# Strategic Research and Innovation Agenda

ETIP Geothermal

www.etip-geothermal.eu

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# EXECUTIVE SUMMARY

Geothermal energy is distinctive as a distinct and pivotal form of renewable energy. Its capabilities encompass electricity generation, heating, cooling, the provision of hot water and thermal underground storage, for short and seasonal storage. Moreover, it also the potential for supplying minerals like lithium. The energy transition will require all these four elements to decarbonise the electricity, heating and cooling and transport sectors.

The challenges to answer the climate crisis, ensuring the security of energy supply, and providing affordable energy must lead us to a climate neutral economy by 2050.

Geothermal is one of the answers of the current energy crisis. Many geothermal technologies can be deployed locally all over Europe thanks to successful technological developments making them competitive.

In the last few years, the European Union has put forth a number of legislative measures to guide the energy transition that will require all of the aforementioned elements. There are already many geothermal technologies and networks that play a key role in sustainable and and environmentally friendly powering from individual buildings to cities. Successful technological advancements have rendered numerous geothermal technologies competitive, enabling their widespread deployment across Europe. In fact, recently, cities have been increasingly interested to deploy geothermal technologies.

The imperative to respond effectively to the climate crisis, ensure energy supply resilience, and offer accessible energy necessitates our journey toward a climate-neutral economy by 2050. To do this, electricity, heating and cooling, and transportation sectors especially need to decarbonise and to do so will require geothermal resources. By 2050, geothermal has the ability to supply (1) 10% or more of overall European electricity consumption, (2) more than 25% of all heating and cooling demands, (3) contribution to the total lithium demand, and (4) underground thermal energy storage (UTES)—the latter of which would largely reduce energy waste, saving energy for usage as demanded by the district network.

To be successful in these endeavours, Research and Innovation (R&I) of improved next generation geothermal systems and technologies are key for new applications, markets, and meeting deployment in the EU for the 2050 milestone. The Strategic Research and Innovation Agenda (SRIA) for geothermal technologies presents the research priorities:

**Chapter 1 (A)** introduces resource assessment, focusing on mainly enhancing exploration and risk reduction. Resource assessment endeavors seek to minimize the risks associated with pre-drill mining, extend the scope of available resources, and refine methods for identifying untapped potential. The initial focus centers on refining technologies to enhance resource prediction accuracy and mitigate uncertainty. These encompass cost-effective exploration techniques that enhance the visualization of geothermal reservoir structures and properties, thereby reducing the financial burden of exploration. Additionally, reservoir characterization and performance assessment emphasize transparent workflows and the incorporation of advanced conceptual models and characterization techniques. Sharing knowledge gained from productive reservoirs and geological analogs contributes to the creation of comprehensive rock property catalogues.

**Chapter 2 (B)** focuses drilling and subsurface engineering through examining both cost reduction and innovative concepts. Geothermal project expenses are heavily tied to drilling and subsurface engineering activities. These financial pressures are particularly evident during the early phases, even before productivity confirmation. This underscores the urgent need for strategies that reduce costs and introduce novel production concepts. The topics under this category span drilling and well completion technologies, ranging from the integration of robotic and AI-assisted drilling methods to optimizing the rate of penetration. Moreover, improvements in drilling fluids and the development of materials for casing, cementing, and completion are central to enhancing well construction. Monitoring and geosteering during drilling processes are integral for well optimization. Furthermore, the inclusion of high-temperature electronics is crucial for sustained operations.

**Chapter 3 (C)** centers on maximizing the efficiency of resource use and system integration. Efficient conversion of geothermal resources into usable energy, coupled with effective heat storage and co-production of minerals, holds the key to resource maximization. This entails advancing power cycles and increasing overall energy efficiency. Flexibility in combined heat and power production further contributes to efficient resource utilization. Underground thermal energy storage at elevated temperatures demonstrates great potential. Simultaneously, the extraction of valuable minerals, particularly lithium, enhances the economic viability of geothermal operations. Moreover, the synthesis of chemicals and other diversified applications of geothermal resources amplify their utility.

**Chapter 4 (D)** is concerned with addressing environmental and market challenges through safe and sustainable resource management. In addition to technical performance challenges, this section underscores the importance of enhancing the environmental sustainability of geothermal power and heat systems throughout their lifecycle. To achieve this, a multipronged approach is necessary. Market uptake of geothermal technologies necessitates addressing systemic challenges, including initial high investment costs, regulatory hurdles, and public perceptions of environmental impacts. Effective communication strategies that highlight the benefits of geothermal energy to individuals, companies, and society at large are essential. Comprehensive life cycle assessment and emissions reduction strategies are pivotal to lowering the carbon footprint. Promoting circularity by reusing materials and managing water use aligns with sustainable practices. Moreover, the management of reservoirs and mitigation of induced seismicity contribute to safe and sustainable operations. Public engagement and acceptance, financial risk mitigation, policy adaptation, human resource development, and effective communication strategies are all vital components in the journey to achieve a sustainable geothermal future.

A key message of the SRIA is that it is not only necessary to strengthen R&I private investments but also to increase the public funding budget for R&I projects at the European, national and regional levels.

# EDITORIAL

In the last few years, a number of political act proposals regarding renewable energy and the green transition have been put forth by the European Commission. Most recently, the Net Zero Industries and Critical Raw Materials proposals, which push for mineral manufacturing and industry recentralization in Europe, is an area where geothermal could play an increasingly important role. Not to mention geothermal energy plays a pivotal role across the European low carbon energy mix as a whole, with potential to supply a substantial portion of electricity heating and cooling beyond 2040 and 2050. While traditionally employed as base load capacity, geothermal power generation has the capacity to adapt to a flexible power system and stabilize energy grids. Europe's history of geothermal resource utilization spanning over a century has resulted in pioneering advancements including innovations like flexible power generation, smart district heating and cooling grids, underground thermal storage, and sustainable extraction of minerals.

With investment and implementation of research-driven innovative geothermal technologies, the networks of cities and energy systems, Europe could create go far beyond one district heating and cooling system. Imagine city networks employing not only geothermal for renewable heating and cooling, but also energy storage to meet varying demands of consumers, energy to power the electricity grids, and the reusage of geothermal brines to extract critical materials (like lithium, used in battery production).

To make this vision into reality, efforts to tap into Europe's untapped geothermal resources have led to the establishment of the European Technology and Innovation Platform on Geothermal (ETIP Geothermal). In collaboration with the SET Plan Implementation Working Group, the platform aims to harness these resources.

**QUOTE from Fausto Batini, ETIP Geothermal President:**

"The ETIP geothermal members have done an immense work to write this Strategic Research and Innovation Agenda on geothermal technologies. I want here to thank all of them. The merge with the RHC-Plaform geothermal panel from 2023 have even strengthened the power of the ETIP and make it an unique and most relevant platform for geothermal R&I.

Developing these technologies will make geothermal the key energy sources of the transition towards climate neutrality by 2050. Geothermal technologies are a solution for the electricity system, the heating and cooling supply, the system integration with thermal underground storage, and the sustainalble extraction of minerals such as lithium.

Geothermal will support local economic development and security of energy supply in a sustainable way."

# A. INTRODUCTION: DESIGNING THE FUTURE OF GEOTHERMAL ENERGY

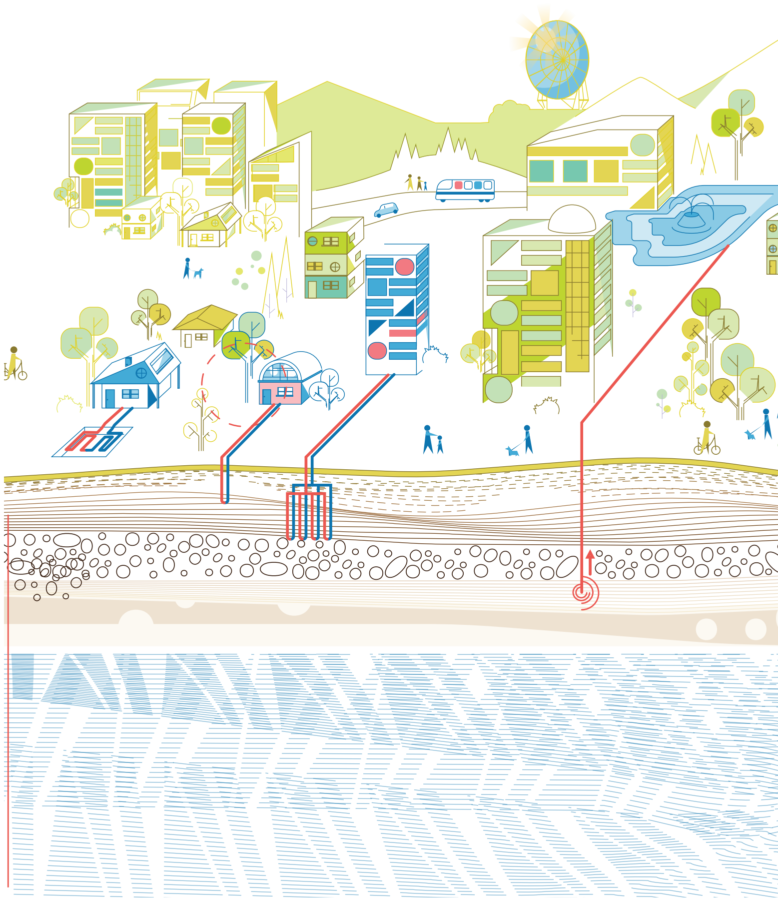
The topics presented in this SRIA have been identified as the main levers for the development of geothermal resources, in the following main themes

- Resource assessment
- Resource development
- Resource utilization and management

The choice and the priorities within these themes might seem subjective as they are intimately linked. However, they allow identification of a number of industrial and R&D trends aiming at meeting ever greater energy and heat production needs in an ever more demanding social and environmental context.

**Key industrial and technological drivers** defining the general frame can be the following:

- Progress can be highly accelerated by **technology transfers from the Oil & Gas industry**. Existing tools and workflows have to be adapted to different kinds of resources (water and heat), different geological settings (basement and volcanic reservoirs) and different environments (high temperatures, high pressures and highly saline fluids), with different ambitions and challenges (smaller scale projects and tighter budgets). To this extent, it is interesting to note that **major service companies now start to focus on geothermal energy**, trying to define viable business models.
- **Artificial Intelligence (AI), Machine Learning (ML), high performance computing and robotization** are key enabling technologies to enhance resource assessment, resource development, lowering levelized cost of energy for operations and promotes safe and sustainable development. There is a wealth of subsurface data from geothermal resources exploration in the past, which serves as an important stepping stone for these technologies allowing to identify and unlock new resources
- **Gaining in productivity does not only mean cheaper** (at least at the scale of a single operation), but implies a global benefit at the whole scale of a project. It means optimizing processes, spending less (and greener) energy, and reducing failures. As far as resource assessment and development is concerned, this goes of course through technological evolutions but also, and maybe above all, through a **better understanding of geothermal prospects** (rocks, stress fields and fracture characterization, temperature, pressure, fluid composition and dynamics) to feed **models, uncertainty analyses and risk assessment.**
- Industrial performance is also a matter of **business models and standards**. The goal to reach has to be defined by asking key questions such as: **what kind of wells does the industry need? What kind of projects do we want to run? At what cost?** In other words: shall we develop tools and techniques for extremely deep reservoirs showing extremely high temperatures, if such targets remain exceptions? And where do we set the cursor for "extremely



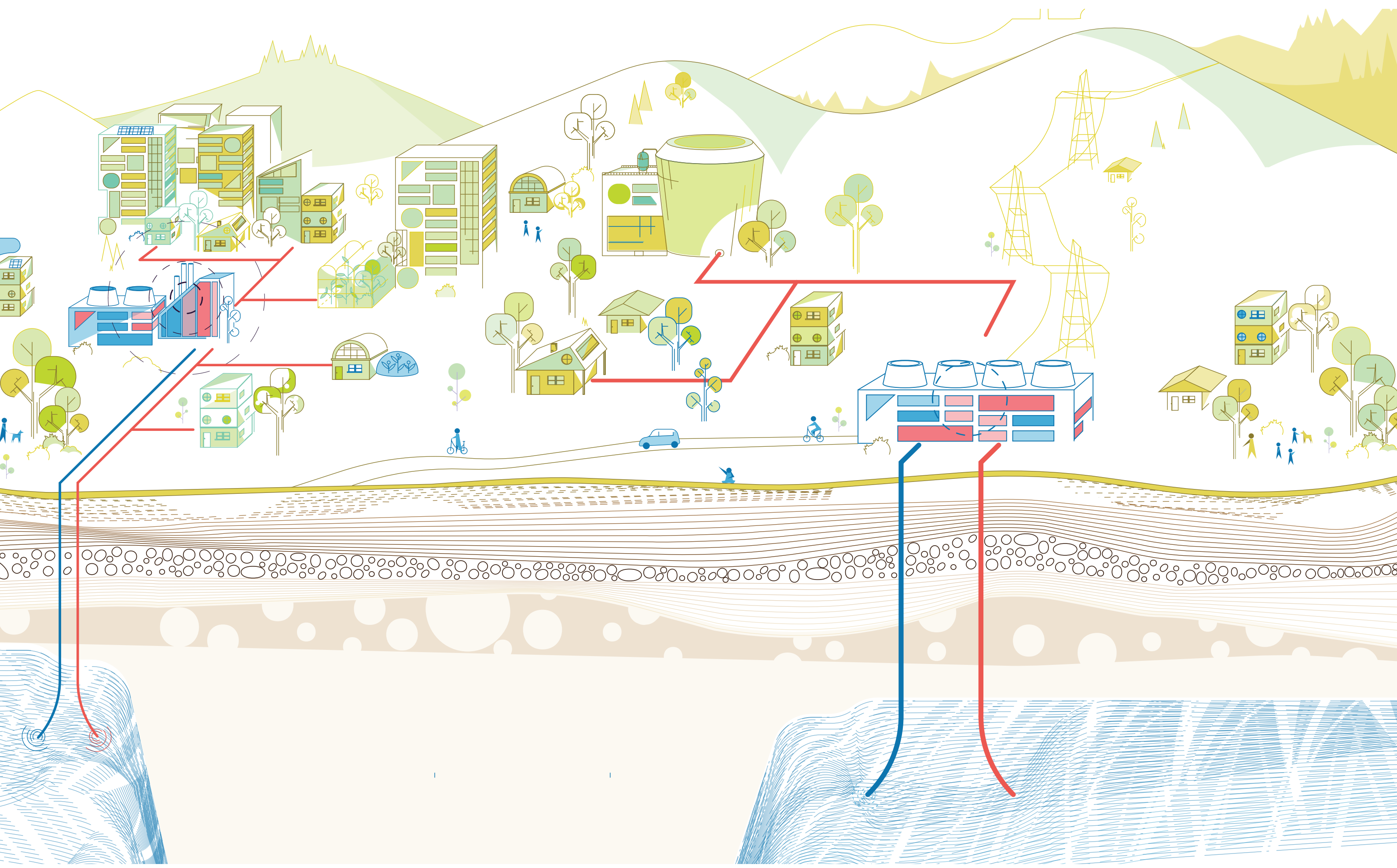
deep" and "extremely hot"? **Industrialization and standardization require well established, benchmarked ranges** which define what a "common geothermal well" should be, whether we talk about materials, tools, exploration or production operations.

- We have to keep in mind that about **50% of the energy used in Europe is in the form of heat**, most of it coming from fossil sources. At this extent, geothermal will be a strong lever to reduce greenhouse gases emissions. Unlocking this potential requires to upscale existing projects and to design assets to be more robust, reliable and efficient.

**The technical and industrial picture has to fit a social and environmental frame which is evolving quickly** and is now fully part of projects management. These aspects are developed in detail throughout the Strategic Research and Innovation Agenda, and link to different project development phases in line with sustainable approaches:

- **The environmental Life Cycle Assessment** on all activities and solutions leading to a sustainale approach, including circularity has to be developed. It includes a socio-economic lifecycle perspective.
- **A sound financial and policy framework** must be established to accelerate the deployment of innovative geothermal technologies.
- **Increasing dissemination, public awareness and engagement** through the promotion of geothermal technologies is essential to the implementation and success of projects not only at the local level, but also at the national level.

*EGEC Illustration representing the geothermal sector*. Source: EGEC Geothermal



# B. RESOURCE ASSESSMENT

Resource assessment research and innovations aim, to extend the resource base and to enhance identification of resource potential increasing the success rate at drilling stage.

Topics 1-3 focus on technologies for improving resource assessment and prediction, prior to drill the deep wells:

**1.** Advanced exploration methods and technologies deal with cost-effective development and demonstration of geological, geochemical and geophysical exploration methods and technologies contributing to improve the imaging of geothermal reservoir structures (geometry and size) the prediction of its petrophysical properties and the chemical composition of bearing fluid.

**2.** Reservoir characterization and performance assessment entails the implementation of cost effective open, dynamic and transparent workflows and improved multi-scale and multi-disciplinary approaches by using advanced conceptual models and reservoir characterization methods.

**3.** Catalogues and databases includes sharing knowledge gained from comparable productive reservoirs (including hydrocarbon reservoirs) and geological analogues, as well as building catalogues of rock properties.

Topics 4-10 deal with frontier resource development and identification of resource potential that (re)use existing subsurface infrastructures:

**4.** Medium-deep sedimentary reservoirs, Geothermal Heat Pump systems and Heat Storage aim to explore geothermal resources at depths typically overlooked from ~300 to 2000m depth which are beyond l ones covered by geothermal heat pumps and below the depth range covered by low enthalpy geothermal systems.

**5.** Deep sedimentary/basement reservoirs aim to unlock geothermal resources at depths between 2000-6000m, which are marked by low natural permeability.

**6.** Cutting edge reservoirs entail the development of high enthalpy resources, including super-critical geothermal systems, and offshore magmatic resources

**7.** Innovative geo-structures consist of the development of technology for the integration of geothermal heat exchangers and heat and cold storage solutions into subsurface infrastructure elements that interface with the ground.

**8.** Transformation of Hydrocarbon Assets entails the development of geothermal energy potential from abandoned or end of life time hydrocarbon reservoirs

Topics 9-10 deals with advancing methods for identification and de-risking of resource portfolio potential

**9.** Play-Based Portfolio exploration for Heating & Cooling deals with the development and implementation of a methodological framework for play based geothermal resource potential

**10.** Assessing resource potential aims at the development and demonstration of innovative approaches for a reliable estimate of geothermal resource potential resulting in a unified definition and harmonisation across Europe

# TOPIC 1: ADVANCED EXPLORATION METHODS AND TECHNOLOGIES

## Objective

Development of cost-effective exploration methods and technologies contributing to improvethe imaging of geothermal reservoir structures (geometry and size), rock properties (e.g. porosity, permeability, density, elastic moduli) and fluid characteristics (temperature, pressure, chemical composition)

These innovative methods and technologies will improve the knowledge of the various geothermal systems, contributing to increase the success rate of drilling and consequently reduce the overall exploration expenditures.

## Current status

The methods of exploration and investigation of geothermal resources are numerous and well described in the literature (e.g., 'Best practices guide for geothermal exploration' by International Geothermal Association and International Finance Corporation). Many projects supported by EU funding programmes over the last 10 years have tackled exploration techniques, including single and integrated survey methods, logging, modelling, performance evaluation, and resource assessment (DESCRAMBLE, DARLINGe, CHPM2030, GEMex, IMAGE, EoCoE, TRANSENERGY, I-GET, GEO-DH, GEOELEC, ENGINE, RESULT).

The methods of exploration and investigation of geothermal resources are numerous and well described in the literature (e.g., 'Best practices guide for geothermal exploration' by International Geothermal Association and International Finance Corporation[1]). Many projects supported by EU funding programmes over the last 10 years have tackled exploration techniques, including single and integrated survey methods, logging, modelling, performance evaluation, and resource assessment (DESCRAMBLE, DARLINGe, CHPM2030, GEMex, IMAGE, EoCoE, TRANSENERGY, I-GET, GEO-DH, GEOELEC, ENGINE, RESULT).

Nonetheless, exploration risk remains high until the first exploration well has been drilled and direct data can be obtained. The high-risk cost of drilling to confirm the existence of a viable geothermal resource remains one of the key challenges the industry faces. The development of further methods is needed to reduce the uncertainties affecting location, size, and productivity characteristics of a given resource. This requires continuous effort as well as periodical R&D&I opportunities to test and optimise newly developed technologies.

## Potential for technological development

Technological development options include:

- Reducing the cost of surveys and improving the resolution of underground imaging through the use of geophysical exploration techniques (e.g. gravity, magnetotelluric, electromagnetic, passive seismic, 2D-3D-4D reflection seismic, well bore VSP CSEM) aided by novel AI/ML approaches
- Harness remote sensing-based methods for geothermal exploration

- Designing an integrated approach using best practice recommendations for must-have and nice-to-have methods by types of resource and geological setting, as well as improving the multidisciplinary nature of exploration methods (geological, geophysical, geochemical). Advanced methods should (jointly) tackle assessment of heat flow, reservoir temperature, thermo-mechanical properties, in-situ stress, flow chemistry, pathways and prioperties (including innovative sensor and tracer technology), seismicity, and include performance tests at high temperatures and in harsh conditions
- Improve data QC and interpretation with specialised data and computational science including (re) processing and machine learning of existing data, joint field acquisition and enhanced numerical joint inversion, and enhancing reservoir information from time-lapse analysis of field data

## Target and KPIs

Development and demonstration of enhanced exploration and monitoring methods for the different resource types (TRL range 3-6)

Demonstration of exploration workflows for different reservoirs types, testing and validating of the exploration methods (TRL 7-9)

KPI 2030:

- Increasing up to 75% the success rate of the first exploratory well by proving the project economic viability for green field reservoirs
- Lowering up 25% the overall exploration costs of prospect portfolios to identify geothermal resources suitable for the project development

**Tentative Budget:** 50 M€

- Development of methods 10 M€
- Field test demonstration and validation 40 M€ (2-3 sites)

## TOPIC 2: RESERVOIR CHARACTERIZATION AND PERFORMANCE ASSESSMENT

### Objective

Development of novel multi-scale and multi-disciplinary approaches using advanced conceptual models for characterization and performance prediction of the reservoir,

The conceptual models should in turn be underpinned by fundamental understanding and confirmation of processes and properties in field and reservoir analogues (see further Topic 3).

