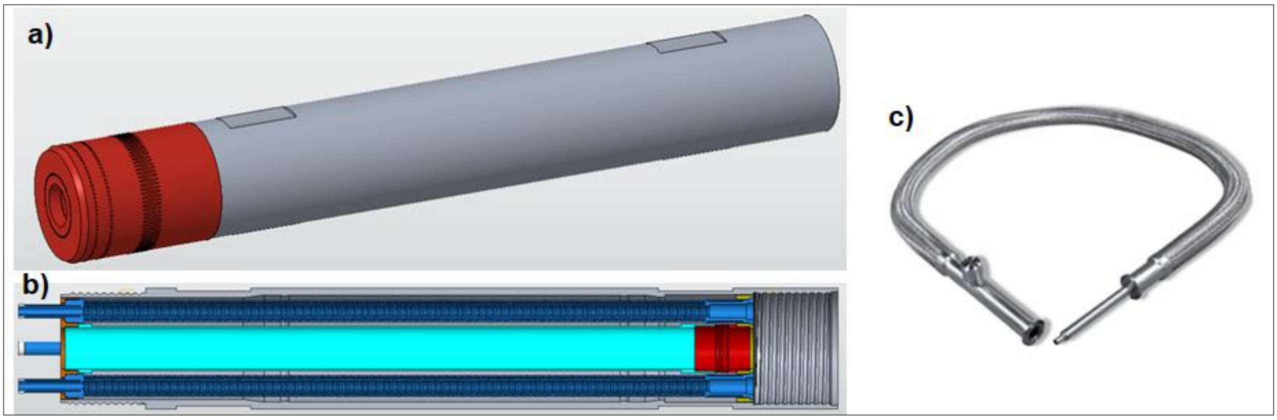

Figure 3: (a) drill pipe as a whole, including the drill head; (b) cross-section through the drill pipe, with the outer and inner tubes and the flexible cryotubes (in dark blue); (c) cryotube with a so-called Johnston male and female coupling.

In the following months, several calculations and tests on the first drill string will be carried out to define at what depth the liquefied gases convert into the gaseous state, considering the upward gas flow generated by gas bubbles and a downward liquid gas flow pressure from above. In addition, the flow rate and power dissipation (W/m) in the cryotubes will be calculated and measured at various ambient temperatures. Moreover, different liquid gases will be pushed through the flexible cryotubes and the special Johnston couplings (Fig. 3c) at varying pressures to test their strength and pressure resistance.

The next step will be to focus on the required wall thicknesses of the drill pipes as well as on the wall thicknesses and insulation of the cryotubes since they affect the overall weight of the drill string. The entire drill string's dead weight must always be kept in mind and considered in the whole design phase because the laser drill string is freely hanging on the drilling rig. An optimal lightweight solution is targeted to combine the issue of the logistic and management of the drilling components with the need to keep liquified gas in a liquid state over long distances, taking into consideration the current material availability and price levels of various liquid gases, especially in light of the existing global gas shortage.

3.2 WP2 – Scaled model U-tube heat exchanger

To achieve the main objective of demonstrating the DeepU technical solution for deep heat exchangers, experiments are carried out in the project to examine the physical basis of the interaction between laser beam, cryogenic gas and rock material. The process states must be recorded in these experiments using suitable measured variables and appropriate sensor technology. Fraunhofer IAPT delivers extensive experience in high-power laser application, especially in rock fracturing by laser. The research institute provides its shipbuilding hall as a vast laboratory and a 30 kW fiber laser for the tests on rock (Fig. 4).

Figure 4: Large gantry system for laser positioning (left) and 30 kW high-power laser (right) at Fraunhofer IAPT facilities.