Uncertainty analysis based upon performance models as well as decision and risk methodologies can further enhance the chance of success

For areas where information is scarce, the aim is to develop and **test novel methodological approaches in order to unlock hidden geothermal potential**. These can be improved by adopting portfolio and option theory approaches developed for the hydrocarbon industry, as well as dedicated exploration techniques.

### Current status

Many exploration concepts and techniques, thoroughly described by numerous papers and books, have been combined and integrated into the geothermal exploration workflow at several selected sites in magmatic and basement/sedimentary environments as part of the FP7 IMAGE project. An integrated approach focused towards multi-disciplinary complementarity, including geological, geophysical and geochemical techniques as well as numerical models was employed to predict the geothermal target (productive resources) and to design the well. This is the approach has been adopted in a number of EU projects (GEMex, DESCRAMBLE, DEEPEGS, DESTRESS, MEET, CHPM2030, GEORISK).

The exploration workflow has been a main focus of the IMAGE project with the development, especially for volcanic areas, based on the experience gained in Iceland and calibrations in the Azores, whereas for sedimentary settings the workflows and conceptual models are strongly rooted in best practices from the hydrocarbon industry and need adaption. The past RI projects highlighted the need for a multi-scale coupled model approach from the continental to the concessional scale, and the different roles played by individual methodologies. Numerous geological processes and conceptual play models are slowly progressing thanks to different projects, data collection and applications involved.

### Potential for technological development

Technological development options include:

- Developing **standard terminology for conceptual and reservoir characterisation models – from lithosphere to reservoir scale for different geological settings**. Conceptual models – starting with the knowledge gained from corresponding areas – and **EU catalogues of temperature, stress, rock composition, properties, etc. are first required to define regional parameters (see topic 3)**. Subsequently, regional evaluation of geothermal resources (requiring key data) would allow for the identification of areas deserving additional exploration.

- **Developing predictive models**, processing existing data and workflows for reservoir characterization for different reservoir types, focusing on multidisciplinary integration and interpretation
- Transfer and adaptation of best practice risk and compliance methods from oil and gas/CCS industry
- Developing **public and transparent performance models** including technical and environmental risk assessment (i.e. stochastic expectation curves, including identification upside and risk of prospects)
- Decision and risk management (DRM) approaches for optimal decision-making as part of the exploration workflow, providing tools and a methodological framework for technoeconomic performance assessment

## Target and KPIs

Development of advanced multiscale, multiphysics, multidisciplinary workflows and predictive models for different resource types (TRL range 3-6)

Demonstration and validation of workflows and models for different reservoirs types, testing and validating of the exploration methods (TRL 7-9)

Public and transparent performance models (derived from advanced models) and DRM approaches for the different resource types, resulting in improved bankability and technical risk management (TRL range 6-7)

KPI 2030:

- Increasing by 10% the success rate in wells drilled for field development (2024-2030)

**Tentative Budget:** 50 M€

- Development of methods: 15 M€
- Field testing and validation: 35 M€ (2-3 sites)

## TOPIC 3: CATALOGUES AND DATABASES

### Objective

**Continuous improvement of multiscale (tens of km to meters) and multi-disciplinary regional and site-based conceptual models** and reservoir characterization capabilities by sharing knowledge gained from comparable productive reservoirs (including hydrocarbon reservoirs) and geological analogues, as well as building catalogues of rock properties (using integrated site and borehole geophysical methods and lab investigations of key samples), fracture network characterization and fluid-rock interaction features. This would lead to improved reservoir characterization in absence of data in addition to multiscale reference models and maps supplying constraints for regional and site models.

### Current status

The characterisation and utilisation of subsurface reservoirs generally relies on geological and geophysical investigation/exploration methods and/or numerical models – both requiring, in turn, knowledge of physical rock properties at depth. In order to avoid time-consuming literature research, problems arising from unwanted generalisations and missing complementary information needed for further interpretation of the measured values a PetroPhysical Property Database has been developed within the IMAGE project. This database contains data selected to represent the (laboratory-derived) properties of the rock matrix, with characteristic scales of rock samples ranging from a few centimetres to decimetres. It does not contain rock property data from fields, which integrate larger rock volumes, and may include open or partly open discontinuities, several rock types and properties. IMAGE and later the GEMex project explored the use of field analogue sites, which serve as input for conceptual models and provide property information, helping considerably to constrain explorative concepts which are then checked during site investigation and development.

### Potential for technological development

Technological development options include:

- Building and extending relevant rock property databases, in synergy with legacy data from hydrocarbon exploration and production
- Develop databases for environmental assessment (e.g., geomechanical and thermal properties)
- Developing new upscaling approaches, ranging from rock sample properties to borehole geophysical logging and integrative exploration geophysics
- Using the empirical correlations of different properties at different scales for geostatistical reservoir configuration/characterization
- Developing a reference set of lighthouse reservoir models and analogues for different geothermal reservoir types also to be used for training and education
- Building multiscale reference maps and models to provide constraints for regional and site models, integrating geophysical, lab and structural models
- Setup guidelines for databases to be embedded in EPOS, EuroGeosurveys (EGDI) and standards for harmonization at transnational level of geothermal data and maps

## Target and KPIs

AI-based methods for quality control methods for handling and processing legacy data from hydrocarbon industry (core, seismic, log, etc), ensuring data and expert workflows do not get lost

Development of laboratory (and field analogue) research infrastructures for different geological settings, focused towards property measurements of geothermal systems, resulting in reference reservoir and analogue reservoir datasets, providing key data for calibration of reference reservoir models.

Enhanced processing and interpretation methods for legacy data, resulting in increased chance of success for (unconventional) geothermal resources. Methods include novel multiscale/multiphysics upscaling approaches and geostatistical techniques, enhanced seismic processing, AI based techniques, etc.

Reference maps, and 3D and lighthouse reference reservoir characterization models for different geological settings. This includes the development of EU catalogues of temperature, stress, rock composition, properties, etc. which serve as stepping stones required to define regional parameters in the exploration workflow.

KPI 2030:

- The methods, reference maps and datasets increase chance of success of exploration projectss, effectively reducing 5-10% pre-drilling exploration costs

## Tentative Budget 100 M€

- AI-based methods for handling legacy data and expert workflows 10 M€
- Development of lab and reservoir (analogue) research infrastructures 70 M€
- Enhanced processing and interpretation of legacy data 10 M€
- Reference databases, maps and lighthouse reservoir characterization models 10 M€

# TOPIC 4: MEDIUM-DEEP SEDIMENTARY RESERVOIRS, GEOTHERMAL HP AND HEAT STORAGE

## Objective

Exploration of medium-deep geothermal resources in sedimentary basins (from about 500m to ca.2000m) and identification of resources for seasonal heat storage

## Current status

A large amount of geothermal energy is stored in regions where the geologic conditions do not display geothermal anomalies and where heat demand is concentrated in urbanised areas. In a large number of these regions sedimentary basins are the dominant geologic setting (e.g. Molasse Basin, Paris Basin, Rhine Graben, Pannonian Basin) where sediment thickness can be up to 6000m.

Geothermal resource potential is widely abundant in sedimentary basins, but most suitable reservoirs have in the past decades mostly been based on a " low hanging fruit" approach: the well studied hydrocarbon reservoir targets, marked by dense data coverage in terms of existing seismic, wells, core and log data.

Consequently, resources which (1) are not corresponding to potential hydrocarbon reservoirs have been neglected in past studies, or (2) that do not exhibit marked heat flow/hydrothermal manifestations that justify harnessing geothermal potential.

Potentially neglected resources correspond in large parts with depth ranges which are outside the hydrocarbon maturation and preservation depth window, which is roughly between 1500 and 3000 meters. However, reservoirs either at shallower levels and deeper provide significant additional geothermal potential, and can facilitate in extending geothermal resource potential in areas where hydrocarbon reservoirs are absent. Existing exploration techniques and workflows to identify suitable resources outside the conventional hydrocarbon depth windows and data dense areas are relatively immature as exploration workflows for sedimentary basins are either based on hydrocarbon industry or relatively shallow groundwater exploration (mostly <100 m).

Therefore, in order to extend the EU geothermal resource base, these underexplored resources need to considered both in this topic of medium-deep geothermal resources (~ <2000m) and in a separate topic on deep sedimentary/basement reservoirs. Note that this topic also covers the exploration for seasonal heat storage, for which highly permeable relatively shallow formations are highly suited (150-500 m). The development of medium-deep reservoirs can benefit from heat pump technology and relatively low CAPEX and relatively small scale of heat networks for heat distribution. Extended knowledge of medium-deep geological sedimentary settings is also key for the development of deep (500-1000 m) Geothermal Heat Pumps (GHP) or socalled Deep Borehole Heat Exchangers (DBHE), which have the capacity to extend renewable heating in urban areas where interference of shallow GHP or noise levels of air sourced heat pumps pose barriers for implementation.

## Potential for technological development

Technological development options include:

- **Exploration methods for heat storage and GHP (<500m)** including reprocessing of legacy data, advanced seismic acquisition and interpretation, dedicated well logging techniques and process-based models
- **Exploration methods for medium-deep geothermal energy production (<2000m)** including reprocessing of legacy data, advanced seismic acquisition and interpretation, and process-based models
- **Exploration methods for deep geothermal heat pumps/deep borehole heat exchangers (500-2000m)** aimed to identify suitable rock formations for low cost, safe construction and high performance (i.e. high thermal conductivity)

## Target and KPIs

Development of exploration methods dedicated to heat storage and geothermal energy production from medium-deep reservoir (TRL 3-6)

Quantitative reservoir performance prediction and resource conceptual development strategies (and well architectures) of medium-deep reservoirs types in different geological settings (TRL 5-7)

Methods for identification of suitable subsurface conditions for deep GHP, resulting in extended geothermal resource base or geothermal heating and cooling (TRL 3-6)

Demonstration of exploration workflows for different reservoirs types, testing and validating of the exploration methods (TRL 6-9)

KPI 2030:

- Reduction up to 25% exploration costs for medium-deep reservoirs and heat storage by improved predrill derisking reservoirs
- Identification of resource base for deep GHP/DBHE
- Enlarged EU resource potential for direct heating and cooling by 100% by 2030

## Tentative Budget 100 M€

- Exploration methods heat storage and GHP 10 M€
- Exploration methods medium-deep reservoirs 10 M€
- Resource potential case studies and validations: in about 10 different geological settings 50 M€
- Deep GHP/DBHE in ca.10 (different) geological settings 30 M€

## TOPIC 5: DEEP SEDIMENTARY/BASEMENT RESERVOIRS

### Objective

Extended geothermal resource base for Enhanced/Engineered Geothermal Systems and closed loop systems in deep sedimentary and basement formations

### Current status

Deep sedimentary/basement reservoirs (higher than 2 km depth) can be challenging because they have typically not been targeted in the past by the hydrocarbon industry, the natural matrix or fracture permeability is typically low, and drilling costs are very high resulting in a poor business case. Natural flow rates can be significantly enhanced thanks to innovative borehole design and/or reservoir stimulation (e.g. hydraulic stimulation, jetting, chemical treatment, thermal cracking). Consequently, these Engineered Geothermal System (EGS) technologies are key to unlocking less permeable geothermal reservoirs and improving poorly performing boreholes. Major exploration challenges relate to predicting reservoir structures and properties, where in combination with EGS deep reservoirs are prospective.

Enhanced Geothermal Systems (EGS) systems, under development since the 70's, have been facing issues related to induced seismicity and with intermittent, often scarce, commercial performances. EGS has focussed, up unitl now, on crystalline rocks and on electricity generation, whereas the H&C sector has focussed mostly on shallow installations and hydrothermal projects. This dichotomy, despite being extremely simplified here, clearly reveals the presence of a gap that needs to be further investigated. In addition, for impermeable formations closed-loop systems can also be considered the current state of the art. Other innovative closed-loop technologies are under development.

The RIA related to the EGS technology itself (i.e. stimulation technology and advancing well designs) and closed loop drilling are covered in chapter B of the SRIA. This chapter deals with identifying suitable subsurface reservoir conditions for EGS and/or closed-loop developments.

There are sseveral open questions when thinking about applying those technologies to deep geothermal sedimentary reservoirs, including:

- What is the natural fracture permeability and in-situ stress conditions?
- Is EGS enhancement enough to sustain commercial production over the life time of a project?
- Are the geomechanical properties of potential reservoir rock suitable to reduce the risk of induced seismicity?
- What are the impacts of mineral dissolution and precipitation on evolution of reservoir properties?

To reply to these questions and to many others that will arise a trans-disciplinary strategy for the assessment of the suitability of deep sedimentary/basement should be implemented in the coming years—starting from feasibility studies and aiming to demonstration projects within 10 years from now, followed by commercial projects, jointly with relevant topics in chapter B and C.

To achieve this goal a research community, industries, local authorities and municipalities should work together to develop a set of mid- to long-term projects in selected regions in Europe where geologic conditions and surface components (e.g. energy systems, infrastructures) can be favorably combined to achieve market uptake.

## Potential for technological development

- Methods and models capable of detecting and predicting sweet spots of matrix and fracture permeability at large depth (>~2000 m), taking into account in-depth understanding and predictive models for properties and processes beyond conventional depths, including structural/fracture, chemical and mechanical properties which are of importance for EGS development
- Methods and models to better predict and constrain the impact of particular reservoir conditions and parameters (i.e. in-situ stress, temperature, geomechanical, chemical properties) which affect enhanced reservoir performance in view of different stimulation techniques (hydraulic, chemical, thermal)
- Methods and models to predict and constrain the impact of reservoir conditions and parameters which affect enhanced reservoir performance in view of different well design (horizontals, multi-laterals, shot drilling, jetting, etc.) and completion technologies (i.e. anisotropy, geomechanical properties)
- Exploration methods for deep closed-loop systems (i.e. capable to detect suitable non-permeable formations, marked by high well bore stability in face of well bore cooling/seismic risk, and high thermal conductivity of surrounding formations enhancing heat transfer)

## Target and KPIs

Advanced methods and (conceptual) models for different geological settings in Europe for the identification of sweet spot matrix and fracture permeability at large depth (>2 km depth), and the impact of subsurface conditions for the potential of EGS discriminating the potential for stimulation techniques and advanced well designs (TRL 3-7)

Advanced methods and (conceptual) models for different geological settings in Europe for the identification of suitable conditions for closed-loop (TRL 3-7)

Pilot and demonstration of the improved methods in at least 3 favourable locations in different geological settings in the EU (TRL 6-9)
KPI:

- Identification of deep geological settings best suited for EGS
- Identification of deep geological settings best suited for closed-loop systems
- Reduction of exploration costs by 10% for deep sedimentary/basement reservoirs, by increased chance of success of exploration drilling
- Demonstration of EGS and closed-loop systems

**Tentative Budget** 400 M€

- Methods and models for detecting sweet spots of matrix and fracture permeability and potential for EGS in different geological settings 20 M€
- Methods and models for the resource potential of closed loop systems 10 M€
- 4 Demonstration projects of EGS in different geological settings 220 M€
- 4 closed loop demonstration plants 150 M€

## TOPIC 6: CUTTING EDGE GEOTHERMAL RESOURCES

### Objective

Cutting edge resources entail the development of high enthalpy resources, including super-critical geothermal systems, and offshore magmatic resources

### Current status

Unconventional geothermal resources, such as super-hot geothermal systems (SHGS > 400°C), deep geopressured hot sources (>200°C) and offshore magmatic resources can significantly contribute to geothermal energy growth in the future. In order to develop these resources the major exploration objective is acquiring the ability to detect suitable reservoirs in terms of temperature, fluid bearing and permeable/drillable zones with acceptable fluid chemistry for production.

Challenges to the exploration of these resources can be most effectively addressed via international cooperation and liasing with (inter)national funding mechanisms for large-scale research infrastructure (i.e ICDP), which would lead to an optimal benefit of shared knowledge and access to costly natural laboratories. R&D for unconventional resources was performed in FP7 project IMAGE and in H2020 projects GEMex and DESCRAMBLE. These projects provided insights into coupled geological processes as well as performance under varying physical conditions and various rock and fluid geochemical compositions in the investigated areas.

### Potential for technological development

Technological development options include:

- Exploration methods for the roots of SHGS geothermal systems, as well as in-depth understanding of and predictive models for properties and processes beyond conventional temperatures. Developing theoretical and experimental methods to estimate the physical and mechanical properties of rocks near brittle/ductile conditions

- Exploration methods for detecting and predicting geo-pressurised systems
- Exploration methods and suitable well architectures for (magmatic) offshore. Enhanced drilling methods are presented in chaopter B.

### Target and KPIs

Development of exploration methods dedicated to different SHGS and deep geopressurized fluids (TRL 3-6)

Development of exploration methods dedicated to offshore resources (TRL 3-6)

Demonstration of exploration workflows and test drilling for SHGS and deep super-hot fluids, demonstrating >5MWe resources from a single well (TRL 6-9)

Conceptual Development and feasibility study for exploration of offshore resources (TRL 2-5)

**Tentative Budget** 150 M€

- Development and demonstration of exploration workflows for SHGS 70 M€
- Development and demonstration of exploration workflows for hot geo-pressurized system 70 M€
- Conceptual development and feasibility studiy for exploration of offshore resources 10 M€

## TOPIC 7: INNOVATIVE GEO-STRUCTURES

### Objective

“Thermoactive geo-structures” consist of the integration of geothermal heat exchangers into subsurface infrastructure elements that interface with the ground. Geo-structures such as energy piles, diaphragm walls, tunnels, and geosynthetic-reinforced retaining walls can utilise the ground for heating and cooling of structures, storage of heat, and the dissipation of waste heat. This is particularly attractive because of the inherent cost-saving involved in combining a required structural element with the harvesting of geothermal energy.

Similar to conventional geothermal heat exchangers, they can be used as pathways to extract heat in the winter and inject heat in the summer, albeit while taking advantage of the construction process, providing a sustainable approach to transfer thermal energy to and from the ground for a lower installation cost than traditional boreholetype geothermal heat exchangers. However, it also presents new challenges for the broader geotechnical engineering profession in terms of technical issues associated with soil-structure interaction, thermal effects on surrounding soils, as well as construction and organizational issues. Furthermore, the widespread application of this sustainable technology is currently hindered by the large heterogeneity in the development, designing methods and regulatory framework in European countries.

## Current status

Thermoactive geostructures are rapidly spreading all around Europe and are increasingly used for heating and cooling of buildings in urban environments. Within this context, two main platforms have to be highlighted: the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) that launched the Technical Committee TC308 on "Energy Geotechnics" and the European network of researchers and engineers interested in the challenges of thermoactive geostructures under the figure of a Cost Action (Action TU1405 – "European Network for Shallow Geothermal Energy Applications in Buildings and Infrastructures - GABI").

Based on multidisciplinary approaches dealing with geothermal energy such as energy efficiency, geological and geotechnical engineering, this heterogeneous group (active between 2015 and 2019) gathered professionals from 26 countries to ensure an inclusive and open platform for scientific discussion and sharing of knowledge and experiences with the aim of defining European best practice rules for geothermal applications, promotion public awareness and confidence in this technique, and fostering the advancement in knowledge through international collaboration especially in countries with less experience.

## Potential for technological development

- **Ground investigation methods** around thermoactive geo-structures and Energy Performance Assessment - One of the cornerstones to address is to search, analyse and compare all the ground and laboratory tests as well as the analytical, numerical and constitutive models existing for the valuation/modelling/forecasting of soil thermal properties. The main problems concern the scale effect (from micro to macro), the saturation conditions, the spatial scatter of soil properties and the sampling effects. This key action is the most interdisciplinary, as it requires consideration of the ground response, as well as all factors affecting the building/infrastructure energy performance. It is also of paramount importance to identify those scenarios where an optimal relation between the building's demands and ground capacities can be established, while also taking into account state of the art solutions and costs in order to facilitate the large-scale deployment of thermo-active geostructure.

- **Thermoactive structure design and performance assessment** - This deals with the development of design methods for thermoactive geostructures according to Eurocodes. Currently, no common design methodology exists to assess the performance of thermoactive geostructures. Three major points must be considered for the design of thermoactive geostructures: the thermal axial displacements (which can induce settlement or heave of the overlying structures), the complementary stresses in compression or tension (due to the constrained movements of the surrounding soil), and the shear stresses mobilized at the soil-structure interface (which control the mobilized resistance in the ground). Furthermore, this work requires the construction of a database of the different research tests performed on thermoactive geostructures and existing monitored installations. Benchmark studies should be conducted by using different national practices in order to identify the main calculation approaches compatible with Eurocodes.

### Target and KPIs

TRL from 6 to 9

Number of thermo-active geostructure installations, number of dissemination events, training courses, manuals, guidelines and best practices documents

Number of Standards in which active geo-structures are included

### Tentative Budget 100 M€

- Development of ground investigation methods for development, design and improve the regulatory framework in European countries.20 M€
- Demonstration of Thermoactive structure installations 80 M€

## TOPIC 8: TRANSFORMATION OF HYDROCARBON ASSETS

### Objective

Develop geothermal energy potential from abandoned or end of life time hydrocarbon reservoirs

### Current status

Many off- and onshore hydrocarbon installations are operational in the EU. The potential for co-produced resources (in the hydrocarbon field this might be producing hot water), or repurposing mature and closed/abandoned hydrocarbon wells have been investigated in only a few areas of Europe. Their abundance and technoeconomic relevance calls for further investigation. The reuse of oil and gas wells reduces uncertainty regarding profitability and allows sustainable solutions for large-scale development to be designed using conventional assets. Furthermore, the conversion of hydrocarbon fields into geothermal ones may be an opportunity to create a positive social response in areas where oil and gas wells are located.

The transformation of hydrocarbon assets touches upon various well construction technologies which are covered in part in chapter B.

### Potential for technological development

Technological development options include:

- Power generation from hydrocarbon producing wells. The past MEET project focused on high water cut wells in onshore oil producing projects. The technology can be further developed to harness geothermal power in existing oil and gas production facilities on and offshore

- Oil and gas reservoir lifetime can be extended by co-generation of geothermal energy production. Renewable synergy options are potentially possible by combining (dissolved) CO2 injection (from burning gas or oil in the produced brine), and gradually transition in a full geothermal field when the produced hydrocarbon energy content becomes minor compared to the geothermal energy produced.
- Abandoned oil (and possibly gas) fields can be (1) potentially be re-used for CO2-based geothermal power production or they can be used for high temperature heat storage in old oil reservoirs, as proposed by KIT in Karlsruhe, or (2) used to higher density thermal storage by adopting Phase Change Materials (PCM) suited for ambient reservoir conditions such as LPG. A potential advantage for refurbishment of existing reservoirs is that uncertainties regarding reservoir behaviour are limited as the reservoir properties are well constrained from past hydrocarbon production.
- Hydrocarbon exploration wells can be considered for geothermal energy production if there is no hydrocarbon found in the reservoir (i.e. they are "dry"), but the reservoir is sufficiently permeable. If a low permeability reservoir is encountered such wells can potentially be plugged at reservoir level and re-furbished for a Deep Borehole Heat Exchanger (DBHE) or be reused as vertical element for a more advanced Closed Loop (CL) system (see chapter B for technical considerations).

### Target and KPIs

- Identify resource potential for renewable energy production from producing oil and gas wells on and offshore. Inventorize and demonstrate technical and economic feasibility of template scenarios of power generation for different on and offshore settings and reservoir conditions, which will contribute to significant reduction of CO2 footprint of hydrocarbon energy production (TRL 6-9)
- Develop methods and resource development scenarios for geothermal co-energy production in and nearby existing hydrocarbon fields (TRL 5-7)
- Identify potential reservoirs for geothermal plume concept and demonstrate technical and economic feasibility (TRL 6-9)
- Develop and demonstrate technical and economic feasibility of high temperature heat/energy storage (with/without PCM) in abandoned hydrocarbon reservoirs, including the need for advanced well architectures to accommodate high flow rates. Identify resource potential for storage in abandoned hydrocarbon fields (TRL 3-7)
- Develop double play and DBHE and CL re-use approaches for dry and abandoned hydrocarbon wells (TRL 5-9)
- Inventory of geothermal resource base and best practice roadmap for transformation of hydrocarbon assets (TRL 5-7)

### Tentative Budget 100 M€

- Identify resource potential for transforming hydrocarbon assets to geothermal energy in Europe 10 M€
- Demonstrate transformation of hydrocarbon assets to geothermal energy, 5 applications 90 M€

# TOPIC 9: PLAY-BASED PORTFOLIO EXPLORATION FOR HEATING & COOLING

## Objective

Development and implementation of methodological frameworks for play based geothermal resource assessment for Heating & Cooling applications combining subsurface characterization and energy demand configuration in a portfolio approach and "source-to-sink" perspective.

## Current status

Integrating geothermal resource assessment to the evaluation of the distribution and configuration of the energy demand is crucial to accelerating the implementation of geothermal energy into the European energy system in particular for Heating & Cooling (H&C) applications.

H&C resources need to be located close to populated areas where H&C demand is concentrated, and need to be derisked and proven before district heat networks can be constructed or adapted to the geothermal resource.

A key challenge facing the geothermal industry is that most geothermal resources suitable for direct use and heat storage are largely unexplored in urban areas because the spatial mismatch with the proven geothermal resource base and urban areas often lack suitable subsurface data density (due to absence of past hydrocarbon exploration and production) as a starting point for derisking potential resources.

Consequently, in such underexplored areas exploration expenditures will be relatively high and a priori chance of success is low. Therefore a single asset focused development often leads to market failure as the potential financial benefits of a successful development of a single prospect will not trade off against the risks of high exploration expenditures (which cannot be recovered when the project is not successful).

Play-based portfolio approaches as developed in the hydrocarbon industry overcome this development barrier. The play-based portfolio concept builds from the notion that chance of success of a geothermal prospect is linked to a number of prospective geological factors that are spatially correlated in the socalled play (play refers to interlinked geological factors contributing to the chance of success; i.e. a high permeability due to certain depositional environment). Consequently, if the geological factor is proven in one prospect it will also de-risk the nearby prospects adding to the value of information (VOI) of drilling the first prospect. Using the portfolio approach the high exploration expenditure of the first prospect can be justified from the perspective of successful development of the whole portfolio instead of the single prospect.

## Potential for technological development

For geothermal energy the portfolio approach requires a spatial multi criteria play-based analysis, adopting state of the art decision and risk analysis methods developed in hydrocarbon industry. In addition, according to the geological settings, the methods need to be adapted to:

1. geothermal specific subsurface and surface constraints,

**2.** objective functions for favourable techno-economic and environmental performance, and depending the locations to produce geothermal resources according to the energy demand, and

**3.** be embedded in a dynamically evolving energy infrastructure and portfolio of (alternative) renewable energy sources and storage buffers.

A tooling framework for the portfolio approach can serve as a backbone for multi-scale decision-making for governments, local administrations, project developers and industry to identify opportunities and gaps and therefore plan the optimal development strategies.

The portfolio approach also accelerates the technological learning curve both for maximizing technical performance as well as environmental performance. Units cost for energy can be lowered as resources for technological development can be shared.

## Target and KPIs

Development of portfolio methodology and tooling framework for application in different geological settings of relevance for H&C (TRL 4-7)

Pilot and demonstration in different geological settings (TRL 6-9)

Key Performance Indicators:

- Portfolio play-based workflow and tooling framework effectively used by >20 regions
- In >10 regions, derisked geothermal resources for H&C and high temperature heat storage by 2030

## Tentative Budget 200 M€

- Develop a portfolio methodology and tooling framework for Play-based portfolio exploration application in different geological settings: 10 M€
- Demonstration projects of play based geothermal Heating & Cooling applications in different geological settings: 190 M€

# TOPIC 10: ASSESSING RESOURCE POTENTIAL

## Objective

Development and demonstration of innovative approaches aiming for a reliable estimate of geothermal resource potential before exploratory drilling and flow testing still require a **unified definition and harmonisation across Europe**. Such scientifically well-defined and harmonized approaches are needed not only for the site development and bankability of projects, but also for regional assessment of potential for the purpose of societal development policies and industrial play-based development. In order to achieve this goal, a reliable methodology and tools to perform resource assessment have to be developed in addition to communication and reporting protocols.

## Current status

Geothermal reporting codes have been developed in Canada and Australia for their specific stock exchange markets. Such codes lack the necessary element for the consistent comparison of geothermal resources with respect to other energy sectors. An internationally applicable scheme for the classification, reporting and management of energy and mineral resources was developed under the auspices of the United Nations Economic Commission (UNFC) for Europe initially for the petroleum and mining sectors before being expanded to include renewable energy sectors, including geothermal.

Although the UNFC takes into account economic, environmental and social aspects/risk management, this classification is essentially related to market aspects. **There is still a need for a comprehensive and common assessment and comparison framework serving as a foundation for a comprehensive overview of current and future energy sustainability scenarios at project, company, national, regional and/or global levels to be used by investors, regulators, governments and consumers.**

## Potential for technological development

Technological development options include:

- Defining best practices for quantification of geothermal reserves and (unconventional) resources, including the estimation of recovery factors and other critical performance parameters (economic, environmental and social), using demonstration sites and calibration with developed resources that cover the full spectrum of EU geological settings as well as resource use cases

- Public and transparent performance analysis tools for resource potential

- Developing methods and protocols for communication and documentation, including the mapping of geothermal reserves and resources as well as communicating the robustness of estimations (at different stages of the project) to stakeholders, for a variety of applications

### Target and KPIs

Development of harmonized methods for resource reporting for different geological settings in the EU, and extended resource use (i.e. heat pumps, storage) and advanced resource development perspectives (EGS, CL, DBHE, etc.) (TRL 5-9)

Public and transparent performance analysis tools for resource analysis reporting and used for resource potential in the EU

Reference protocols, case studies and documentation of best practice workflow

**Tentative Budget** 20 M€

- Develop a reliable methodology and tools to perform resource assessment:10 M€
- Define quantification of geothermal reserves and resources: 10 M€

*Innargi drilling site visit.* Source: EGEC Geothermal

# C. RESOURCE DEVELOPMENT: DRILLING AND SUBSURFACE ENGINEERING

A large part of the costs of geothermal projects are related to drilling and subsurface engineering. Moreover, most related expenditures occur during the early life of a project, and even before productivity is confirmed in the case of exploration works. Cost reduction and performance improvement as well as novel production concepts related to design and subsurface engineering of production/injection wells (which are tightly linked) are critical for business plans when it comes to consider drilling. Adapted upstream investments, whether in the choice of equipment, techniques or specific designs, might result in optimized operations and a substantial reduction in costs in the long term.

Topics 1-6 deal with with enhanced technologies for drilling and completion of wells.

**1.** Towards robot and AI assisted drilling technologies

**2.** Optimized penetration rate technologies

**3.** Drilling fluids

**4.** Materials for casing, cementing and completion

**5.** Monitoring, Logging While Drilling and geosteering

**6.** High temperature electronics

Topics 7-10 deal with enhanced design and subsurface engineering, improving productivity of wells.


*Innargi drilling site visit*. Source: EGEC Geothermal

**7.** Well architectures and stimulation

**8.** Shallow Closed Loop technology (<500m)

**9.** Deep Closed Loop technologies (>500m)

**10.** Enhanced production pumps

# TOPIC 1: TOWARDS ROBOT AND AI ASSISTED DRILLING TECHNOLOGIES

## Objective

To develop and test robot-assisted and AI-asssited drilling and casing-setting technologies which

- **reduce lost time** due to wellbore collapses or lost-in-hole accidents, typically occurring in unknown, poorly predicted or harsh geological reservoir settings.
- **consider technologies** which have to be **as simple as possible** and to be based on properly defined, yet limited, and well controlled sets of geoscience information to **ensure a reliable implementation of automation.**
- ensure **HSE, well integrity and adaptation to specific geothermal environments** (temperature, pressure and rock characteristics.

In addition, the **standardization** of drilling equipment and operational workflows is also seen as an important driver for reliability and economic performance, alongside adapted and optimized **design studies** and **work**.

## Current status

Nowadays, robot-assisted drilling and casing setting lies on a trend which is clearly observed in the Oil & Gas industry to support and possibly replace human-controlled operations and maintenance roles:

- **Drilling**: including borehole stability, setup and management of the bottom hole assembly, definition of operating parameters and implementation of the associated feedback loop, etc.
- **Casing setting** which can be envisaged with integrated and time saving, yet challenging, "casing drilling" solutions.

It is also seen as a way of technical and performance improvement, and a key factor in technical as well as health, safety and environment risk reduction through process automation.

Robot drilling relies on the data fetched from the borehole and surface installations, specifically on the **ability to collect this data and get most of the value of the subsurface information**. To this extent, there is a clear interest to work on **technology transfers from the mining and exploration industries.** These have put a lot of efforts into developing new downhole sensors, data transfer techniques up to the surface, as well as data analysis and interpretation to feed the action loop on operations in real time. Major service companies are even currently working on fully and unmanned automated processes.
It is important to consider that if **cross-discipline collaboration is necessary**, it also needs to be complemented by specific solutions adapted to the geothermal industry:

- **From an economic point of view:** many tools developed by the oil & gas industry cannot realistically meet budget constraints.
- **From a technical point of view:** geological settings, such as volcanic or basement fractured reservoirs, are considered as highly "unconventional" compared to sedimentary clastic or carbonate hydrocarbon prospects. Rocks involved are different, and many pieces of equipment (mechanical or electronic) are still not designed to operate with temperatures above 175-200°C.

## Potential for technological development

Themes to be studied can be gathered and listed in a few (but non-exhaustive) categories, benefitting from the results of the work performed on other topics presented in this document:

- **Focus on cheap and with "as less geoscience information" options as possible.** The idea is not to look specifically at "low cost" or "low tech" solutions, but to keep them direct and simple to allow a robust and cost-effective implementation in harsh environments. In high-risk areas **slim-hole and deviated wells** can also be good approaches to maximize data collection and reduce exploration costs. **Standardization of equipment and workflows** plays an important role here.
- **Focus on key drivers for automation** such as monitoring, data analysis, AI-driven algorithms definition and programming, including hardware and software development, as well as workflows design and testing
- **Optimize the rate of penetration (ROP)** (cf. topic 2) **and apply less force on the drilling bit**. This deals with the monitoring of pertinent drilling parameters, aiming at real-time adjustment to set an adapted feedback loop on the bottom hole assembly (including the analysis of vibrations, for example). It also deals with tool design and rock mechanics.
- **Continue efforts on technology transfers from the oil & gas and mining industries** (e.g., logging while drilling). This is a key integration subject, requiring wise adaptation and testing in the field.

All this might lead to **think about drilling a different way** and optimize operational processes.

## Target and KPIs

Reduce drilling cost by up to 10%, through enhanced Rate of Penetration (ROP) , reduction in tripping time, whilst contributing to enhanced safety and reduced energy consumption

## Tentative Budget50M€

- Progress in robot and AI assisted drilling technologies: 20 M€
- Test robot-assisted drilling: 30 M€

## TOPIC 2: OPTIMIZED PENETRATION RATE TECHNOLOGIES

### Objective

The aim is to develop and test novel (combination of existing) drilling and associated engineering and model technologies for optmized Rates Of Penetration (ROP). Optimized means smooth, where maximizing ROP should not come at the expense of the quality of the borehole and the data acquired while drilling or later (e.g., testing), and production.

### Current status

Drilling is all about developing efficient and safe ways to break rocks and create mechanically stable boreholes in an energy and cost-effective way (both notions being tightly linked). The question of cost is a key driver in the geothermal industry, where business models can be fragile and budgets limited, especially regarding deep and complex reservoirs. Time is money and drilling fast is a key. Yet maximizing rates of penetration should not come at the expense of the quality of the borehole and the data acquired while drilling or later (e.g., testing), not to mention the production. “Optimizing” ROP should therefore not be read as “fast”, but as “smooth, safe and efficient”.

**Understanding the nature of the drilled rock** is key as it often (but not always) dependent on interpretation and prediction. The **adapted tools** (drill bits) and methods are selected accordingly. **Real-time monitoring**, through logging while drilling and the follow-up of drilling parameters, is of primary importance (cf. topic 1).

**Rotary is currently the main drilling method used** by far. Nevertheless, many alternative methods have been imagined and tested, considering the high impact on projects no matter the geological setting. **Hammer drilling**, for example, has been widely used in the mining and geotechnical sectors for a long time. On the other hand, a wide range of new approaches are studied, often at R&D stage, such as flame-jet and electric discharge drilling.

Several industrial techniques are developed and implemented at various levels of technical readiness. The following, among others, can be listed:

- **Downhole fluid hammer** (high power, mud-driven percussion drilling) with pre-commercial tools, designed for hard rocks, and tested on the field.
- **High pressure hydraulics drilling** also successfully tested
- **Wireline drilling** developed alongside robot-drilling (real-time management of drilling parameters; cf. topic 1).
- **Unconventional tools** such as laser or plasma drill bits; also considering R&D on nano-composite materials

Innovation can also derive from a combination of these different methods with considerations on the materials used to design the bits and the drilling string components.

## Potential for technological development

The way forward will be set through, among others, the following main subjects:

- **Development of engineering algorithms and models for real time ROP optimization** (autonomous analysis of drilling data, which can pave the way towards complete automation)
- **Development of new drilling technologies** optimized through the integration of inputs from geology (combined mechanical and non-mechanical rock breaking processes), as already presented in the previous version of the SRIA. In particular, some focus areas are suggested:
  - Integrated mechanical drilling action combined with jet drilling.
  - Enhanced diamond semi-round top inserts to be utilized on hammer bits. The recent development of fluid hammer technologies can also extend the range of geothermal applications where percussive drilling is feasible.
  - Cutting elements tailored to volcanic and intrusive rock drilling.
- **Design and test of adequate bottom hole assemblies**, in particular to manage vibration issues (also to be monitored)
- **Strong focus on geology and rock mechanics** during the modelling and design phases, but also as part of the feedback loop during operations.
- **Development of MPD systems** (managed pressure drilling): such systems allow to adjust the hydrostatic pressure of the fluid column in real time to balance the formation pressure.
- **Strong focus on the quality, cleanliness and stability of the borehole** as ROP is not the only subject and going fast is not the only bottleneck when it comes to consider the aim of a well (among others: getting data, set a good and enduring completion, remain mechanically stable along production time…)
- **Benchmarking** on new drilling technologies and therefore a driver for the R&D.

The ultimate goals remain to **save energy and time**, to **extend the life of equipment** (and therefore money) all while **ensuring good data collection**.

## Target and KPIs

Reduce drilling cost by up to 10%, through optimized Rate of Penetration (ROP), safety and energy consumption improvement

## Tentative Budget 100 M€

- Development of new drilling technologies: 30 M€
- Test new drilling technologies: 70 M€

## TOPIC 3: DRILLING FLUIDS

### Objective

The aim is to develop and test drilling fluids with enhanced **cooling ability, controlled behaviour in harsh environmental conditions** (pressure, temperature and reservoir fluid chemistry), **physical and chemical stability** through variations between surface and downhole conditions, and **compatibility with the drilling solution**.

In addition the developments aim at using **environmentally friendly products**. The goal is to design and provide a range of drilling fluids to accommodate needs for a given type of well, in a given geological context, respecting growing ecological constraints. To this extent, **technical compromises** have to be studied to mitigate the impacts on performance.

### Current status

Drilling is an intrusive operation which can raise public concerns, especially when it comes to district heating in densely populated areas. One of the identified issues and key risks that comes up regularly for instance is the pollution of freshwater aquifers in France and the Netherlands. Working on non-polluting drilling fluids makes sense when it comes to **gaining social acceptance** and limiting of pollution risks that could jeopardize future projects.

Additives are used to enhance thermal and rheological properties. Some traditional ones for water-based muds are bentonite, xanthan gum, starch, synthetic polymers, copolymer and tetra-polymers.

Depending on needs, other products such as gases or nanoparticles can be used depending on density and rheology requirements. Playing with phase change (from solid to liquid or liquid to gas) is less conventional but can be used to enhance cooling.

**The use of "green" additives is more or less limited to vegetal natural debris, fibres or floor** to accommodate mud losses and plugging needs, though R&D is starting to tackle the subject from a chemical point of view.

### Potential for technological development

Working on "eco-friendly" fluids and additives with enhanced and dedicated properties requires close collaboration with industrial providers and service companies. It also implies to involve R&D institutions on specific, related topics (for instance nanomaterials and polymers, as well as associated physics or chemistry).

Trends to push forward could be the following:

- **Moving to "green" components** in drilling fluids is needed for a better acceptability from administrative and water authorities (link to chapter D). It might become a strong constraint in the near future. For example, the **cementing industry is moving to new cementitious materials** that eliminate the release of large CO2 volumes into the atmosphere. Such materials will need to be adapted, and proven to be safe and efficient for applications in geothermal wells in order to replace currently used portland and calcium-aluminate cements.

- **Designing new fluids** that remain stable under high temperatures, high pressures and aggressive chemical settings
- **Designing new coating technologies** that, with advanced (HP/HT) materials, could help to decrease scaling, corrosion, friction and improve casing stress resistance and coupling with cement, which would result in an extended life of the casing and/or tubings of the well.
- **Making fluids reusable** which encompasses solutions to develop and improve the expensive processing of the solid fractions (cuttings)
- **Making fluids also friendly for the well and drilling pieces of equipment** that protects them against corrosion from highly mineralized geothermal waters or acid gases, and also potentially improving drilling performance
- **Improvement of mud losses control**: to this extent, it may also be interesting to consider new cost-effective cementing materials in cases where problems of losses were not resolved while drilling and/or happened during cementing operations.
- **Evaluation of underground formations where wells could be completed without cementing** may be very beneficial. The experience of creeping formations that provide excellent zonal isolation without well cementing exists in Norway, for example, but also applies to sedimentary rocks with high unconfined compressive strength (UCS). With sufficient knowledge of the underground environments, they could be adapted on a wider scale.
- **Normalization and standardization of products** dedicated to the geothermal industry, also to differentiate from oil & gas from a communication point of view (link to WG7 - circularity and sustainability). This point could be difficult to cope with depending on the various regulations of European countries.

Resulting products will have to be tested through **implementation on pilot projects**.

**Keeping solutions as cost-effective as possible** remains a key concern.

## Target and KPIs

Development of eco-friendly drilling fluids that reduce up to 5% costs of drilling and completion, by reduction of tripping time and ROP, that are stable under high-temperature and high-pressure conditions and that effectively protect drilling equipment against corrosion (TRL 4 – 5 by 2024, TRL 6 – 7 by 2026, TRL 8 – 9 by 2030)

## Tentative Budget50 M€:

- Develop “eco-friendly” fluids and additives with enhanced and dedicated properties: 15 M€
- Testing through implementation on pilot projects: 35 M€

# TOPIC 4: MATERIALS FOR CASING, CEMENTING AND COMPLETION

## Objective

The materials subject is not limited to the alloys used for tubulars or downhole equipment. It also has to cover cements, couplings and joints, and more generally the way assemblies are impacted by heat, pressure and corrosion. The ultimate goal is to preserve well integrity—in other words **improve the resistance to wear and mechanical failures** over the production lifetime.

The tracks to follow are:

- **Identification of high-performance and cost-effective materials** regarding both drilling and casing phases, with adapted resistance to corrosion.
- **Ways to set casings and ensure proper coupling to the formation** (i.e., cementing), whatever the geological and fluid chemistry environments, optimizing heat transfer and resistance to stress and strain. Casing and cementing issues are especially important for hot-EGS and superhot systems. In this domain, flexible couplings should also allow axial movements of casing strings.
- **Development of standards** to ensure the integrity of geothermal wells.

On the other hand, **controlling scaling and corrosion**, which means improving the lifetime and efficiency of installations (wells and production facilities) also has a strong impact on **economic** (workovers and energy consumption) and **environmental** (pollution) **performance of projects.**

## Current status

A recent survey by the Dutch Mining Ministry showed that basic wells tend to age quickly, especially in salty environments. A lot of technical solutions, mostly developed for oil & gas, are available to tackle corrosion and scaling issues: special cements, chromium or corrosion-resistant alloy grades, glass-reinforced epoxy liners... They are however considered too expensive for the geothermal industry. If stainless steel casing types and nickel alloys have promising resistance against corrosion from hot highly mineralized fluids, they cannot be considered as ultimate solutions through time. **The application of protective coatings has to be considered as an alternative** to be more deeply studied.