Since the rock is not only to be broken up in the new process but also completely melted by laser and then pulverized by the gas, a new processing head and a new drill string are required for the experiments. Fraunhofer IAPT is one of the leading institutes in the field of 3D printing and will use this technology to create the necessary components made of very heat-resistant materials such as titanium or Inconel. The laser and gas experiments will take place in a large metal box filled with stones or other soil formations. Simulation models for laser and gas interaction with rock material have to describe and predict the process flow for different rock types. Optimizing the process parameters, the drilling speed should be increased up to 20 to 30 meters per hour. That is at least ten times the drilling speed compared to conventional methods, which only reach about 1 to 2 meters per hour in hard rock (Anders et al., 2017). The speed increase will reduce the drilling costs to 1,000 Euro per meter for deep boreholes, i.e. to a quarter compared to the established methods.

Fraunhofer IAPT has realized the experimental set-up in a press container (Fig. 5). On the one hand, this large box serves as a safety enclosure for the laser machining process and, on the other hand, it offers the possibility of compacting the soil with the pressing function if necessary for the tests. Initial results of the experiments show symmetrical and accurate drill holes with a diameter of approximately 90 millimeters in sandstone and 80 millimeters in granite. Surprisingly, these first process applications have already achieved projected drilling speeds of up to 20 meters per hour.

Figure 5: Experimental set-up in a press container and first drilling results in a sandstone or granite block.

3.3 WP3 – Petrophysical characterization of rock samples

Another fundamental research step is to analyze the thermal effects of the laser and cryogenic gas combined action on several kinds of rocks, both before and after exposure to severe thermal stress conditions (melting and cooling phases). On the one hand, it is essential to determine the laser beam impacts on the petrophysical characteristics of the tested rocks. On the other, to verify the state of vitrification along the borehole walls resulting from the cryogenic gas inflow. The overall thermal shocks induced on the samples will be analyzed to understand the change in the rock thermodynamic equilibria during melting and crystallization, also recurring to numerical simulation. In addition, the drilling residues (cutting material and gases) produced/released by the melting and/or evaporation phases will be characterized to assess the potential environmental, health and safety risk and the particle tendency to re-agglomerate, creating an obstacle to successful DeepU drilling.

The lithic materials will be analyzed by optical microscopy (OM) and electron microscopy (SEM-EDS) to characterize the mineralogical-petrographic and microstructural characteristics of the pre- and post-vaporizing/melting effects. X-ray powder diffraction (XRPD), solid-state NMR (MAS-SS-NMR), and vibrational spectroscopies (FTIR, Raman) will be performed on micro-volumes of samples to fully determine the mineralogical nature, specific microstructural elements, and neoformation phases (Fig. 6).

Figure 6: (a) Dual beam FIB-SEM and (b) XRF spectrometry laboratory for 2D and 3D characterization of geological samples and solid materials at the University of Padova.

Samples of granite, sandstone and limestone with the dimension of 500 x 350 x 150 mm are under testing at Fraunhofer IAPT (Fig.7). These three lithologies were selected as the first to be tested because they represent the hardest rocks (granite) to be drilled at deep depth and the most common geothermal reservoir rocks (sandstone and limestone). The first tests were performed on granite and sandstone (Fig. 7a-b) using only the laser beam and without the cryogenic gas. As shown in Fig. 7a, some crack fractures developed due to the thermal shock induced by the laser beam and the absence of confining pressure.

Up to now, eight samples' blocks (2 granites, 2 sandstones, 2 limestones) have been sent to Padova for further analysis. For each lithology, one block is made of fresh unaltered rocks from the quarry, and the second one undergoes laser drilling by the drill string and drill head prototypes already realized. The obtained hole diameters vary according to lithology and laser use. In this research phase, the rocks are melted only by the laser beam and are not yet cooled down by the cryogenic gas. At the time of writing, the sample slabs are undergoing petrophysical characterization at the Geosciences laboratories of the University of Padova. The rocks will be characterized as fresh material and then in the close proximity of the hole generated by the laser beam, both by direct and indirect method.