Scaling is studied both through:

- **Modelling aspects** regarding the characteristics of reservoir fluids but also the way they impact materials
- **Monitoring** performed at various points of the well and surface installations, allowing to properly plan maintenance actions

**Cement materials** have been studied and tested in order to tackle both heat transfer and lifetime issues, but **the technical readiness level remains low, and standards have must be set**.

## Potential for technological development

All paths considered are oriented towards t**echnical performance** and **cost reduction** in an **environmentally friendly way**:

- From a technical and scientific point of view, **works on corrosion-resistant materials and couplings remain essential**. Complementary solutions such as **cladding**, which might be efficient and cost effective, have to be pushed forward.
- **The cost of state-of-the-art materials or technologies** inherited from the oil & gas industry should be assessed over the full life of assets. The benefit of such upstream investments has to be considered on the long term. More generally, **cost versus lifetime should be studied and benchmarked**, as cost should not be envisaged as a bottleneck. This is related to the way projects are considered and financed (upfront CAPEX)
- **A strong focus has to be set on new completion designs**, which should also take into account technically and economically efficient ways to restore wells. In particularly harsh subsurface environments, replacing critical components of a completion might be unavoidable whatever the materials used. **Optimizing workovers is therefore a topic of prime interest.**
- A new set of standards with novel standards for diameter of the casing can encourage the development of more efficient, cost-effective and environmental benign well design.
- In the same order of ideas, "Double casing" or "double skin" architectures in front of sensitive aquifers are now more and more a standard. This emphasizes on the **relation between adapted materials and well design considerations**.
- Regarding scaling and corrosion, **the use of inhibitors, and chemicals for cleaning opens to environmental issues** (pollution risk) and alternatives to existing products have to be proposed. **Monitoring** also requires efforts both from **data acquisition** (wireline logging tools, also inherited and adapted from the oil & gas industry) and **modelling**.

## Target and KPIs

Development of effective and environmentally benign measures and chemicals to prevent and control scaling and **corrosion** (TRL 6 – 8 by 2024, TRL 9 by 2026)

Development of safe and environmentally benign measures to remove scaling (TRL 6 – 7 by 2024, TRL 8 – 9 by 2026)

Development of materials, including casing couplings and cements, to improve overall heat transfer and guarantee integrity and resistance to fatigue over the well's lifetime under the challenging conditions encountered in geothermal applications. Timeline:

- development and laboratory testing during the period 2020 – 2023 (TRL 5 – 6)
- testing under realistic conditions and in the field during the period 2023 – 2026 (TRL 7 – 8)
- application in one or two demonstration projects by 2030 (TRL 8 – 9)

**Tentative Budget** 150 M€:

- development and laboratory testing during the period 2020 – 2023 (TRL 5 – 6): 30 M€
- testing under realistic conditions and in the field during the period 2023 – 2026 (TRL 7 – 8): 40 M€
- application in one or two demonstration projects by 2030 (TRL 8 – 9): 80 M€

## TOPIC 5: MONITORING, LOGGING WHILE DRILLING AND GEOSTEERING

### Objective

Two key goals have to be achieved through **subsurface data acquisition**:

- Properly **characterize the drilled geological section and the reservoir**.
- **Acquire, process and use data in real-time** to optimize drilling (see also topic 1).

Challenges to tackle are:

- **Defining key data to be monitored and information to be acquired to drive drilling parame**ters and to support planning as well as decision making. This goes through improved and innovative downhole recording and communication
- **Setting new technological systems allowing changes in operating conditions** to be anticipated within a relevant timeframe. Traditional technologies for the monitoring of drilling and testing operations, as well as production, need to be adapted to the **hostile downhole conditions encountered in high-temperature geothermal wells**.
- **"Looking ahead" of the bit with the development of tools and workflows** allowing rig operators to integrate formation evaluation, anticipation of overpressures and bottom hole temperatures, as well as risk prediction… Moreover, the possibility of providing 2D and 3D imaging of the formations around and ahead of the bit will provide precious important information about the characteristics of the geothermal reservoir (lithology, fault and fractures).

Again, the role of **technology transfer** from the mining and oil & gas industries will play an important role.

### Current status

**Oil & gas service companies are now turning towards geothermal** with a full range of high technology tools (which can be used in data acquisition workflows) still need to be adapted. This starts with geological environments which are quite different from the conventional sedimentary reservoirs explored and produced by the oil & gas industry. In this frame, costs remain a key point of consideration.

Single well imaging techniques, including seismic sources and receivers close to or included in the bottom hole assembly are an important way of progress. These techniques have already been tested but require further development. Other innovative imaging techniques include seismic while drilling (SWD), cross-well SWD and vertical seismic profiles while drilling (VPSWD), but also non-seismic techniques (i.e. resistivity or logging while drilling). Generally speaking, **solutions related to well seismicity offer a variety of technically sound solutions for the imaging and characterization of formations** both from a petrophysical and mechanical point of view from the close neighbouring of the field up to tens of feet at reasonable cost.

## Potential for technological development

**Technological developments are needed** to guarantee effective measurement and logging while drilling in high temperature geothermal wells, but also improved analysis of reservoirs while drilling (i.e. based on analysis of drilling fluid and well cuttings), and in challenging surface and geological settings (i.e. densely populated areas, mountain regions, areas where shallow geology disturbs wave propagation, deep crystalline rock or melting zones reservoir settings…).

These include:

- **Tools operating in harsh conditions** (high temperatures, high pressures, aggressive reservoir fluids, in highly deviated or horizontal wells).
- **Tools set on the drilling string and near the bit**, including for SWD
- **Improvement of reservoir imaging** by performing lithological, petrophysical and mechanical rock characterization close to the target with as high resolution data as possible
- **Analysis of reservoir heterogeneities**, borehole waves and reverberations, also linked to the mechanical properties of the drilling system
- **Implementation and improvement of deviation follow up** thanks to real time data processing and interpretation, as well as related, optimized workflows
- **Enhancement or development of new technologies for data transfer** towards the surface (i.e mud pulse, electro-magnetic methods, acoustic drill pipe…)
- **Surface-synchronized down-hole memory recorders** which can afterwards be synchronized with surface system data following tool retrieval

## Target and KPIs

Among others, improve imaging through better resolution of SWD in different geological settings, reduce noise in the drill string (torque absorption and coupling)…

## Tentative Budget 50 M€ :

- Technological developments for logging while drilling in high temperature geothermal wells, and in challenging surface and geological settings

## TOPIC 6: HIGH TEMPERATURE ELECTRONICS

### Objective

Electronics and (more generally) sensors, have to resist to the extreme environmental conditions encountered in geothermal wells. But more specifically, the impact of temperature, pressure or aggressive fluids might result in damageable and costly loss of information, whether it is not recorded or biased. Materials need to resist through time, on the longest possible term; **sensors need to work and remain reliable whenever needed and for the duration of the required operations.**

The main goal is therefore to **enhance and develop electronics and sensors** to be used downhole, for measurement while drilling (MWD), logging while drilling (LWD) and testing.

Beyond the devices themselves, **improved cooling solutions based on the circulation of mud** can be developed for tools that are used during drilling operations.

### Current status

As already mentioned, **oil & gas tools are more and more adopted by the geothermal industry**. Most sensors and logging tools are limited to 175°C with new generations now operating up to 200°C. **There are actually very few tools which can monitor and support the optimization of the drill string or drilling parameters in real time at higher temperatures.**

Projects such as DESCRAMBLE (Tuscany, Italy) showed that a range of tools could be designed to record and provide data at temperatures above 450°C. Yet such tools still show low technical readiness levels (ability to be used routinely by the industry) and strong efforts have to be put on MWD and LWD devices (see also previous topic 2.5).

Issues that need to be tackled and directly depend on the **development and increased reliability of sensors** include:

- Limited knowledge of **predictive models of BHA performance** at high temperature
- Limited number of tools available for **well logging and in high temperature wells**
- Few real time **downhole monitoring tools** during injection and production along the production string and in the reservoir
- Little knowledge of **intelligent completion hardware, software and devices** (i.e. inflow devices, production logging and monitoring…)

### Potential for technological development

Considering the needs expressed above regarding deep geothermal wells, and particularly in support to monitoring, MWD, LWD and geosteering (topic 5), future technological developments might cover:

- **High-temperature electronic components** which can withstand temperatures up to and above 350°C, also considering **communication line**s, that benefit from new technologies such as **fibre optics**

- **Improved heat shields** (e.g. Dewars) and **improved cooling techniques** for electronics and sensors, allowing the use of standard electronics.
- **Development of new and potentially “lower tech” devices** with less (or simpler) electronics and more based on robust mechanical principles.

### Target and KPIs

Develop electronics and sensors that can withstand temperatures up to 350°C by 2030

### Tentative Budget 100 M€:

- Develop High-temperature electronic components,
- Improve heat shields (e.g. Dewars) and improve cooling techniques for electronics and sensors, allowing the use of standard electronics.
- Development of new and potentially “lower tech” devices with less (or simpler) electronics and more based on robust mechanical principles.

## TOPIC 7: WELL ARCHITECTURES AND STIMULATION

### Objective

The main goal is to **enhance the productivity of low permeability rocks in order to increase energy extraction**.

Technologies based on production stimulation, usually referred to as Enhanced Geothermal Systems, still face numerous hurdles and two main paths have to be investigated:

- **Hydraulic stimulation**: used to enhance permeability, still requires an advanced injection strategy in order to control fracture propagation and simultaneously **reduce the risks of unwanted seismic events** below a given threshold that reflects the vulnerability and exposure of people, buildings and infrastructure. In this context, **social acceptability** is a fundamental and rising parameter to properly take into account.
- **Chemical (or thermal) treatments** may be a viable alternative and provide sufficient improvement in well productivity and injectivity depending on the geological context. In case of relatively high permeabilities, they help in the clean-up of drilling-induced damage in the matrix or natural fracture networks to restore permeability and reduce skin. **Environmental issues are also a key** in the development of such solutions.
- Alternatively, **new heat extraction solutions** could be developed. They would not require the enhancement or creation of fracture networks, but rather rely entirely on fluids circulating within boreholes (closed loop solutions).

## Current status

**Enhanced Geothermal Systems** (EGS) are engineered reservoirs developed to extract economical amounts of heat from geothermal resources with low porosity and permeability. These systems can be exploited by enhancing reservoir conditions or advanced by creating an "underground heat exchanger" using drilling techniques only.

The main fields of study and experimentation are the following:

- **Well architectures** can considerably enhance the contact area of wells with flow zones in geothermal reservoirs, and consequently increase productivity (and injectivity) in geothermal reservoirs: technologies include extended well bore contact areas by sub-horizontal and multilateral well designs, as well as radial jetting, laser based techniques and shot drilling enlarging contact with fractures or flow zones by smaller radius wells.
- **Stimulation techniques**: promoting hydro-shearing, to enhance connection to existing fracture networks, or enhancing poor matrix permeability. The mechanical approach can be optimized through various techniques including flow rate control or radial water jet drilling, possibly combined with thermal fracturing (injection of cold water) and chemical treatments. In some cases, **propping agents** may be used to keep the natural fracture network open and to maintain higher conductivity achieved through hydraulic stimulation.
- **Ensuring the sustainability of fracture opening** with respect to unwanted effects like induced seismicity and hence reducing the probability of perceived events. This goes through a better understanding of the geological model (structural geology, stress field analysis…). Adapted well deviation designs, including horizontal sections in the reservoir, allow to maximize the number of intersections with conductive fracture networks, fault corridors and/or sedimentary permeable zones in the geothermal reservoir.
- **Use of 3D numerical models** in order to improve the geological and mechanical knowledge of the reservoir, also aiming at reducing the number of hydraulic stimulation operations (including the use of chemical products) that are more and more questionable **in a context where environmental awareness is growing**. Fracture network simulation (including coupling with thermal, hydraulic, mechanical and chemical effects) can help to predict complex fault and fracture growth, as well as potential induced seismicity.

## Potential for technological development

Technology for hydraulic stimulation certainly requires further R&D and development, yet environment considerations clearly move the focus on alternative and complementary solutions:

- **Enhance drilling and completion techniques for advanced well architectures (e.g. radial jet drilling, shot drilling, horizontals, multilaterals)** to enhance the productivity and injectivity of marginal reservoirs, fault zones and fracture networks
- Enhance predictive numerical **simulation and optimization workflows for location and stimulation strategies and optimization of trajectories** prediction (linked to resource assessment topics integrating relevant **geological, geophysical, geomechanical and thermal modelling techniques)** targeted at best possible technical (sustainable flow rate) and environmental performance (i.e. induced seismicity)

- In addition, lab and field tests are needed to **evaluate the viability of "fully drilled" heat extraction concepts** to calibrate and refine the numerical models.
- Based on a better knowledge of the subsurface, **optimize well stimulation through adapted and combined methods** with workflow and operational designs specific to a given geothermal prospect.
- Within the range of available solutions, **"greener" products** have to be further developed and tested as potential alternatives to traditional chemical treatments.

### Target and KPIs

Well design and completion concepts optimized for different geological settings

First field and lab pilots and then with validation during demonstration

### Tentative Budget 100 M€:

- Develop well design and completion concepts optimized for different geological settings: 20 M€
- Test in field and lab pilots: 30 M€
- Demonstration projects: 50 M€

## TOPIC 8: SHALLOW CLOSED LOOP TECHNOLOGY (<500M)

### Objective

Continuing previous research (despite improvements due to research) there is still room for improvements in several areas. Much can be expected from further reducing manual work in drilling and installation through automation and robotics. R&D in specific shallow geothermal drilling technology is also required to further reduce the impact on the surroundings (e.g. sensitive clays, groundwater), to provide techniques to control borehole deviation, etc.

The efficiency of heat exchange with the geological strata can be increased by R&D for optimisation of components such as borehole heat exchangers (design, pipe material, grouting material), well completion materials, compressors and pumps. One more concern is about the identification/development of an environmentally benign, low viscosity antifreeze ("thermal transfer fluid") fluid for closed loop geothermal HP systems in order to have thermal characteristics that are equal to, or better than, mono-ethylene glycol.

## Current status

In the past years, several R&D projects have dealt with the production of improved piping materials (GEOCOND), optimised drilling solutions (CHEAPs, GEOTECH) and other issues of concern. Progress has been made also in the formulation of grouting with optimised features in terms of pumping stability and the inclusion of Shape Stable PCM additives to enhance the capacity of the system to capture heat. Another interesting area of research is the robotization and automatisation of the drilling process. Nowadays it is still a cumbersome operation and one of the key factors for the high relative cost of the technology.

Though the machine and drilling technology has improved with the inclusion of concepts such as the coaxialpenetrometer developed in CHEAPs, the automatization of the process  enhance safety and reduce labour costs has not yet been in the focus. This promising line of research must be continued to bring these concepts into close to market conditions.

Plastic materials with very interesting properties could also be deployed in higher temperature and deeper borehole ambient, allowing a substantial cost reduction for the operation. Even higher thermal conductivities could be reached with the inclusion of nano-additives. PCM materials together with grouting can have also a range of applications (also in the domain of District Heating Systems), but an upscale of current experiences is necessary.

## Potential for technological development

1. **Enhanced plastic piping materials for BHEs in shallow and deeper shallow applications:** The outcomes of projects like GEOCOND, CHEAP-GSHP or GEOTECH have shown the potential of improvements in critical aspects of geothermal HP technologies and materials. New plastic materials for larger depth applications or including additional features, like data transmission and monitoring. Advanced grouting concepts to enhance the surrounding soil or improved grouting mixtures can still offer a range of improvement in terms of system efficiency & ease of installation.
2. **Development of fully robotized/automatized drilling solutions for shallow and deeper borehole applications.** Drilling is still a major cost and safety factor and safety. Robotization and the use of AI driven drilling systems could enhance speed, safety and cost of operation substantially.
3. **Development of very shallow closed loop geothermal HP systems**: In many suburban or rural settings there are less spatial restrictions on the installation of closed loop systems. In combination with the development of more energy efficient housing with an increased annual energy balance between heating and cooling, shallow closed loop systems (indicative interval between 5-50m depth) are of interest. These systems can stand-alone or become integrated in to a district system, preferably with a strategy for optimisation and communication with the required electrical input used for running the systems. Shallow systems will allow local contractors to move into the shallow geothermal market without the risk of drilling to greater depth (failure, environmental, investment, etc.)
4. **Improved and eco-friendly antifreeze**: The objective is to produce with long-term stability at least as good as mono-ethylene glycol, and preferably derived from a sustainable source. Such antifreeze could contribute to system efficiency by reducing power demand of circulation pumps, and to acceptance with authorities by imposing no threat to the groundwater.

### Target and KPIs

TRL from 5 to 9

Reduction in the unit cost of drilling (€/MWh), % improvement of overall conversion efficiency of geothermal

installations at different thermodynamic conditions, % reduction of production costs of geothermal energy (€ct/ kWhth), decrease (%) of number of boreholes per kW energy produced, % reduction in time for the competition of a standard borehole of 100m, % increase in the thermal capacity of a unit volume of grout with PCM.

**Tentative Budget** 100 M€:

- Improve materials and equipments: 25 M€
- Development and denonstration of a fully robotized/automatized drilling solutions: 35 M€
- Development and demonstration very shallow closed loop geothermal HP systems: 40 M€ (2-3 sites)

## TOPIC 9: DEEP CLOSED LOOP TECHNOLOGIES (>500M)

### Objective

To develop technologies for heat extraction solutions (including design and material considerations, drilling and completion technologies and working fluids) that rely entirely upon fluids circulating within deep boreholes. These closed-loop solutions primarily aim to extract heat through heat conduction at the borehole-rock interface. These technologies allow unlocking of vast geothermal resources that are stored in impermeable deeply buried, compact sediments and hot crystalline rock which otherwise remain largely unexploited. The technology can also bring solutions for non-productive geothermal wells or repurposing oil & gas wells.

### Current status

Over the last decade, a number of concepts for (semi-)closed loop geothermal systems have emerged. Concepts range from deep (500-1500m) geothermal heat pump (GHP) for district heating, and to extract heat from deeper so that the output temperature is high enough for direct district heating & cooling, industrial applications or electricity production

Based on the layout and the contact between the working fluid and the rock, the concepts can be divided in four categories: closed single well systems (deep borehole heat exchanger or DBHE), fully closed U-shaped systems, (semi-)open single well systems and closed multilateral well systems.

If these can be successfully developed, they should meet the ambition of minimal environmental standards and are marked by very long lifetimes. As these systems mainly depend on conductive heat transport, a minimal thermal output can be calculated from the system design and the thermal and mechanical characteristics of the targeted formation. This reduces the technical and financial risks. On the other hand the heat production per meter of "well bore" drilled is significantly lower than open systems (up to one order).

The concepts are at different TRL levels. DBHEs are being used as a source for district heating at a few locations. The thermal output strongly depends on the design and completion of the well. In case of an existing well, the design and completion may not be optimal, but the lower energetic performance may be compensated by lower investment costs. A recent review of existing DBHEs and modelling results learns that in most cases, closed single well systems are currently not profitable in case a new well needs to be drilled. The (semi-)open single well system is being used as low temperature heat source in combination with heat pumps at a few locations in Switzerland. The closed, U-shaped system is currently being tested at Rocky Mountain House in Alberta, Canada. New concepts of drilling and completing long (semi-)horizontal wells and wand small diameter laterals are being developed and tested by several companies.

## Potential for technological development

Major frontiers for innovation are:

A. Enabling to construct deepened GHP at low costs
B. Low cost drilling technologies for impermeable deep reservoirs, and high temperature targets
C. Well and heat exchanger designs and materials adapted for specific conditions to improve performance or reduce costs
D. Developing new ground coupling materials and concepts

To tackle these challenges, the development of (semi-)closed systems request further R&D and the demonstration of new technologies for:

- Further development of underground heat exchanger concepts in geothermal systems to reduce their material and/or installation/operating costs
- Development of cost-efficient solutions to increase the conductivity and thermal capacity of the underground in the vicinity of borehole heat exchangers with environmentally acceptable and stable solutions
- Improve our understanding of the thermal and mechanical properties of rock under varying thermal regimes
- Develop tools to predict the mechanical behavior of rocks and the stability of excavated structures under different geological regimes
- Develop predictive models to evaluate heat flow towards (semi-)closed heat extraction systems at large depths
- Perform laboratory and in-situ testing of different working fluids to optimize the performance of (semi-) closed loop geothermal systems
- Develop and enhance (unpumped) convective circulation in closed-loop systems to take advantage of the different temperatures of the system fluids and eliminate the need for a circulation pump
- Optimisation of heat transfer and pressure drop in the closed heat extraction system
- Perform conceptual design and field-testing and demonstrate (semi-)closed heat extraction systems.

### Target and KPIs

By 2025: Demonstration of published concepts of (semi-)closed loop systems under different geological conditions with focus on verification of long-term energetic performance and system optimization (TRL 5-6)

By 2030: Demonstration of (semi-)closed loop systems as a reliable heat source for geothermal applications (e.g., geothermal (micro-)district heating, industrial heat, HT-heat pump) (TRL 7-8)

To allow market uptake the cost of energy produced should be reduced. Under most conditions, the cost of heat produced by (semi-)closed loop systems is above 6.5 €ct/kWh. The targets and KPI are set to make the systems competitive with other renewable heating technologies.

- Demonstrate the technical and economic feasibility of geothermal heating using (semi-)closed loop systems by 2025
- Ensure a production cost of 6 €ct/kWh for heat by 2025 and less than 5 €ct/kWh by 2030
- Increasing the average annual thermal output by 15% by 2025 and by at least 35% by 2030
- Reduce the cost of drilling and completion by 15% by 2025 and by 25% by 2030

**Tentative Budget** 100 M€

- Concept development, lab experiments and validation (TRL3-5): 5 RIA projects, 1-2.5 M€ per project
- Demonstration and prototyping (TRL 6-7) to bring technologies to TRL8: up to 3 industrial scale demonstration projects 10-15 M€ per project

## TOPIC 10: ENHANCED PRODUCTION PUMPS

### Objective

Pumps are an **important component of the production process from a CAPEX and reliability point a view** (impact on the well lifetime). During operations, energy demand for pumping as well as the maintenance and replacement of production and injection pumps can be a burden on overall plant efficiency and profitability. As a result, the overall objective is to improve pump efficiency and longevity, secure production reliability, and develop tools for avoiding two-phase flow in areas such as wells in order to enhance exploitation economics.