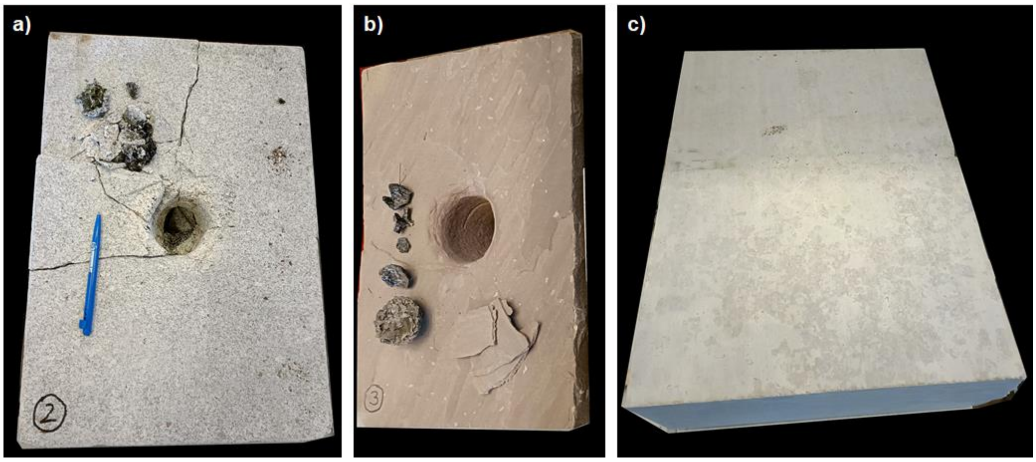

Figure 7: Rocks samples of granite (a), sandstone (b) and limestone (c). (a) and (b) show the boreholes obtained by laser drilling, the block thermal fracturing and some rock melting; in (c) the sample has not been drilled yet.

3.4 WP4 – Standards & Regulatory Integration

The innovative laser and cryogenic gas drilling offer challenges in technology integration with existing drilling practices and the completion of deep geothermal heat exchange systems. To ensure that market penetration of such new technologies can be achieved as part of their development, the environmental health and safety aspects around the design and operation of laser drilling need to be better understood. Similarly, the completion of deep borehole heat exchangers with this new methodology that will provide the potential for vitrification of the borehole needs to be documented in the context of current regulatory conditions for underground drilling and completions. An assessment of the legislative and regulatory requirements in Europe that address risk management, drilling practices, as well as underground energy storage and geothermal production, is being undertaken to determine the applicability of the new technologies to the European market. This assessment will build on the work recently completed by other projects such as GEOENVI (Manzella et al., 2021), GeoDrill and Opti-Drill that have carried out extensive reviews of geothermal regulatory frameworks and on the optimization of drilling solutions. The review will provide the basis for completing a detailed environmental health and safety (EHS) plan for DeepU and developing recommendations for integrating the technology in the context of best practices and applicable standards. These will include a review of current drilling practices from the point of view of risk management, waste management, well control and the operation of industrial lasers using cryogenic gas to inform the EHS plan for Deep U at both the construction and operational phases of a project. The EHS will also address drilling rig requirements, well life-cycle planning and decommissioning requirements. The market potential for deployment of the DeepU technology and the compliance with environmental and safety standards will be demonstrated for the virtual case jurisdictions in Italy and Ireland, both of which will be used to illustrate the potential for adopting the technology.

As part of the implementation steps of the project, two main tools, including a Failure Mode & Effects Analysis (FMEA), are being developed to identify different project processes and steps whilst making recommendations during the development of the DeepU technology. The FMEA focuses on both regulatory and practical aspects of developing laser-based deep drilling technology, the use of cryogenic gas and the completion of deep geothermal and energy storage boreholes. FMEA represents a live support document that will help the project technologies comply with EHS requirements when using the laser drilling methods and completing closed-loop DeepU boreholes. In addition, a risk register and risk assessment matrix are being developed to achieve EHS compliance and allow for drilling and underground energy project operational risks to be identified and suitable mitigation measures proposed. The main objective of the risk register will be to focus on the market integration potential of the technology and demonstrate how this can be deployed in sub-surface projects in Europe. Detailed recommendations for integrating DeepU into the market will be compiled based on the FMEA and risk register outcomes. These will provide the basis for future up-scaled deployment of the technology outside the laboratory environment.