The main goals are to:

- Analyse the existing production pump operations of existing geothermal plants in terms of premature failures
- Develop appropriate condition monitoring tools to predict operation failures and optimise Electrical Submersible Pump (ESP) and Line Shaft Pump (LSP) construction

- Develop new technical solutions and components for ESP and LSP for existing operations up to 140°C, up to 150 L/s and installation depths up to about 900m in order to reach normal longevity for standard applications
- Develop second-generation geothermal pumps with prolonged lifetimes under aggressive fluid conditions or development of alternative lifting technologies
- Improve submersible pump operational efficiencies and longevities, securing sustainable single-phase liquid (i.e. gas/steam free) production at optimum power ratings within the 120-200°C binary cycle geo-power temperature range
- Bridge the higher temperature 200-300°C technology gap expected from oil and gas ESP steam flood practice and LSP in-house manufacturers' experience in addressing sensitive fluid environments

## Current status

Of the three submersible pump concepts eligible for deep seated, hot and thermochemically sensitive reservoir environments, namely electro-submersible (ESP), enclosed line shaft (LSP) and turbopump (TP) the first two widely dominate the geothermal production market. TPs, once popular within geothermal district heating, have been progressively abandoned essentially as a result of their lower structural efficiencies and occasionally due to shortcomings in terms of in-hole packing. LSP and ESP artificial lift are currently applied at temperature, depth and power ratings within 80°C-180°C, up to 900m (ESP) and 500m (LSP) installation depth, and between 500 and 1600 HP.

The pros and cons of LSP versus ESP technologies, often opposed in the past, have now somewhat blurred as a result of newly set performance ambitions in both categories. The higher efficiencies claimed by LSPs (surface motor) over ESPs (in hole elongated motor) can be somewhat offset by the larger submersion depth and subsequent shaft length (750m) sought by LSP manufacturers, and its presumably higher reliability and longer life expectancy is mitigated by a complex enclosing tubing/shaft/bearing assembly, compared to a simpler ESP shaft transmission design.

At present, high-temperature serviced ESPs operate at approx.. 250°C in steam flooded horizontal wells aimed at recovering heavy crude via the so called SAGDS (Steam Assisted Gravity Drainage) process. However, it should be borne in mind that (i) power ratings limited to approx. 250 HP, and (ii) the induced motor winding temperature is 300°C. Elsewhere such operating conditions would require considerable efforts to design high-temperature resistant enclosed line shaft/bearing assemblies and stable shaft lubricating mixtures.

Beyond the search for higher temperatures (>200°C), the booming development of medium temperature (80°C-180°C) resources in combination with large scale district heating and combined heat and power (CHP) production urges the pump industry to solve current technical problems in order to build pumps with a high power rating (1600 HP or more) in order to cope with a high lift (up to 1000m) and high flow rates (80 L/s or more). Limitations resulting from the shaft drive have to be solved and a technical solution is needed to avoid permanent lubrication losses.

If the lifetime and power rating were improved, two things would be required in order to achieve production in thermochemically hostile fluid environments; firstly, robust downhole chemical injection lines, and secondly, permission from the relevant authorities to inject environmentally compatible inhibitor agents. Submersible pumping systems being set below the flashing front (i.e. in single phase liquid state, multiphase flow production) would address the issue of two-phase geothermal reservoirs and deserve specific technological research accordingly.

## Potential for technological development

Technological development options include:

- Development of high-temperature resistant, appropriate, high-efficiency ESP technology
- Construction of a ESP geothermal seal unit as core component of ESP systems
- Compatibility of ESP components from different suppliers as an incentive for necessary alternative suppliers
- Improvement of enclosed LSP technology for the production of high to very high temperature pressurised liquid resources, and at larger depth in low-to-medium temperature reservoirs
- Reliable utilisation of highly mineralised and saline reservoirs
- Establishment of European collaborations in the pump technology sector and its related areas of activity (e.g. implementation of a pump test site)

## Target and KPIs

For second generation geothermal pumps with prolonged lifetimes under aggressive fluid conditions or development of alternative lifting technologies: TRL 6-7 by 2024, TRL 8-9 by 2026.

**Tentative Budget** 100 M€:

- Develop new pumps: 35 M€
- Demontration of application of  enhanced production pumps: 65 M€

*City of Radicondoli.* Source: iStock

# D. RESOURCE UTILIZATION AND MANAGEMENT

Geothermal resource can be converted to energy (power, heat) but also used for heat storage. In addition co-production of lithium and other minerals, chemical production can significantly contribute to efficient use of geothermal resources and lower the levelized cost of energy production.

Topics 1-5 focus on enhancement and cost reduction of energy conversions, heat storage and coproduction

**1.** Advanced binary cycle, power cycles & efficiency improvement

**2.** Combined Heat & Power flexible production

**3.** High-temperature underground thermal energy storage

**4.** Lithium & other mineral exploitation

**5.** Chemical production and other uses

Topics 6-9 deal with enhanced embedding of geothermal resource use in energy system

**6.** Smart integration into different generations of DHC networks

**7.** Resource management in dense installation environments

**8.** Heating and cooling usage

**9.** Flagship projects for DHC Netowrks in Metropolitan Heating & Cooling

## TOPIC 1: ADVANCED BINARY CYCLE, POWER CYCLES & EFFICIENCY IMPROVEMENT

### Objective

The objective is to develop advanced binary plants for geothermal exploitation at different temperature level. On one hand, the goal is to minimise second-law efficiency losses. On the other hand, from a techno-economic perspective, the cost-efficiency pursued depends upon the economics of each project. The primary aim is to develop techno-economic solutions which reduce overall plant costs or maximise plant efficiency. Moreover reliability, availability and grid-balancing flexibility are key factors reflected in the implementation of redundancies for critical items.

### Current status

According to the second-law analysis ([1]), currently installed binary plants are close to the maximum efficiency, reaching almost 75% when exploiting fluids at different pressure levels with cascaded heat transfer processes. Pushing plant efficiency to its highest level however is not recommended as it would lead to cost increases, therefore jeopardising project feasibility.

At the present time, most of the worldwide installed geothermal binary power plants utilize hydrocarbons as working fluid. Due to the European and local regulations on the amount of flammable fluid employed, technical solutions that face significant constraints in terms of engineering the size and features of technical components that include auxiliary systems when addressing challenges such as firefighting and operational issues, must be provided. There are only few geothermal power plants installed which use organic non-flammable working fluids (i.e. refrigerants). The number of installed geothermal plants utilizing such working fluids could only increase as a result of technical and commercial development of new and more readily available refrigerants.

The current state of the art includes supercritical cycles, with some examples using CO2, even if none of the available working fluids respond to the required boundary conditions (i.e. the geothermal resource) does not allow the critical temperature of the working fluid to be reached. In fact, thermal efficiencies are very low because of the small temperature difference between hot and cold sources. R&D examining the use of hybrid renewable systems that could significantly improve thermal efficiencies is underway.

### Potential for technological development

Cost reduction for binary systems will be achieved by:

- Reducing the plant footprint and the overall costs, thanks to the development of new geometries and arrangements together with the employment of more cost-effective and specific materials for each plant component
- Increasing average turbine efficiency throughout continuous development in the Computational Fluid Dynamics (CFD) technology

1 Second-law analysis is the most powerful tool for understanding the rationale of a power cycle and the potential efficiencygains that can be achieved in relation to a well-defined ambient environment and a resource at a given temperature.

- Increasing net cycle efficiency with the use of new fluid mixtures both in subcritical and supercritical configurations
- Reducing thermal waste without increasing either the number of rotating components or plant complexity by designing new multilevel configurations which also enable a reduction of the irreversibilities between the thermal cycle, the resource, the environment and the end use
- Reducing Balance of Plant (BOP) costs
- Upscaling the capacity of power and heat plants

Technological development aiming to improve plant performance should focus on the working fluid, which is one of the most impactful variables in the thermodynamic balance. Features to be considered for these improved fluids are:

- Saturation conditions
- Thermal stability
- Flammability
- Explosivity
- Low Ozone Depleting Potential (ODP)
- Low Greenhouse Warming Potential (GWP)
- Cost reduction

Given a wide range of working fluids to choose from, the versatility of the Organic Rankine Cycle (ORC) could be enhanced, and boundary conditions that were previously incompatible with techno-economic feasibility could become exploitable.

Disruptive solutions such as gas-lift or other non-conventional systems could play a game-changing role in increasing the amount of primary energy available for power production processes.

Another technological challenge is improving specific components of the binary cycle: heat exchanger, selecting material, surface structure and coating to enhance heat transfer and minimize scaling. It inlcudes increasing cooling system efficiency by improving the air-cooler/condenser, and matching in order to cycle the efficiency of components (also developed in other topics below). Hybrid cooling of binary cycles working with low temperature geothermal sources, and integration with heat or cold supply via novel cascading concepts also require improvements.

Lastly, a standard technology which is suitable for limiting the release of Non-Condensable Gases (NCG) could reduce the overall carbon footprint of geothermal binary plants.

## Target and KPIs

- Short Term: By 2025, develop and demonstrate (up to TRL 7) new and novel solutions increasing by 5-10% of the total efficiency while proportionally reducing GHG emissions (tons of avoided CO2 emissions)
- For long-term 2030 and 2050, develop and demonstrate (up to TRL 7) new and novel solutions increasing up to 15-20% of the total efficiency while proportionally reducing GHG emissions (tons of avoided CO2 emissions)

**Budget** 200 M€

Prototyping to bring technologies to TRL8 (50 M€)

Demonstration at industrial scale (3-4 projects) 150 M€.

## TOPIC 2: COMBINED HEAT & POWER FLEXIBLE PRODUCTION

### Objective

For combined heat and power production by means of geothermal energy, it is the **main objective to increase efficiency, flexibility and economics**. This combined production of electricity and heat allows to adapt to current demands flexibly and to exploit more energy commodities from geothermal. Moreover, an increase in efficiency will inevitably lead to reduced emissions and a more sustainable energy supply.

### Current status

The current state of the art in geothermal power plant design are rather static concepts based on a single ORC operating at optimal pressure, where the heat is either decoupled in parallel to the ORC heat exchangers or even in a serial configuration after the ORC heat exchangers. For high-enthalpy heat sources based on flash-cycles and direct steam cycles, similar configurations can be determined.

It is important to note that the optimal configuration is highly dependent on the power and supply temperatures of the heat consumers (e.g. district heating system, etc.).

Therefore, more advanced concepts allow for an integrated and thus more flexible heat extraction at different temperature levels. For example, splitting the geothermal brine flow between evaporator and pre-heater and combining this with serial or parallel concepts allows for higher flexibility. Configurations with higher efficiencies are based on cascaded two-pressure ORC systems, which allow for a higher power output. Heat extraction and/or conversion for Chilling purposed is possible at different temperature levels with optimal power production.

In view of combined scenarios of power production and direct heat use (for heating and cooling), **one sub-objective** for a geothermal heat source is to operate continuously at the design point in order to avoid operational problems. In order to achieve this, the overall geothermal heat source utilization needs to be optimized by **reducing the reinjection temperature** to the technical limitations. Reducing the reinjection temperature with valorisation of the heat is only possible if return temperatures from ORC and/or district heating networks are reduced.

Another **sub-objective is to maximize the power output** while assuring heat supply at any time. The optimal system architecture for this purpose varies strongly, depending on the consumer needs in terms of power and heat supply temperature.

The next **sub-objective is the use of storage technologies** to decouple heat and power production is also of high relevance – not only from a security of supply perspective, but also from a load balancing and control power perspective. The locations of these storages can either be centralized or decentralized.

## Potential for technological development

Following the sub-objectives, different approaches need to be further developed to increase their TRLs.

More **integrated concepts** for combined heat and power production are necessary, which allow more flexibility in terms of decoupling heat at desired temperature levels as well as power production. These concepts can be based, for example, on multi-stage turbines combined with turbine bleeding.

Another approach is to increase the efficiency of the ORC in flexible operation by optimizing the operation of the turbines and expanders in part-load. Conceivable here is a development of a turbine suitable for ORCs with adjustable blade geometry for covering a larger load range with high efficiencies. It is necessary to investigate whether the higher efficiencies in operation justify higher investment costs.

**Heat storage** allows for further flexibilization in time: short-term heat storage (e.g. based on sensible, latent or even thermochemical heat storages) can allow for balancing diurnal or daily fluctuations, and a more steady operation during the day. Long-term geological storages in suitable geothermal layers and thermochemical storages might allow balancing seasonal variations in heat supply and might allow to increase the flexibility and power output during colder periods.

Furthermore, large heat pumps could extend the thermal performance range of CHP geothermal plants. It has to be investigated to which extent heat pumps can be integrated into the process scheme of a single- or two-stage ORC in an economically optimal way.

The accessible flexibility needs to be assessed by a thorough **market analysis** in order to determine appropriate remuneration schemes both in view of heat and electricity production.

Other solutions can be found closer to the consumer side, interacting with or affecting geothermal energy use. These technologies comprise heat pumps and sorption chillers and have interfaces with geothermal hybridization.

## Target and KPIs

- Reducing reinjection temperatures with 5K by smart control of the supply and return temperatures in the district heating networks (e.g. by demand side management based on machine learning control)
- Reducing reinjection temperatures with 5K by optimal control strategies and necessary hardware changes in the ORC to control the outlet temperature while minimizing the decrease of electricity generation efficiency
- Maximisation of the yearly power production of the ORC with 5% by optimal design of the ORC for multiple working points, by optimal forecast and control of the heat demand (e.g. demand side management) and by optimal cooling of the ORC (e.g. Hybrid cooling) while taking into account the heat demand in the district heating network

- Increasing the ramp-up and ramp-down rates with x% while maintaining the efficiency of the ORC by integrating new components, adaptations in the design and integration of intelligent control to meet the requirements in the grid (e.g. FCR, aFFR, mFFR).
- optimal integration and control of short-term storage (e.g. sensible and latent heat storage) to decouple net heat demand and power production in order to increase energy sector coupling, to support the integration of other renewable sources in the networks and to reduce the use of fossil fueled peak boilers (e.g. reduction of usage of peak boilers with 90%).
- optimal combination of short-term and long-term thermal energy storage to maximise the support of the electricity grid while assuring heat supply at any time

**Tentative Budget** 50 M€ (suggestion)

1. Demonstration at industrial-scale up to TRL 8-9 : 40 M€ ( 2 projects)
2. Development of pilot projects up to TRL 5-6 :10 (2 projects)

Both suggestions might be merged to two IA, but in that case IA should allow in part also lower TRL research in the future.

## TOPIC 3: HIGH-TEMPERATURE UNDERGROUND THERMAL ENERGY STORAGE

### Objective

The main objectives are to implement commercial projects of of high temperature underground thermal energy storage technologies (HT-UTES), lowering the cost, reducing risks, improving the performance of HT-UTES (~25°C to >100°C) and to optimize heat network with demand side management (DSM).

### Current status

The heating and cooling sector is vitally important for the transition to a low-carbon and sustainable energy system. Heating and cooling is responsible for approximately half of all final energy consumed in Europe. The vast majority—85%—of the demand is fulfilled by fossil fuels, most notably natural gas. Low carbon heat sources (e.g. geothermal, biomass, solar and waste-heat) need to be deployed and heat storage plays a pivotal role in this development. Storage provides the flexibility to manage the variations in supply and demand of heat at different scales, but especially the seasonal dips and peaks in heat demand. Underground Thermal Energy Storage (UTES) technologies need to be further developed and become an integral component in the future energy system infrastructure to meet variations in both the energy availability and demand.

Underground thermal energy storage (UTES) involves the temporary storage of thermal energy in the subsurface. When excess heat is available this is transferred to a fluid and stored in the subsurface, and when the heat demand is high the stored heat is retrieved. Key high temperature UTES (HT-UTES) technologies were addressed and demonstrated in the HEATSTORE project, and demonstrators are developed in the Horizon Europe PUSH-IT project. This includes aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), mine thermal energy storage (MTES) and pit thermal energy storage (PTES). Thermal energy storage is already implemented in heating networks in the form of surface tanks storage and, although still highly limited, by UTES to support the use of surplus heat from industry and the implementation of renewable heat sources such as bio-Combined Heat and Power (CHP), geothermal, and solar energy. It provides the opportunity to integrate variable renewables (wind, solar) and baseload thermal heat sources (geothermal, biomass, surplus heat, ambient heat) in future sustainable heating systems.

Compared to other storage techniques UTES is economically competitive and it is compatible with many (local) renewable energy sources. An especially interesting synergy is possible when heat and electricity sources with low marginal cost are available (e.g. geothermal, solar thermal, waste heat, environmental heat with heat pumps). It is an environmentally benign storage technique with limited use of rare earth materials required. The insulating properties of the subsurface allow for high volume and long-term storage with tolerable losses. Additional benefits of storing heat underground, although technology dependent, help reduce the spatial footprint of the future energy system.

## Potential for technological development

Underground thermal energy storage has the potential to overcome short- and long-term mismatch between demand and supply and therefore support the energy system by providing flexibility and reliability (i.e. adequacy) in a sustainable way. It is one of few long- duration storage technologies that can store vast amounts of energy up to tens of GWh per cycle. The application of UTES can therefore help solve the problem of seasonality in heat demand and can reduce the carbon footprint of the energy sector. The technologies can be widely applied in energy infrastructures supplying sustainable and low carbon heat to industry, agriculture and district heating grids. Especially (district) heating networks with temperature ranges between 25 and below 100 °C are highly suitable. The main advantage of HT-UTES compared to low-temperature systems (~25°C) is that the heat that is retrieved can be used directly for heating purposes and is suitable for more applications without a heat pump. For industrial heating networks with higher temperatures the technology could be applied in combination with heat pumps.

UTES also provides valuable services to the electricity sector through sector coupling as it allows the absorption of electricity surpluses through power-to-heat solutions, decoupling electricity production and heat demand from the short to seasonal timescale. Globally, low temperature UTES systems already account for several TWh of storage. The high temperature UTES options can best be defined as either early commercial or in the pilot/demonstration phase, depending on the technology. Over the next few decades these technologies and the project portfolio of HT-UTES systems could grow towards tens or hundreds of TWh of storage capacity in the EU energy system. HT-UTES has the potential to become the largest heat storage option and be an integrated part of the energy system in large parts of Europe. This entails that hundreds to even thousands of large-scale HT- UTES systems need to become operational in Europe in the next thirty years.

It is critical for HT-UTES to further reduce technology risks and improve technical performance.

The recently ended HEATSTORE programme proved that demonstration sites, as set upin in PUSH-IT, are crucial to ensure that tested technologies can be brought to market and valorised by the relevant stakeholders. Learning by doing is the best way to gain skills and improve the knowledge base.

For this purpose, demonstration sites with extensive research programmes and strong industrial engagement are key with the following technical challenges:

- Reduce Well cost
- Improve PCM and Working fluids
- System optimization
- Enhanced resource base
- Renewable sources/balancing heat

### Target and KPIs

- Support Pilot projects: 20 pilots in 5 years
- 10 to 30% Reduction of drilling costs for BTES and ATES
- Increase storage volume > 300'000m3 for HT-ATES, and >20'000m3 for HT-BTES to improve efficiency
- Improve Thermal demand of 5 MW for HT-ATES
- Lower cut-off temperature (the lower the better) for HT-ATES to improve efficiency
- Set a clear regulatory framework for HT-ATES

### Tentative Budget

200 M€ (suggestion)

- Develop HT-UTES technologies: 40 M€
- Demonstration with 20 pilots: 160 M€

## TOPIC 4: LITHIUM & OTHER MINERALS EXPLOITATION

### Objective

The objective is to develop novel and potentially disruptive technological solutions that can help satisfy the European needs for energy and strategic metals and other economic non-metallic materials in a single interlinked process. Geothermal plants may optimize the production of both energy and metals/materials according to the market demands, exploiting deep geological formations. By exploiting mineral production, geothermal plants will also become more economically competitive, create new market and supply chain opportunities, and reduce their impact with a circular economy approach.

Specifically, regarding lithium, geothermal plants will also contribute to the reduction of the carbon footprint of lithium production compared to standard extraction methods (like hard rock and evaporation pond mining) which are significantly more harmful to the environment and CO2 intensive than geothermal lithium.

## Current status

Worldwide several pilot plants have been built to extract salts, silica, lithium and specific metals from brines, but industrial production is only taken place at a few places and limited to the production of silica, lithium, bromine and zinc. Many countries have also placed strategic value on lithium and are using public financing to stimulate domestic extraction and production.

In Europe, the geothermal sector has been instrumental in designing and piloting methods to extract lithium from geothermal systems without hampering their energy generation activities. Many projects and exploration activities are already in process in Germany, France and Italy.

Furthermore, the European geothermal industry has already invested more than €50 million into this sector.

In most cases, however, the brines have been regarded as wastewaters in need of treatment to meet the imposed environmental discharge limits, discharged as is or left to evaporate instead of being regarded as a source for non-metallic and metals elements. This is mainly due to the dilute metal concentrations of the brines, as well as their complex nature, that make the extraction hardly sustainable from an economic point of view. High metal concentrations (e.g. >10 mol/m3) can usually be handled with conventional physicochemical, adsorption and electrochemical separation technologies. Yet, dilute metals in solutions require special methods. Moreover, geothermal brines are complex mixtures that make removal of specific components difficult.

## Potential for technological development

With respect to recovering chemical components from geothermal brines the following developments are envisioned:

- Further mapping the resource and ensure accessibility and sharing of this data
- Increase the selectivity and efficiency of the separation techniques
- Develop new, potentially disruptive technologies to separate, increase concentration and transform chemical components from geothermal brines into more valuable products
- Develop technologies that take advantage of the chemical energy potential of geothermal brines

When it comes to integrating the separation technologies in geothermal plants the following developments are envisioned:

- Extend the operation conditions of existing separation technologies to the pressure and temperature conditions of geothermal plants
- Develop technical solutions to increase the separation capacity in order to deal with high flow rates that are typically encountered in geothermal plants
- Ensure reinjection compatibility for a sustainable reservoir management
- Develop conceptual designs of a new type of future facility that is designed and operated, since the very beginning, as a combined heat, power, and mineral extraction system

### Target and KPIs

Technical solutions to increase lithium and minerals, while improving the geothermal plant economics by additional excess revenues with at least 5%

Conceptual designs, pilots (and demonstration)

**Tentative Budget** 100 M€:

- Develop technical solutions to extract minerals: 40 M€
- Test soluctions in demonstration sites: 60 M€

## TOPIC 5: CHEMICALS PRODUCTION AND OTHER USE

### Objective

Global energy consumption and concerns over environmental contamination continue to increase, and it is imperative to develop renewable energy resources that neither rely on fossil fuels nor emit carbon dioxide (CO2). Despite the recent advances in the improvement of conversion efficiencies of new technologies like solartohydrogen (STH), the cost of producing chemicals and fuels using this approach is too high to be competitive with the present-day industrial processes.