3.5 WP5 – Exploitation planning and IPR management

Drilling tests and subsequent analysis of the lab samples in previous work packages will provide information to simulate the energy extraction potential of a deep U borehole at a large depth. This information, in turn, also allows for estimating the drilling costs using this new technology, extrapolating the drilling parameters from the lab tests. The total capital and operating costs for a 5MWe and 10 MWe power plant will be defined in two virtual locations with known underground conditions, one in Italy and one in Ireland. The scale-up plan will determine costs and additional research for drilling at different depths, starting with a proof of concept in the field in a volcanic area at limited depths to contain the costs of the next phase but with representative underground conditions. Also, funding amongst potential stakeholders like multi-utilities will be explored during dissemination. Concerning the Intellectual Property Right (IPR), partners already own patents or filed requests. Further patentability of the generated knowledge will be evaluated as the project progresses.

CONCLUSIONS

The first DeepU project results show the solidity of the proposed approach and indicate the effectiveness of the path taken in achieving all the set goals.

Step by step, all the WPs started their activity.

First of all, the technological developments taken in **WP1** led to the design and manufacturing of the drill string able to convey the laser beam downwards (outer tube 100 mm, inner tube 60 mm), also considering possible alternatives to convey the cryogenic gas flow (i.e. flexible cryotubes). In addition, four gases (argon Ar, krypton Kr, helium He, nitrogen N) were considered potential cryogenic gas for the innovative DeepU technology. For the potential use with the drill strings, the cryogenic gas needs to remain liquid for a very long distance and to keep a low temperature for a very long time and length. Each gas's triple and critical points must be considered to meet these constraints. Ar and N show similar supercritical behavior. However, while N has the advantage of being abundant in the atmosphere and of remaining liquid for a very long time, Ar and Kr are present in traces, while He easily escapes in the atmosphere and already shows a supercritical state at 3° C. Therefore, N seems the best choice for the minor cost perspective and because it can be supplied to the construction site in easy-to-manage insulated tanks. The target is to maintain it in the drill strings with increasing depth at a pressure of > 30 bar and a T < -146.96 °C. However, an issue is the potential energy loss of the gas with depth due to the increasing ground temperature. In the future, the DeepU project will investigate these aspects more deeply.

In **WP2,** the laboratory set-up for rock melting/vaporization and vitrification was prepared. A container is adapted as a safe housing to run laser experiments. The container, equipped with side windows for visual inspection of operations and housings for sensors and monitoring devices, is ready to host rock samples to be tested, the drill string with laser and the gas processing head. In addition, the first tests concerning granite, limestone and sandstone samples have already been performed.

WP3 was not active in the first six months, but strict cooperation with WP2 allowed us to select suitable rocks for lab tests and define the laboratory test devices to be used later in the project. The sample blocks, drilled up to now only by the laser action, were just sent to the University of Padua, where they will be analyzed to characterize the petrophysical and thermal behavior of the samples before and after laser interaction.

WP4 was silent from month 1 to month 6. However, preliminary work was already prepared. Legislative and regulatory aspects and standards for gas flushing medium in deep drilling, factors related to drilling, well completion and deep U heat exchangers have been tracked down. They will be explored in depth in the next future.

Also, **WP5** was silent in the first six months. Anyway, the discussion about the criteria for selecting the two virtual case study sites in Italy and Ireland has already started.

Given this background, the near future is expected to provide more fascinating results through research and planned technological advances, including characterization of what happens inside the rock once it undergoes melting.

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