It is therefore of crucial importance to find alternative efficient routes for CO2 conversion and valorisation into high added value chemicals and fuels. The integration of these processes with geothermal activity can mitigate the effects of the burning of fossil fuels (for example by converting geothermal CO2 to fuel before it is emitted to the atmosphere) and of the chemicals production like methanol and ethanol, reducing also the environmental impact of geothermal projects and enabling new market opportunities.

### Current status

The conversion of geothermal CO2 to fuel has been demonstrated since 2012. In Iceland, the Svartsengi plant is converting the CO2 as a replacement for petrol. CO2 is transported to Carbon Recycling International's (CRI) fuel plant, which was the first in the world to convert CO2 into methanol through synthesis with hydrogen.

Some technologies to converting CO2 to fuel have been developed but are not yet at a commercial stage.

Some geothermal fluids may contain hydrogen, especially if sourced from ophiolite rocks.

## Potential for technological development

With respect to enabling chemicals production using the geothermal resource the following developments are envisioned:

- New and more efficient and renewable hydrogen production technologies, possibly integrated with the use of geothermal resource (to enable chemicals production that require for example the use of H2 combined with geothermal CO2)
- Methane separation technologies for application in geothermal NCG streams (low methane concentration)
- New and more efficient chemicals (methanol, ethanol, ethylene, etc) production technologies, possibly integrated with the use of geothermal resource (i.e. CO2+energy)
- New efficient and low cost boric acid extraction technologies (to be market competitive with traditional boric acid production)
- Ammonia separation technologies for application in geothermal NCG streams (low ammonia concentration)

## Target and KPIs

- Proof of concepts, and lab underpinning of novel production and extraction technologies for chemical production complemnetary to mineral extraction (topic 4). The chemical by products enhance the business case and reduce LCOE
- Pilots and demonstration

**Tentative Budget** 100 M€:

- Proof of concepts, and lab underpinning of novel production and extraction technologies: 35 M€
- Pilots and demonstration: 65 M€

# TOPIC 6: SMART INTEGRATION INTO DIFFERENT GENERATIONS OF DHC NETWORKS

## Objective

Development of intelligent systems promoting geothermal as future principal CO2 neutral component for urban district heating networks (DHC)

## Current status

Current DHC are in general dominated by the supply from fossil fuels, waste heat from industrial plants and incineration plants. Besides and as a consequence from the operation of CHP, DH can be fed into the grid and utilized with high temperatures/steam, constantly, and with high thermal loads from one site. Geothermal will necessarily not take place at locations that have formerly been used by fossil plants. The implementation of CO2 neutral geothermal resources therefore requires modified systems and new solutions either due to substitution of former generation as well as for erection of new grids, junction with and combination of new geothermal generation sites.

## Potential for technological development

The supply of geothermal energy for heating and cooling and its applications represents enormous potential for technological development. Cities need reliable techniques for CO2 neutral DHN and this has to be fulfilled rapidly in accordance with the objectives of the green deal. Innovative solutions have to be applied and supported, amongst others:

- Transition from steam to heat conditions, application of low temperature grids and supply, application of hybrid heat pump systems
- Intelligent compensation of fluctuating load management (from seasonal to daily) from the perspective of the consumer and the supplier
- Integration of seasonal heat storage
- Intelligent combination of heat generation, storages and cooling systems
- Enhanced materials and working fluids for geothermal heat transport and mitigation of frictional and heat losses in DHC
- Application of monitoring systems and artificial intelligence

The potential synergies between DHC heat and cooling and industrial process heating and cooling are also of relevance. Industrial production consist of different processes with different temperature levels, pressure requirements and performance from fluctuating or continuous requirements. Therefore this mixture requires holistic concepts for industrial heat transition with direct supply from geothermal and the implementation of CO2 neutral cooling.

## Target and KPIs

Solution and realisation of the technical prementioned challenges and integration into DHC in different cities for different stages of DHC (new, early, advanced….). Application of a matrix based evaluation:

- Time horizon: 5-10 years
- Acceleration of permission procedure for DH network with the objective to realize geothermal exploitation and grid installation intersectingly

- Staged infrastructural support according to a "DHC City Status Matrix"
- Determination of a quota for low temperature grids (proposal: new DHC: min. 50%, existing DHC: 20 %)
- Optimize synergies of industrial heating and cooling and geothermal techniques for urban DHC networks
- Installation of risk mitigation funds

**Budget** 100 M€:

- Develop technical solutions and optimization: 30 M€
- Demonstration in different urban environments: 70 M€

## TOPIC 7: RESOURCE MANAGEMENT IN DENSE INSTALLATION ENVIRONNEMENTS

### Objective

Identify design methods and organizational concepts that result in the most effective and sustainable use of subsurface space by indirect, direct and storage geothermal systems such UTES, ATES and BTES systems in dense urban areas. Evaluation of the interaction between other urban uses of the subsurface (e.g. subways, underground utilities, buildings), including structural foundation elements of buildings, tunnels, slabs, energy sheet pile walls, etc., with potential geothermal heating, cooling, and sinks or storage opportunities

### Current status

Geothermal energy systems concentrate and cumulate in urban areas, where many old and some new buildings stand side by side. The temperature distribution around the wells/boreholes of these systems depend on subsurface conditions and the energy demand profiles of the associated buildings. Uncertainties inherent to future weather conditions, to the climate and use of the building, lead to uncertainties in their energy demand and causes its associated use of subsurface space to vary and make it hard to predict. At the same time, the spreading of heat in the subsurface is invisible, difficult and expensive to monitor. To deal with these uncertainties and possible interaction ATES and BTES systems are typically over-dimensioned and kept at a large mutual distance to prevent negative interactions between them. In addition, little attention is paid to operational aspects such as variation in energy demand between and over the years, which results in both suboptimal use of the subsurface and in reduced thermal efficiency. These different aspects cause underutilization of potential GHG savings with UTES systems. Thus, both the design and organization of UTES must be improved to safeguard optimal and adequate use of the subsurface.

### Potential for technological development

- Optimal utilization of geothermal resources and thermal energy storage in urban settings; Subsurface underground models for a sustainable geothermal use in cities
- Studying the impact of subsurface urban heat islands (SUHI) on the potential of shallow geothermal energy use in cities

- Best practices strategies for subsurface land-use plans in European cities; Well/borehole placement strategies
- Mutual interactions between systems, effect on efficiency of storage, and energy performance

### Target and KPIs

TRL from 6-9

Adoption level of UTES in cities, percentage of subsurface space utilized for shallow geothermal.

**Tentative Budget** 100 M€

- Optimize  Resource management: 30 M€
- Demonstration in  in dense urban areas: 70 M€

## TOPIC 8: HEATING AND COOLING USAGE

### Objective

The goal of this topic will be to boost the usage of geothermal energy of heating and cooling, in particular extending supply to the agri-food and industrial sector to contribute to its decarbonisation, improve its sustainability and promote efficient and circular development.

### Current status

Energy is a fundamental input in food systems, both directly and indirectly. There are many opportunities for clean energy technologies to support food production, drying, cooling, storage, transport and distribution. Yet, energy use in agriculture and food still relies heavily on fossil fuels, with relatively limited penetration of renewables in these sectors to date.

Industrial utilization of geothermal energy is still niche, especially for low or middle enthalpy geothermal resources. While announcing climate neutral objectives in the past, industry focused on electricity and neglected the portion and importance of heating and cooling from renewable resources especially from geothermal—not only a question of geological availability but also a question of economical discrimination in comparison to fossil fuels. Since industry currently discovers the merit of a green production and ecological made products and beyond that requires CO2-neutral standards from their suppliers, pressure is raising to demonstrate industrial feasibility in praxis and reduce compensation with certificates.

Geothermal heat can be used for a wide range of agri-food applications and industrial sector for process gear, including, among others: agricultural drying (grains, vegetables, fruit, fish and other agricultural products), heating of greenhouses, soil and water (including for aquaculture), and industrial process heating. In addition, geothermal resources contain by-products such as dissolved minerals, non-condensable gases, brines and steam condensates that can be used for various applications. In many developing countries, unmet demand for affordable and sustainable energy is a key constraint to the development of the agri-food market segment and represents a significant opportunity for countries endowed with geothermal energy to utilise this resource.

Agri-food applications that utilise geothermal heat are widespread throughout Europe, notably:

- greenhouse heating in Iceland, Italy, Hungary, the Netherlands, Russia and Turkey
- aquaculture heating in Iceland, Italy, Poland, Romania, Serbia, Slovakia, and Switzerlan
- spirulina cultivation in Greece, Iceland, and Italy
- crop drying in Greece (vegetable/fruit dehydration), Iceland (seaweed and fish drying) and Serbia (grain drying)
- food-processing applications in Bosnia and Herzegovina, Iceland (salt extraction) and Italy (milk processing); as well as in Greece, Iceland, and Italy (wine making and beer brewing)

Food and agri-food production in Europe requires further steps to reduce the carbon footprint. The integration of geothermal energy in this sector as a direct use can play a key role to increase food and agri-food production in highly productive circular systems, and can help geothermal projects to reduce LCoE and environmental impacts improving their sustainability. New concepts are needed to demonstrate how it is possible to exploit the various conventional and non-conventional geothermal streams, in a circular system integrated with this sector, also promoting new business opportunities and job creation. Besides the direct benefits it can create additional socio-economic and environmental benefits including increasing food production, enhancing efficient use of labour, reducing pollution and greenhouse gas emissions, lowering costs and raising incomes for farmers and entrepreneurs, as well as contributing to inclusivity, gender equality and employment.

## Potential for technological development.

In order to accelerate geothermal applications in the food and agri-food sector, the following actions should be taken into account:

- Mapping of potential supply and demand of geothermal energy for agrifood systems
- Identify and develop solutions to use geothermal CO2 (i.e. that discharged from power plant, or coproduced hydrocarbons in sedimentary basins) in production phases that require it (i.e. algae), improve geothermal CO2 purification technologies to enhance direct uses for (food) industry, harmonized processes at European level for the qualification of geothermal CO2, water and other streams for food applications
- Building harmonized legislative frameworks at European level to enable different uses of geothermal resources in the food and agrifood sector
- Food supplements production (i.e. minerals production for food market—Iceland experience)
- Identify solutions to shorten the supply chain, increasing local production, depending on the food to be produced
- Improving the energy efficiency and quality of geothermal by lowering required temperatures (i.e. for greenhouses), and deployment of heat pumps respectively

- Combining geothermal for H&C and storage and other renewables for power supply to create off-grid productions
- Identify alternative sources of proteins that can be produced by using geothermal energy supply

### Target and KPIs

Decoupling increase in food production from fossil fuel use will require fundamental changes in global food systems. More analysis is required on how a shift to a less fossil fuel dependent food sector would affect food security, food prices, energy access, climate change resilience, technology uptake and capacity building.

KPI 2030:

- Lower the geologic and financial risks by the implementation of adequate risk mitigation measures
- Increase profits by 20%
- Lowering the energy inputs by 30% in essential areas, such as (but not limited to) heating and cooling, electricity supply can help the food sector to improve its reliance
- Implement financial mechanisms to support the deployment of energy efficiency and renewable energy
- Reduction of food waste by 30%
- Support pilot projects: 10 pilots in 5 years with priority to direct uses of shallow to medium depth geothermal resources
- Increment of geothermal share in energy supply by 30%

**Budget** 50 M€

- Technological improvements: 10 M€
- Support pilot projects: 10 pilots: 40 M€

## TOPIC 9: FLAGSHIP PROJECTS FOR DHN IN METROPOLITAN HEATING & COOLING

### Objective

Focussing on geothermal heat transition in the big cities in order to highlight the potential and its feasibility in densely populated areas, to exchange and concentrate experience and reach a Metropolitain geothermal strategy with increased public attention and encourage other cities.

### Current status

Currently only a few European Metropolitain cities pursue a geothermal strategy as component and objective of their climate neutrality. Although geothermal is applied successfully or at least intended to be applied (e.g. Paris, Rotterdam, Vienna, Munich, etc.), the conviction to implement these strategies in other cities still is low. Reasons are different since the conditions either geological, economical or infrastructural are divergent.

But at the same time the geothermal components and requirements are congruent: drilling techniques, geothermal pump systems and thermal water utilization, district heating and electricity generation, heat storage, sustainabilty and public acceptance, financing, etc. These topics are essential for the success of geothermal heat transition and, due to the high numbers of consumers, not spread widely enough.

Only a few lighthouse projects demonstrate how heat transition can be realized in the Metropolitain cities, with still only a small percentage. Therefore, these few metropolitain cities should be encouraged and supported to join activities and coact in the same fields. These Metropolitain beginners normally do not dispose of data and specialists to accelerate the speed according to the (new) objectives especially regarding the fact that the branch still has to be regarded as small. The knowledge of the big players can serve as a pattern and nucleus to initiate the first required step of other cities. A formation of a financed consultation platform could help to transfer knowledge practically and effective to the “beginners”.

## Potential for technological development

Best practise for all technological aspects of geothermal supply and the demand on the climate neutral DH market of big cities should be brought together and thus utilized effectively. Subsequent item represent the technological prospect:

- Common database and technological platform as premise, technological exchange and solutions in an interdisciplinary context
- Comprehensive conceptional design based on best practice in other geothermal cities
- Minimization and avoidance of technological failures

Development of new concepts, especially for urban geothermal projects (e.g. zero-noise-emission rigs, minimized size ratio for drilling and operation, subsurface technological design and realization (plant), general risk mitigation, transformation concepts for geothermal integration, etc.)

## Target and KPIs

The overall target is to connect the “geothermal cities” and concentrate know-how, experience and public attention.

- Foundation of a Metropolitan geothermal group with professional support, consultation and coordination of activities
- Financial stimulation of the European Metropolitan heat vision: “10 new big city” in 10 years

## Tentative Budget 50 M€

- 10 pilot projects

# E.RESOURCE SUSTAINABLE MANAGEMENT

In addition to challenges dealing with technical system performance, the objective in this section on identifying those topics which enhance  environmental performance of geothermal power and heat systems over their entire lifecycle, and to promote market uptake.

Enabling geothermal energy to be one of the main contributors to the European climate and energy targets and deploying at large scale geothermal technologies entails many systemic challenges, notably as regards plants' initial high investment cost, the legal and administrative barriers, and the unawareness or the perception of the environmental issues of technologies influencing the well-being feeling of individuals. The geothermal market uptake depends heavily on its capability to demonstrate the benefits for individuals, companies and society as a whole while addressing and mitigating the challenges effectively in a well-balanced manner. Therefore, the research and innovation activities must be complemented by additional activities to implement regulatory, financial, political and social solutions.

Topics:

1. **Life Cycle Approach and Emission Footprint reduction**: Assess and Lower environmental footprint of geothermal energy production, including lowering Carbon footprint.

2. **Circularity:** Enhance circularity, by reuse of materials and recyclability.

3. **Water use management and Groundwater protection** to reduce the water consumption and promote a sustainable water-use management.

4. **Sustainable reservoir management** includes methods to enhance sustainable reservoir management, in particular in promoting tools for safe operations and associated potential environmental risks.

5. **Innovating with and for society** sets the scene for a responsible development of both policies and projects that are aligned to social needs and expectations at different scales (from the local, to the global). New social-scientific research on the desirability of geothermal energy, citizen and stakeholder engagement actions, are key to build alliances among different actors towards common goals.

6. **Financing and risk mitigation**: Bring the right financial support schemes  for geothermal technologies and minimise the uncertainty associated with geothermal energy.

7. **Policy and regulatory** Set ambitious policies at the EU and national levels to allow the development of the geothermal market and the penetration of innovation in the sector. Adapt policies and better permitting regulations.

8. **Qualification and training** Ensure first-class skills and human resources to avoid shortcomings in skills development and lack of an adequate workforce, and consolidate the scientific base to educate the next generation of geothermal pioneers.

9. **Communication and public awareness** Develop effective communication with the general public and increase awareness about benefits to use geothermal.

## TOPIC 1: LIFE CYCLE APPROACH AND EMISSION FOOTPRINT REDUCTION

### Objective

A robust environmental, social and economic impact assessment is a fundamental prerequisite to the deployment of the geothermal resources, in order also to improve the general perception of new projects. The concept of Life Cycle sustainable Assessment (LCSA), compiling environmental, social and costs approaches, allows analysis and comparison of the sustainable impacts of different energy production technologies, including geothermal, over their life cycle stages—from extraction of raw materials to production, transport, use and end-of-life. Bringing down the carbon footprint of geothermal technology, in particular focusing on zero-emission for the operational lifetime of geothermal plants, is a target.

### Current status

The assessment of the sustainable aspects of geothermal energy using a lifecycle approach is spreading worldwide and an increasing number of publications on this topic have been finalized in the last years. Life Cycle Assessment is a standardised, holistic, and multi-criteria method to estimate the environmental, economic and social impacts of a system or product throughout its entire life cycle. For environmental LCA, each step is defined in the ISO standards 14040 and 14044 and the Joint Research Centre also provides recommendations on this framework (European Commission and Joint Research Centre, 2010; ISO 14040, 2006). However, these recommendations are general and leave the LCA users with several choices when applying LCA to energy pathways. This results in large variation in published LCA studies of energy generating technologies which can ultimately impact the confidence in LCA results and their use in decision-making processes. This lack of harmonized methodology still affects the systematic application of this approach, especially among stakeholders.

Methodological guidelines for geothermal LCA studies have been developed recently in the frame of the GEOENVI EU H2020 Project. The guidelines are referring to the midpoint LCA level of assessment, which is the minimum required by the LCA standards. Normalization and weighting, in some methods passing through an endpoint (or damage) evaluation, allow eventually to evaluate a single score sustainability index (commonly referred to in terms of eco-points, EP). This step is not included in the mandatory part of an LCA although is highly appreciated at the level of general evaluation, decision-making, and social perception of sustainability.

From LCA analysis for resources in vulcanic areas, they may contain percentage of incondensable gas (Non Condensible Gas, NCG), which have a negative impact on the environmental footprint when released into the atmosphere. Therefore NCG need to be reinjected or used (as e-fuels for example) to avoid unsolicited emissions. Depending upon reservoir enthalpy and pressure, different power cycles may be designed to perform the objective of the total reinjection.

For low-enthalpy systems in sedimentary basins settings, dissolved hydrocarbons or CO2 contribute to unsolicited emissions when separated from the production stream and released in the atmosphere and/or burned. In order to avoid emissions, the hydrocarbons or other gases (or flue gases after burning hydrocarbons) need to be reinjected, or treated in an environmentally friendly way.

The plant configuration largely adopted around the world to deal with non-condensable gases in the geothermal fluid consists of the separation of the gas stream from the liquid flow. The gases are then sometimes treated to abate the polluting elements (e.g. hydrogen sulfide), and then released to the atmosphere. The reason why total reinjection is not applied is not only economic but also due to the fact that it is linked to the scarce knowledge of the reservoir behavior when gas reinjection is performed, and the lack of data regarding design and operating behavior of necessary equipment.

The goal is to develop research activities to implement total reinjection plants both in low enthalpy and in medium-high Enthalpy Geothermal Resources through the implementation of modeling tools, lab test and pilot plant. The ultimate goal is to transform traditional geothermal plants in total reinjection plant. The GECO Project is trying to answer to part of these questions. In principle, total reinjection in the same liquid dominated reservoir used for production is always feasible not implying any significant chemical transformation.

## Potential for technological development

The need for representative and accurate LCAs of different energy pathways counterbalanced with the difficulty of conducting extensive and harmonized LCA calls for novel tools for a wider and easier application of LCA, particularly by non-LCA experts. LCA could be accompanied by other environmental assessment criteria, which can consider site-dependent matters or whose evaluation involves social or qualitative acceptance. A wider dissemination activity of the LCA approach is also essential to facilitate the adoption of the methodology among stakeholders and decision makers:

- to inform policymakers and stakeholders in a more transparent way about the sustainable character of geothermal over their entire life cycle
- to provide a solid method on LCSA contributing to the criteria defined on sustainable finance regulations
- to identify the stakes of social acceptance, through science-based evidence and tools to better respond to potential misperception phenomena

It is also important that Life Cycle Analysis tools are harmonized in the field of renewable energy. Geothermal energy can appear less attractive than other renewables (such as wind or solar), but may prove competitive from many points of views, such as use of land and the limited use of rare raw materials. Another point to be analyzed in this perspective is the End of Life, which includes the definition of best practices for materials recovery.

Introduction in the LCA of normalized and precise standardized indices for a project evaluation based on a numerical scale of merit. The indices must be calculated on the basis of irrefutable numbers declared in the project, measurable and binding for the manufacturer.

For example:

- land consumption expressed in m2/Mwh net electricity produced
- soil consumption expressed in m2/Mwh net heat produced (hot and cold)
- expected years of operation of the plant and decay index of the MWh/year produced
- GHG savings in tons/year, tons/10 years, relative savings in %
- production in hours/year
- LCOE (€/MWh el) and unified calculation methodology

- LCOE (MWh term)
- Index for Atmospheric Emissions Concentrations/MWh
- Visual impact index (methodology to be identified)
- Index expressing advantages and initiatives (direct and indirect) related to geothermal production and quantifying index of their socio-economic value
- Reward index in the case of combining electricity + heat production + H2 production + other valuable productions
- Social acceptability index (methodology to be identified)

The outcomes of the LCA should be readable by anyone who is not technical, written in a standard format and finally report a summary table with coded and measurable standard numerical indices. The evaluation of the goodness of a project must not be discretionary and the data presented must not be questionable but strictly of obvious understanding (subjective data must not be considered in the final evaluations).

In order to reduce emissions in the operational phase, development of suitable technologies starts with a good understanding of the geothermal fluid and NCGs in the wellbore and the reservoir. Geothermal fluids have a variable composition and gas concentration, depending on the geological formation of the reservoir, fluid temperature and depth. Although Geothermal gases have a natural origin, different from those generated by industrial combustion or other anthropic processes, European and national regulations enforce rules to guarantee air quality. Mitigation of degassing requires specific treatments, which are often applied also in the case of emission factors below the reference thresholds defined for human health and environmental safety. The following potential technological developments are foreseen:

- Prevention and mitigation activities, such as the installation of abatement systems like the "AMIS" technology used in Italy, and the development of new technologies aiming at the complete reinjection of the fluid have been proven to be effective in reducing the emissions related to the use of geothermal energy. A clear relation between geothermal projects and the modification of total natural emissions in the geothermal areas has not been established. Therefore, a deeper understanding of natural emissions, in other words the air quality baseline, has to be promoted.
- Development of total reinjection power cycles is presently challenging. Main difficulties are linked to the scarce knowledge of the behavior of the main necessary equipment and the interaction with production and reinjection wells for different types of power cycles (high temperature binary, ORC, Flash)
- Cost effective technologies are needed to reinject dissolved hydrocarbons directly and/or reinject flue gases/$CO_2$ when burning the hydrocarbons produced. For the latter a NER300 supported demonstration project has been developed in Croatia, but in many other geological settings in the EU similar approaches need to further mature (techno-economic feasibility is strongly dependent on reservoir conditions) and public support for injecting $CO_2$ in the subsurface can be challenging.
- In performance assessment the mitigation of emissions needs to be an integral part of performance evaluation.

The adoption of mitigation measures, best practices and harmonized guidelines, together with a better definition of the emissions baseline, will reduce the concerns and boost the use of geothermal energy.

Total reinjection in the presence of high gas content and two-phase flow in production and reinjection wells must be considered innovative with a TRL 6 as soon as GECO project is completed. Further technological development would require studies and specific engineering such as described in the objective box.

In particular compression equipment, not conventional lifting systems, behaviour of reinjection wells when two phase flow injection is performed, optimisation of total reinjection energy conversion cycles combined with heat utilisation, are themes which should be developed to reach TRL 9 and allow total reinjection be utilized on a wide scale.

### Target and KPIs

The long-term target is to demonstrate the feasibility and the cost effectiveness of the total reinjection regardless of the original gas content at least for water dominated reservoir. This would require standard procedures of equipment design which will allow a cost reduction for the total reinjection solution.

Underlying targets are improvements in the main equipment as well as to develop full scale demonstration projects to investigate reliability of design hypotheses to bring technologies to TRL8.

### Tentative Budget 100 M€

- LCA reference tools and approaches: 5 M€
- Lab pilot plants to test reliability of codes for total reinjection technologies: 25 M€
- Field demonstration of total reinjection in different geological settings: 70 M€

## TOPIC 2: CIRCULARITY

### Objective

Embedding geothermal energy into the circular economy is a core topic for geothermal development. The integration of geothermal in the circular economy would include materials, components, equipment and systems which are optimized, used and re-used, repaired, redistributed, refurbished and/or remanufactured.

One aim is also to develop quality brand for the geothermal products, components and systems, becoming greener and eco-friendly.

The objective is to establish a system in which geothermal materials, components, equipments and systems have durability and recyclability from the design stage so that they can be reused, or made into new raw materials—thus reducing waste volumes and energy consumption and preserving natural resources.

## Current status

A first Circular Economy Package for a more sustainable economy was published in 2016 by the European Commission. The EC adopted the new circular economy action plan (CEAP) in March 2020. The EU's transition to a circular economy aims to reduce pressure on natural resources. The new action plan announces initiatives along the entire life cycle of products. It targets how products are designed, promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented and the resources used are kept in the EU economy for as long as possible. Geothermal manufacturers, designers and developers have endorsed this initiative and are working on producing greener products but the sector is not yet organized to be fully integrated in the concept of the circular economy with all its components.

Circular use of resources and materials is a recommended practice for sustainability. This is normally thought referring to large-scale production items. However, circular economy can be applied also in other contexts with similar effects. Currently, Geothermal is thought as a business dealing with electricity and direct use of heat (industrial or district heating). The idea is to apply systematically a circularity approach, allowing to produce what is locally needed and useful, promoting the transformation of waste streams into valuable products. This can be applied to liquid, gaseous and materials streams, and it includes electricity in cross-sectoring, deploying the power-to-X declination which will be one of the pillars of the energy and ecological transition.

Fluoropolymers are used in the geothermal sector. They are incorporated in equipments used for drilling, for well completion, and in production pumps, sensors, cables and geothermal heat pump systems. Alternatives do not exist on the market to replace these PFAS.

## Potential for technological development

The next steps should be:

- Research and innovation to have new technologies to improve the "design to recycling" approach and for waste separation and management:
  - "Design to recycling" considering all the geothermal project phases with materials selection (use recyclable materials where possible)
  - Waste separation and management, i.e.:
    - Scaling reuse in the reinjection stream (instead of waste disposal)
    - Scaling reuse as anti-corrosion cladding of pipes/equipment
    - Silica
    - Heavy metals
    - Cuttings coming from wells & construction activities
    - Contaminants
- Develop innovative greener and eco-friendly geothermal components, equipments and systems, begin using sustainable materials. Improve the applicability and use of recycled/secondary materials/waste in geothermal plants
- Develop alternatives to PFAS used in the geothermal equipments and components.
- Adopt geothermal standardization procedures and quality brand about the circular economy to make progress on the consumer or legal authorities confidence on geothermal

- Monitor the use of raw materials in geothermal, especially the critical ones in terms of availability: identification, classification and quantification of data regarding raw materials and promote interoperability and comparability with other materials
- Develop new business models with geothermal eco-friendly actors

### Target and KPIs

Develop innovative greener and eco-friendly geothermal technologies

### Tentative budget 50 M€

for technological improvements

## TOPIC 3: WATER USE MANAGEMENT AND GROUNDWATER PROTECTION

### Objective

Enhancing water management in drilling, testing and operation of geothermal resources and surface installations, as well as minimizing subsurface environmental risk of unsolicited connection of aquifers (other than the geothermal resource) with fluid intrusion from wells, and interference with (potable) groundwater.

### Current status

Use of water in construction and operation of geothermal power plants is inevitable. During construction, water is needed for mud and cement, and during the plant operation, small amounts of water can be consumed to minimize scaling, and power plants using the wet (water) cooling towers, or fluid losses in closed loop systems. A proper conscious use and implementation of all the best practices available from a circular perspective, can significantly reduce consumption while improving the sustainability of geothermal plants.

During drilling and production and reinjection of geothermal brines/working fluids, there is a risk of accidental connection of aquifers via the wellbore or disturbance of non-targeted aquifers with fluid intrusion (geothermal fluid, testing fluid, drilling mud, etc.). The phenomena is driven by differential hydraulic pressures between layered aquifers, and can be caused by well barrier and integrity failures due to poor cementation practices, mechanical damage during well development, corrosion and scaling, geo-mechanical disturbances, underground blowout, thermal stress and material failure or degradation, and aging over the life cycle of operations. It can be triggered during the drilling process and through all life stages of a geothermal project, and also result from improper reinjection applications. In addition, cooling or heating along the well bores can cause chemical reactions and density anomaly driven flow disturbances

Losses and water consumption are recorded by operators and used to compute the periodical sustainability balance. Although it may not be possible to avoid fully the use of water in the operational phase of a geothermal project (i.e. required to minimize scaling, cooling towers) it is possible to contain its consumption. A common way to successfully reduce the amount of water to be used during drilling is the recirculation of drilling mud, and the quick plugging of mud losses zones. The freshwater consumption is reduced by using meteoric water collected and stored in containers, as in Italy, for the preparation of mud and cement slurry during drilling phase. Discharged geothermal fluids or low-quality water are used to support cooling and/or as make-up fluid. In some projects, surface water (e.g. canal water) is used for drilling purposes, after checking its quality to avoid the risk of polluting drinking water aquifers (i.e. by the presence of certain bacteria).

To check casing condition in geothermal wells, and to intervene in case of detection of incurrent or potential damage, various monitoring systems have been implemented in different countries. These measures include adding corrosion inhibitors when reinjecting the geothermal fluid in the reservoir, using thicker tubing, wellbore integrity scans to assess deposit thickness and corrosion evolution. Flow rate, pressure and water quality are monitored during the operation phase to identify potential leakage. The quality of cementing work during and after drilling is tested through pressure tests and borehole logging.

The potential interference of operational wells with aquifers can be monitored in particular potable aquifers, in conjunction with the recording of meteoric conditions, in particular the rainfall and snowfall regimes. A continuous monitoring of piezometric regimes and periodical chemical analyses of waters reveals the hydraulic parameters of the freshwater resource, and establishes the correlation between the aquifers and meteoric inflow, and thus defines if there is any correlation with geothermal fluid production. Water quality controls of intersected aquifers allow to be reactive in case of contamination and take actions to contain pollutant propagation. Different preventive and remedial solutions are implemented in order to mitigate the risk of connection between aquifers and their disturbance.

### Potential for technological development

With respect to reduce the water consumption and promote a sustainable water-use management the following developments are envisioned:

- new technologies for water use reduction and water management
  - Water saving for construction & drilling
  - Water saving in the operation phase (i.e. for cooling)
  - Re-use of steam condensate in PPs
  - Waste water management
- new technologies for groundwater protection
  - well integrity monitoring & mitigation
  - groundwater system monitoring
  - prediction & control models for long term sustainability

Use of numerical modeling can ensure the absence of negative hydrogeological-qualitative-quantitative interference between geothermal wells (both new and existing) and other water withdrawals or precious aquifers, drinking water, protected water systems, etc.

It is proposed to expand the use of models in an operational and decision-making sense to solve the following issues with numerical parameters:

1. Decide on the optimal geometric location and usage pumping/reinjection data of geothermal wells (both for production and reinjection)
2. Ensure that geothermal activities do not cause qualitative and quantitative interference with existing or planned critical water withdrawal points such as: other deep and superficial geothermal wells, hydro-potable and hydro-mineral wells, agricultural wells and other uses as per existing concessions and acquired rights
3. Predict the hydrogeological evolution of potentially affected aquifer systems in the short, medium and long term
4. Forecast costs-revenues to be included in the business plans
5. Define a standard parameter of univocal objective meaning to express a merit judgment on the potential of the aquifer and its guarantee of safety
6. Other plant management and economic-financial objectives

## Target and KPIs

Operational and monitoring strategies for water for optimal use of water and groundwater magements

Ensuring safe operational envelopes and contributing to enhanced environmental performance and control

**Tentative budget** 50 M€

for Enhancing water management

## TOPIC 4: SUSTAINABLE RESERVOIR MANAGEMENT

### Objective

Develop methods to enhance sustainable reservoir management, in particular in promoting guidelines, methods and monitoring & control tools for safe operational envelopes for reservoir thermal-pressure-chemical changes and associated potential environmental risks including induced seismicity, subsidence or uplift.

### Current status

Many projects funded by EU target induced seismicity understanding and its control either directly (i.e. GEISER, MEPHISTO, COSEISMIQ, GEoREST, DEEP) or indirectly (DESTRESS, GEOENVI, GEORISK).

National regulatory bodies are focusing on producing guidelines to assess induced seismic effects related to deep geothermal (Switzerland: GRID method, Netherlands: Quickscan method, Austria: in progress, France: in progress, Italy: in progress).

Due to limited data sharing, comparisons are difficult between different projects. One can identify the few sites with seismicity problem, but little information is available from the sites. Methods must be improved to identify probable mechanisms and provide reliable statistics on the number of geothermal projects affected by seismicity.

Tools to manage seismicity, TLS (Traffic Light System) has shown its limits several times (Basel, Pohang, etc.). More elaborate methods including predictive tools based of physics based understanding (e.g. ATLS) are still in the development phase, and not yet ready for industrial use.

### Potential for technological development

Develop predictive models usable by industry either developing further statistical models or finding way to better constrain physic-based models for different geological settings in Europe.

Establish a European code of best practices to monitor, control, share data and exchange best practices on seismicity to address any potential environmental effect and a more efficient communication.

Develop collaborations and research infrastructures to ensure access to data on seismicity to help research advances on this topic

Develop methods to predict and validate a seismic reservoir deformation as a major mechanism for accommodating reservoir strains,

Assess ways to use this data, to better understand its relationship with induced seismicity as a function reservoir types and thermo-mechanical properties.

Improve operational conditions, including temperature, pressure and chemical changes and their effect on reservoir strains and induced seismicity.

To this end, also improve knowledge and ways to assess fault geometrical and frictional properties as well as local stress field.

### Target and KPIs

Stochastic methods usable by industry capable to predict safe operational envelopes for reservoir temperature, pressure and chemical changes for different geological settings in Europe (in view of induced seismicity and subsidence/uplift)

European code of best practices to monitor, control, share data and exchange of best practices, as well as strategies for public engagement.

The KPIs are:

1. Safe operational envelope (i.e. max temperature and pressure changes) in specific reservoir settings allowed to avoid the occurrence of seismicity felt by local community
2. Monitoring, control and public dialogue strategies ensuring public trust in geothermal technology

**Tentative budget** 100 M€

- Develop methods to enhance sustainable reservoir management: 40 M€
- Test these methods on site: 60 M€

## TOPIC 5: DEVELOPING WITH AND FOR SOCIETY

### Objective

The key issue is transforming the image of Geothermal industry - from a provider of electricity and heat to the possibility of generating business and welfare and advanced services to communities, with a substantial involvment of responsible end-users.

To make sure that geothermal energy can play its role in Europe's future energy supply in a sustainable and responsible way, it is essential to foster strong interactions among strategic groups of stakeholders in the research and innovation process.

The objectives are then:

- To better understand a range of social and cultural aspects and factors that shape the relationship between geothermal technologies and society (individuals, communities and their interactions in the energy transition);
- To foster mutual learning among different stakeholders, enhancing the contribution of all societal actors,unleashing the potential of geothermal energy and building trust among the quadruple helices (civil society, research and academia, businesses and policy-making);
- To design, implement and assess open innovation approaches (e.g., co-creation, technology assessment, citizen science) for the upstream inclusion of citizen and other stakeholders' perspectives in the innovation process of geothermal energy technologies, preventing possible social conflicts around geothermal technology developments;
- To experiment new forms of citizens and stakeholder engagement actions (e.g., public deliberation for policy making) within the geothermal policies' cycle (i.e., from the design to the monitoring), therefore building better policy outcomes, making governance more inclusive and enhancing citizens trust in democratic institutions.
- To study and experiment responsive, fair and inclusive energy communities to empower citizens.

### Current status

As Geothermal Energy is a regional Resource, the modern view of building trust and avoiding social conflicts should be to facilitate the development of projects that are aligned to social needs and expectations at different scales (from the local, to the global).

Geothermal regions (Tuscany in Italy is an example) already profit considerably: environmental compensation resources and technological developments have improved local infrastructures and air quality. Local small and medium enterprises are highly involved in the maintenance activities with considerable business and welfare fallouts. Direct benefits such as low-price DHC are offered.

Although social and other non-technical aspects are increasingly considered key determinants towards the transition of a low-carbon society, the studies on social impacts of geothermal energy in Europe are still scattered and often lack a homogenous approach. The public has the possibility to participate in the development of geothermal projects. However, the modalities and quality of the dialogue varies, as EU legislation on public participation foresees that the member states determine how they wish to inform the public.

Various methodological approaches and research techniques have been applied in order to engage the public in relation to geothermal projects, including surveys, interviews with key stakeholders, focus groups, media analyses, roundtables, public events, workshops, local referenda, seminars, information campaigns and education activities. Social indicators based on analytical results from these consultations have not been clearly defined. The definition of engagement standards would help in valorising meaningful and accountable participation processes, that help in building trust among societal actors.

Another important way to ensure social engagement and trust in geothermal projects is to share benefits with the customers and the citizens. The objective is to develop organizational models and best practices with geothermal energy projects sharing economic or other benefits created by the projects with the local communities (e.g. through local co-ownership, & local crowdfunding, (financial) compensation mechanisms or the creation of local green jobs).

## Potential for technological development

- Develop effective tools for engagement with the public and stakeholders
- Foster Energy Communities and energy citizenship
- Analyse the social effect of an increase of geothermal energy in the energy mix
- Rolling out a programme of information packs for schools (link with topics 8&9 and chapter E) - teach the kids and you also teach the parents.

## Target and KPIs

Targets:

- Build trust in geothermal energy technologies among different stakeholders
- Improve knowledge from society towards better technologies
- Generate and account public benefit in geothermal development

KPIs:

- Establish standards for meaningful participation in geothermal energy projects, also in comparison with other RES
- Number of geothermal Energy Communities

## Tentative budget 50 M€

- Develop tools: 20 M€
- Implement defined methodologies: 30 M€

## TOPIC 6: FINANCING AND RISK MITIGATION

### Objective

The two objectives are to bring the right financial schemes for all geothermal technologies and to minimise the uncertainty associated with geothermal project development and operation with guarantee schemes.

On financial risk management, it must build paths towards a Europe-wide system to cover risk associated with geothermal project development all over Europe. Following the adoption of the updated EU Directive on renewable energy sources, the provisions of article 23 must be implemented by all member states of the EU: "creation of risk mitigation frameworks to reduce the cost of capital for renewable heat and cooling and waste heat and cold projects, inter alia allowing for the bundling of smaller projects as well as linking such projects more holistically with other energy efficiency and building renovation measures;".

The second objective is improving the accessibility of financing for geothermal technologies, being private finance or public support schemes. Financing R&D&I helps to remove major barriers to technological development across the whole value chain. It also reduces the delay in scaling technology innovation up to market readiness.

Financial instruments fitting for the specific constraints of geothermal allow more projects to be undertaken and innovation to be achieved.

### Current status

To mitigate the resource risk, which is the major barrier to entry for geothermal project developers and especially municipal DHC entities, several countries established financial risk mitigation schemes (France, The Netherlands, Switzerland, Hungary, Belgium (Flanders), Turkey, Denmark). They aim at proposing financial guarantee schemes that manage to transfer the geology-related resource risk to the financial scheme. In such a manner, project developers can accept their fair share of the resource risk whilst lowering their financial exposure in case of failure, to develop a geothermal reservoir on one site, as well as minimized societal costs. They all start with public funding, but as costs decrease and markets develop, the private sector is able to manage project risks with, for example, private insurance schemes, and attract private funding for public-private partnerships like in France.

With the notable exception of these few European market participants operating in well-developed geothermal regions, project developers have very little capability to manage the financial risk that is related with poor knowledge of the deep subsurface and/or lack of technological progress and high cost. In effect the probability of success/failure weighted net present values of project cash flows tend to be overly negative, thus effectively shutting out private capital from investing in geothermal energy.

However, technology development (increasing the probability of success of finding and developing geothermal reserves) coupled with experience, and thus reductions in cost, project developers will eventually be able to accept and, where appropriate, transfer project risks (technical, economical, commercial, organizational and political) in such manner that private funding will become available. Until then, a Geothermal Risk Insurance Fund is seen as an appealing public support measure for geothermal.

The recently achieved GEORISK project was aiming at supporting the establishment of insurance schemes in Europe.

Geothermal technologies are capital intensive. Public financial support  is required to compensate market failurs and to help geothermal costs to decrease. Public funding is also needed to attract private financing in a difficult investment climate. Geothermal large scale projects take some years to develop and with their risk profile, tailored financial instruments are required.

European and national research, innovation and development programmes support R&I in geothermal for an amount of circa 50 million euros per year. In top, national support schemes on investment phase or operational phase bring financial supports in some members states through grants, feed-in premium, contract for difference…

Public finance can serve to mobilise private financing for geothermal, project, with a huge leverage effect. A greater involvement of the private sector is essential. Not all financial institutions and private investors are familiar with the complexity of geothermal technologies. A diffident approach towards the sector is needed as that lack of capital, notably during the early project- stages, has commonly been a barrier hindering the growth of geothermal. Private financing in the geothermal market can be still considered in its early stage. Significant investment, higher level of risk, long project development cycle and long expectation for the return of investments (RoI) are the key challenges of a geothermal project. Every project has its individual financing requirements due to the specific project parameters related to geology, finance, politics and technique.

## Potential for technological development

Research areas on these topics include:

On De-risking schemes:

- Development of a specific resource assessment standard. Shared resource assessment methodologies exist in oil & gas business. They facilitate the dialogue between companies and financial institutions.
- Survey of exploration or pre-cost risk in other industries (notably hydrocarbons but not only) and how cost and risk are managed and integrated in the overall business model. Benefits/drawbacks analysis of portfolio vs insurance schemes. Analysis of the specific issue of moral hazard in insurance schemes.
- Establish schemes for allowing exchange of geological data, knowledge and experience between geothermal, oil & gas and other subsurface services companies.
- Create of simulation model for establishing sustainable risk mitigation scheme with a medium-term perspective. 0
- Establish a Financial Risk Management schemes and risk-sharing facilities (Risk Insurance Mechanism)

On finance:

- A retrospective survey of developments following the final investment decision of geothermal projects in order to assess the nature and level of the remaining uncertainties which can impact investment profitability.

- Developing innovative financing mechanisms adapted to the specificities of geothermal technologies and the maturity level of markets and technologies, notably to allow market deployment of innovation. Financing demonstration projects must be going beyond the "one-size-fits-all approach".
- When designing a support scheme or a sustainable financing programme, policy-makers should take a holistic approach, such as non price criteria, which goes beyond the LCoE and includes system costs and all external factors with a LCA approach. Alternatively there is the possibility of offering geothermal a bonus for the benefits it provides to the overall electricity system both in terms of flexibility and base load. The base load characteristics of geothermal and its contribution to electricity grid stability should be adequately remunerated, as should the production and use of heat.
- Public support schemes covering different financial needs such as R&D, demonstration, the exploration phase identifying areas of interest, and the drilling/production phase (market conditions) in order to support technological progress throughout the learning curve.
- Establish an innovative financial support scheme for Geothermal deployment (Heat Purchase Agreements, permitting and remuneration within the state aid framework)
- Develop energy market models able to properly remunerate the various benefits of geothermal energy and allow to sell heat and power on different markets

## Target and KPIs

- Geothermal resource assessment standards and potential evaluation in view of Energy market simulation models
- Harmonized transparent methods for resource assement, supporting bankability and development of geothermal projects, lowering LCoE by 5-10%
- EU harmonized financial support schemes for Geothermal deployment (Heat Purchase Agreements, permitting and remuneration within the state aid framework)
- EU harmonized Financial Risk Management schemes and risk-sharing facilities (Risk Insurance Mechanism)

**Tentative Budget** 50 M€

# TOPIC 7: POLICY AND REGULATORY

## Objective

To develop geothermal in Europe, for juvenile or mature national markets, geothermal market actors need a European and national suitable political frame for short, medium and long term, which:

- Sets up a level playing field at the European and national levels to help the development of geothermal energy in Europe, and therefore allows for overall consistency with the vision for geothermal energy in Europe
- Have a clear roadmap and industrial strategy at EU and national levels to better plan the development of geothermal energy and engage towards the better set of the policies and regulations on geothermal.
- Establish dedicated policies that allow reaching then 2030 and 2040 climate and energy objectives, and the 2050 climate Paris objectives with carbon free technologies in the energy supply like geothermal
- Establish a long-term vision, inserted in energy modelling, for the development of geothermal in Europe
- Define the role of geothermal in the energy system, notably in the electricity market and the supply of heating and cooling.

The goal is also to establish a legislative framework allowing for geothermal deployment, its penetration, and profitability, while guaranteeing that resources are properly managed.

This includes the establishment of appropriate European and national legislation and regulations by:

- Better regulations: Mapping the regulatory issues affecting the geothermal sector and highlighting best practices at each step of a geothermal project, from exploration to decommissioning, to be replicated. It includes assessing and optimising the environmental, social and economic footprints of geothermal and establishing provisions for geothermal energy in various codes (Mining, Environment, Water, etc.)
- Simplify permitting: Introducing a unifying process for geothermal projects (one address for all Public entities) a suitable licensing processes (first-come, first-served, licensing rounds, competition window, etc.) and on works authorisation processes

## Current status

In terms of policies and regulations contributing to the development of geothermal energy, European and some national climate and energy frameworks with national roadmaps have been established for 2020, 2030 and 2050. In addition, at the European level, there is a long-term objective to reduce emissions by 80% to 95% by 2050, to which the addition of the Paris agreement raises the objective to the achievement of carbon neutrality in the middle of the century. This long-term objective is pursued through intermediary targets, notably for 2030. These targets are the cornerstone of the support schemes and the focus given on RES which enabled the recent development of geothermal energy in Europe in the past decade.

Geothermal energy is a heavily regulated sector and typically requires a specific support framework. When considering the European regulatory and policy framework, various interlinked regulations and policies create a complex regulatory background.

The most important pieces of European legislation underpinning the regulatory framework for geothermal are: Climate policies (Emissions Trading Scheme/Effort Sharing Decision Regulations for the non-ETS sectors), Energy policies (Electricity market rules, Renewable Energy Directive, Energy efficiency and buildings directives) and packages (2030 Climate and Energy Framework, REPower EU) and EU Environmental Directives ( Air Quality Directive, Water Framework Directive, Environmental Impact Assessment Directive, National limitations on air pollutants, Radiation Protection Legislation)

The GEOENVI project provided recommendations for harmonising environmental regulations across Europe, and developing a life cycle approach to assessing the environmental impact of geothermal.

## Potential for development

To attract the attention of decision makers, and particularly to get them dedicating resources for technological RD&I on geothermal energy, it is valuable to provide evidence as to the benefits of geothermal energy. For this, there are four research priorities that have been identified:

1. Developing a welfare analysis of the increase of geothermal energy in the energy mix through a comprehensive assessment of the potential deployment and impact of geothermal energy on economic growth, social welfare, employment, environmental benefits (Life Cycle Analysis), trade balancing
2. Screening and mapping, exchanging and replicating best practices on policies relevant for RD&I in geothermal energy. This includes an analysis of stakeholders and their roles (i.e. business models, policy incentives, goverrnance, political dialogue, public engagement and co-ownership) for the efffective development of (geothermal) energy communities, and underlying RD&I needs
3. The establishment of a system approach and exemplary ecosystems to test and validate policies for (geothermal) energy communities. This facilitates a more integrated development of innovative technologies and increasing cooperation across the value chain as well as the diffusion of technology innovation.
4. A long-term vision and industrial strategy for geothermal, as well as follow-up of developments and market evolution are crucial elements to guide policy making and ensure the consistency of a sound integrated framework.

## Target and KPIs

- Set simplified legal and regulatory framework among European countries: develop traffic light systems for go-to-areas and mapping resources
- Publich national geothermal roadmaps and industrial roadmaps
- Develop Guidelines for licensing and EIA
- Develop fair competition between energy sources and reinforce integration with other technologies (including royalties and energy taxation)
- Optimal inclusion of geothermal in energy planning, in particular in urban areas

**Tentative Budget** 10 M€

## TOPIC 8: QUALIFICATION AND TRAINING

### Objective

The deployment of geothermal market will trigger a real boom in labour-intensive activities such as exploration, drilling, installation, construction and manufacturing.

The overarching aim is to prepare a well-educated and high-skilled workforce needed for a competitive fast growing geothermal market with quality. To this end, the specific objectives are:

- Training a growing and skilled workforce for the geothermal sector to face the present and future energy challenges of Europe and to maintain the quality for delivering energy with reskilling, upskilling and cross-skilling.
- Set a quality mark for geothermal energy skills that is recognized by professionals and end users
- Establish a network of academies, institutes, training centres to educate and train the geothermal workforce

The goal is to ensure the existence of necessary skills in the sector. It requires action at all levels of qualification and training, meaning technical and scientific education, training and continuous learning. In order to achieve the proper education reforms, cooperation between all organizations involved is required.

### Current status

Geothermal education and training is not organized at national and European level. A coordinated effort in this field within an industrial strategy would be beneficial both for higher specialization and for outreach and job creation. A cooperation between research and training institutes, professional associations and companies is needed in order to create networks for implementation and training.

The European Commission is placing skills at the heart of the EU policy agenda, steering investment in people and their skills for a sustainable recovery after the coronavirus pandemic. The European Skills Agenda is the framework for EU skills policy cooperation and will continue to help individuals and businesses develop skills and to apply them. In the Pact for Skills, a large-scale partnerships on Renewable Energywas created in 2023, to answer REPowerEU targets which require the creation and upskill up to over 3.5 million jobs by 2030.

In 2023, there were more than 40,000 jobs directly related to geothermal in Europe. Geothermal energy jobs can be broken down into different types, from engineers, drillers and workers in equipment factories to project managers. Geothermal also generates indirect jobs, for example with suppliers of raw materials and induced jobs. However, to unlock opportunities for more and better jobs, as well as growth and competitiveness, the training of skilled educated manpower as the upskill or reskill of current workforce in declining industries are crucial to succeeding in the needed scaling–up of the geothermal European industry.

## Potential for development

The potential of the geothermal industry can be achieved only through the attraction, retention and renewal of the workforce. Companies and research organisations need to adopt a range of measures which will allow them to have access to the highly skilled workforce they need. Several actions are needed:

- Develop a job task analysis to establish status, needs and gaps of geothermal employment
- Set up an employment action plan to develop a coordinated implementation and training programme, coordinated with other RES and sectors (oil & gas, CCS, etc.) and including reframe of skills
- Define a certification scheme for professional skills
- Create networks for geothermal energy implementation and training involving professional associations, industrial platforms, universities and research centres with competences in geothermal energy-related disciplines—geosciences, material sciences, mechanical engineering, computational sciences, social, economic and legal sciences. This action should include also shared research and demonstration infrastructures.

## Target and KPIs

Number of certified professional and trained employees

Average expenses on training per employee

**Budget** 5 M€

## TOPIC 9: COMMUNICATION AND PUBLIC AWARENESS

### Objective

A first objective is to contribute to sound, science-based information communicated in a clear way, and increase awareness of geothermal externalities and benefits. It is important to clarify the role of geothermal in the future (e.g. 25% of homes will be heated by geothermal by 2040) and the sustainability (environmental, economical, societal) of geothermal technologies. Public communication actions supported by public institutions with a neutral role should be implemented and adapted to the target audience. Risk communication should be a significant part of this action.

A second objective is to establish information sharing practices tailored to different audiences. As underlined in the GEOENVI project, "quality communication which includes access to relevant information and environmental data sharing is essential for building trust between the project developers and the public". Transparent information sharing is a way to fence off possible misinformation from other sources and to present an opportunity to communicate success stories.

A third objective is to experiment modern communication and information tools, also oriented to young generations (e.g. comics, games and interactive tools including augmented reality), which would enrich the information package for schools (link with topics 5&8 and chapter E)

### Current status

Public awareness of geothermal technologies is crucial to their deployment. Based on competitiveness, sustainability and energy independency, geothermal energy may play a main role in the energy transition. It often appears that the general public is not well-informed about geothermal technologies and is not able to distinguish between different geothermal energy systems and related environmental and technological issues. It is not well-known enough that in the comparison of environmental impacts of energy generation technologies geothermal performs much better than the fossil competitors and very well also with respect to other renewable technologies.[2] Communication regarding risk is difficult and may result confused or ineffective. Moreover, official statistics and industry statistics on geothermal are often inoperable and fragmented. In many countries, statistics on geothermal are not collected systematically, often because the utilisation is considered too small to devote resources to the collection, and so estimates or other often inaccurate methods are used. This can prove to be problematic for the geothermal industry when there are no reliable statistics to use for research or the promotion of geothermal energy as a reliable energy source. In addition, the statistics and information collected are not easily available, sometimes even very difficult to access, and the lack of data can be interpreted as a lack of transparency.

### Potential for technological development

- Develop effective communication with the general public of technology, risk and benefits, also strengthening the collaboration with other RES and sectors

2 https://eeb.org/library/the-reference-environmental-standards-for-energy-techniques-reset-guidance/

- Increase transparency of information and amount of shared geothermal data, also by definition of standards to improve data consistency and allow comparison. A part of these standards should be defined in collaboration with other RES.
- Launch targeted communicaitons campaigns to increase awaress of citizens, decision makers and end users,

### Target and KPIs

- Number of earned media mentions
- Sentiment (perception: positive, negative, or neutral)
- Number of projects abandoned due to lack of public acceptance

**Budget** 5 M€


*Building of the Cartographic and Geological Institute of Catalonia.* Source: EGEC Geothermal


# F. DATA AND KNOWLEDGE SHARING

Enabling Europe's energy sector to meet the challenges and opportunities of the 21st century and fulfil the expectations of society requires intensified and sustained research efforts. It is essential that this takes place in a coherent way. Sharing knowledge is crucial for support to all research and innovation actions as well as non-technical barriers/enablers.

Establishing an open-access policy to geothermal information (including standard exchange formats) will ensure open and easy access to data and information. A cultural shift has already begun as leaders in industry, academia and regulatory agencies recognize the value in increased transparency and data sharing and are focusing on how—instead of why—data should be shared. Beside improving the accuracy of research, strengthening collaborations and accelerating research, data sharing restores trust in data. Many countries provide public data, but they are scattered and inhomogeneous. The scope of this cross-cutting action is to facilitate access to geothermal information at the European level via the development of an information platform, and the creation of standard and common data models at the EU level. This should be achieved through progressive harmonization of national data to facilitate data discovery and data mining.

It is also vital to demonstrate capacity building, industrial technology transfer and science & academic partnerships via know-how throughout Europe, and with the shared goal to develop high quality, competitive and sustainable geothermal energy projects. This includes supporting the existing pan-European infrastructure of experimental test and monitoring facilities and infrastructures including laboratories and making efficient and coordinated use of them. In several EU countries, research infrastructure for basic and applied research in the geothermal field is fairly well established. There is definitely a need for a well-organised exchange on test standards for various technologies spanning from exploration, drilling, and generation to operation. A joint effort for large-scale demonstration is needed to ensure successful market introduction. At the same time, the next phase of development will require focus on technology transfer and widespread demonstration projects. This cross-cutting action also aims at training and educating new geothermal professionals (details in chapter D: Topic 8: qualification and traning).

Below we summarize the major topical for data and knowledge sharing. It is assumed that implementation is largely steered through long term and task-based (i.e. not R&D oriented and not limited to geothermal) financial instruments which are implemted on national and EU basises. Examples include Geological surveys and the overarching EUgeosurveys network, EU funded research infrastructure programmes such as EPOS the European Plate Observing System (epos-eu.org) and EGDI – European Geological Data Infrastructure (europe-geology.eu)

## TOPIC 1: UNDERGROUND DATA SHARING - UNLOCKING EXISTING SUBSURFACE INFORMATION

### Objective

Facilitate open access to subsurface data from geothermal, hydrocarbon exploration and production, and mining.

Promote the access to geothermal information at the European level via the development of an information platform, the creation of a standard and common data model at EU level, and harmonization of national data to speed up data discovery and mining. This is an important step to help scientists, stakeholders, investors and geothermal developers, and the basis for a more accurate resource assessment and feasibility studies.

### Current status

A wealth of information of geothermal prospects is available from past subsurface exploration and production. For exploration, it is estimated that at least 1000 billion euro has been invested in exploring oil and gas reservoirs in the past 50 years. Data includes well bore cores and logs, geophysical surveys including seismic images and other geophysical datasets, temperature and stress measurements. In most countries in Europe the data is not easily accessible and/or not in a format suitable for geothermal exploration. Geothermal data and mining are also of great relevance.

Various national initiatives are highlighting the importance of data-sharing, geothermal databases and resource mapping: ThemoGIS in The Netherlands, GEOTIS in Germany, GEOTHOPICA in Italy, Thermo2D and Geothermie Perpectives in France, DOV in Flanders, and the web-GIS platform of Switzerland. Actual databases have format and structure defined at the national level.

Need for common data-sharing is also well recognized on EU level (e.g. in the frame of Geothermal ERA-NET the concept of a European Geothermal Information Platform was developed following the interest of research and industry). At the moment only a small pilot is implemented for testing the concept. Both the concept and the pilot were tested and evaluated by stakeholders who showed high interest in the matter.

Geological data is freely available to project developers in some countries like the Netherlands where it is binding to release data after a five year period.

### Potential for technological development

Technological development options include:

- Definition of standards (e.g. for database format, services which make automatic uses of data) and data models
- Set principles of geological data freely available after a period of time in national regulations (details in chapter D: Topic 7)
- Data preparation, harmonization and publication through national web-services
- Development of the geothermal information platform, providing services for open-access data harvesting, data mining and data management (e.g. graphs, statistical tools, etc.)
- Inclusion of geothermal properties and resource mapping taking the advantage of a common geothermal exploration protocol (see resource assessment item)

## TOPIC 2: ORGANIZATION AND SHARING OF GEOTHERMAL INFORMATION

### Objective

A rapid search of valuable information, and transparent and harmonized methods and instruments for technical and financial risk management, contribute to market uptake and accelerated innovation. The main aims on this regard are:

- Facilitate the access to geothermal information at the European level via the development of an information platform, creation of standard and common data model at EU level and harmonization of national data to facilitate information discovery and data mining, to foster the technical and non-technical knowledge exchange on a European level.
- Create a web-based knowledge transfer system related to technical and non-technical aspects of interest in different European countries, and create a community that fuels this system at the same time.

## Current status

While there is an abundance of information already contained within many websites, databases and more, getting access quickly and easily to the right information can be difficult. Currently geothermal information (including technical topics as well as national energy policies, economical and regulative information, geothermal energy production, market and social requests, and training offer) is organized separately by each member state, and only a few cases is the information organized and coordinated at European level (e.g. energy production and installed capacity for Eurostat). In the frame of the Geothermal ERA-NET project the strategic importance of sharing the knowledge was evidenced, and two joint activities were proposed on this challenge.

The concept of a European Geothermal Information Platform (EGIP), a Web tool gathering data and knowledge from national and scientific providers following the European INSPIRE directive (i.e. data remain the property of the providers who host them) was investigated. The state-of-the-art and needs regarding geothermal data and existing tools to manage them were described, the interest to the various topics was prioritized by means of a questionnaire, and the concept and its application were described in various documents. EGIP is meant to be interoperable with other pan-European data platforms (e.g. EGDI). At the moment it remains to be uncreated, besides (1) a Pilot Platform for a few underground data and documents sharing and (2) the Search Engine of European project documents realized within the ETIP-DG website (EGRISE), recently expanded to retrieve data and documents from strategic repositories (e.g., OpenAIRE, Zenodo, Pangea) and scientific journals and reaping meta information of each single research products.

Another concept of knowledge sharing developed by Geothermal ERA-NET was OpERA-pedia (operational issues of geothermal installations in Europe) to contribute to optimal availability of information regarding operational issues, which were identified as some of the main barriers for the development of geothermal energy and as an urgent R&I need. This activity was funded by some countries and a wiki-style knowledge platform on operational issues is currently in development.

## Potential for technological development

The building of knowledge sharing tools, which, following the track of Geothermal ERA-NET, require the following:

- Definition and prioritization of technical and non-technical topics and issues to be organized (to finalize the activity already initiated in the Geothermal ERA-NET)
- The coordination of European and national contracts/subsidies on chosen topics, handled nationally by the national ministries/governmental agencies, bringing together national experience
- Creation of working groups of the national experts and stakeholders (industry, research, public and administration, depending on the topic) to provide a collection and an overview of documents and of technical issues and their applied and potential solutions

- Definition of standards (e.g. for database format, services which make automatic uses of data) and data models
- Data preparation, harmonization and publication through national web-services
- Development of the Geothermal Information Platform, providing links to tools (e.g. common wiki-style tools) and services for open-access data harvesting, data mining and data management (e.g. graphs, statistical tools, etc.)
- Explore and test new tools (e.g. available energy signposting) and development of innovative ones for sharing information

## TOPIC 3: SHARED RESEARCH INFRASTRUCTURES

### Objective

Achieve excellence in highly-demanding scientific fields related to geothermal energy and its development and simultaneously contribute to the European Research Area (ERA) and Innovation Union.

Enable the greatest discoveries in geothermal technology, attract researchers from around the world, and build bridges between research communities.

### Current status

Research infrastructures (RIs) are facilities, resources and services used by the science community to conduct research and foster innovation. They are traditionally made of major scientific equipment, resources such as collections, archives or scientific data, e-infrastructures such as data and computing systems, and communication networks. In the geothermal sector the availability of demonstration sites, with access to wells and plants for testing and developing innovative concepts and technologies, is crucial, but only a few are currently available.

While research centres working in the geothermal sector may already participate to large RI in various fields (e.g. EPOS), there is no shared RI specifically dedicated to geothermal topics.

### Potential for technological development

To build a shared geothermal RI by recognising single-sited RI (single resources at a single location) of European interest, and foster Integrating Activities projects for transnational access, open to all European researchers from academia and industry

# G. CONCLUSIONS AND MISSION

First and foremost, we would like to thank the members of ETIP Geothermal. After over 2 years of work and the COVID pandemic, the SRIA has finally been finished. In conclusion, the 2023 Strategic Research and Innovation Agenda (SRIA) undertook an in-depth exploration of resource assessment strategies, seeking to mitigate the inherent risks associated with exploration while simultaneously amplifying the latent potential of resources. This endeavor prominently revolved around the refinement of predictive technologies and advanced visualization methodologies. Subsequently, the SRIA intricately examined pioneering drilling innovations and cost-efficient methodologies, accentuating novel approaches and the integration of cutting-edge materials in well construction. Progressing further, the subsequent section illuminated pathways towards optimal resource utilization, underpinned by advancements in power generation cycles and the extraction of valuable minerals. Lastly, the ultimate segment of the document underscored the paramount significance of sustainable practices, deftly navigating the intricate terrain of market dynamics and environmental imperatives. Collectively, this comprehensive compilation serves as an indispensable roadmap for realizing a sustainable and impactful trajectory in the realm of geothermal energy.

## Mission

The ETIP Geothermal's mission is to share knowledge and innovation amongst members of the Platform. The mission of the ETIP Geothermal is to accelerate the development of geothermal technologies in Europe by focussing on overall cost reduction, including social, environmental, and technological costs. The mission complies with the targets of the SET-plan Implementaiton Working Group on geothermal:

*"Geothermal IWG Vision for 2050*

*The IWG envisages a net-zero Europe in 2050, where:*

- *Geothermal heat supplies more than 25% of Europe's demand for space heating and cooling, and more than 25% in the agricultural sector (greenhouses) and 5% in industrial sectors in the low to medium temperature range.*
- *10% of the power production in SET Plan countries is from geothermal power.*
- *Underground thermal energy storage supplies more than 10% of Europe's demand for space heating1 mainly for district heating, thus requiring collective systems.*
- *Co-production of minerals and critical raw materials (CRM) such as lithium for resilient transportation sector and strategic autonomy is established in at least 10 European regions.*

*In line with EU goals on resilience, the IWG aims to increase resilience of the geothermal energy supply chain, and to have 40% of the supply chain "Made in Europe" by 2030.*

The SRIA is one of its main publications, along with the Vision. The ETIP Geothermal Vision will be a separate and complimentary document that frames the future with a geothermal energy forward focus. In addition, it also publishes a roadmap for geothermal energy every two years. We invite you to have a look at the latest available Vision and Roadmap. Should you be interested in becoming part of ETIP Geothermal or collaborating with us, please do not hesitate to contact us via our website.

# GLOSSARY AND ABBREVIATIONS

# GLOSSARY

**Base load**
The minimum amount of energy that a utility or distribution company must generate for its customers, or the amount of energy required to meet minimum demands based on reasonable expectations of customer requirements.

**Binary system**
A type of geothermal plant that uses geothermal fluids to heat a secondary fluid, which is in turn used to generate electricity by means of a turbine. It differs from Flash Steam systems in that the water or steam from the geothermal reservoir never comes into contact with the turbine/generator units.

**Capacity Factor**
The ratio between the energy actually produced and the energy that would be produced at full capacity.

**Cascade uses**
Sequential operation of geothermal heat by integrating different technologies using progressively lower temperatures. The resulting poly-generation exploits the available energy remaining after each use and optimises generation benefiting from different uses at lower temperature requirements.

**Consumers**
People purchasing and consuming energy (or any goods and services in other contexts).

**District heating**
A system using a network of pipes to distribute hot water generated in a centralised location for residential and commercial heating requirements such as space heating and water heating.

**District heating and cooling**
An expansion of the district heating concept, combining technologies for centralised generation and distribution of heating and cooling.

**Environmental footprint**
A measurement of the effect upon the environment involved in the production of the energy under consideration (or any other good or service in other contexts).

**European Strategic Energy Technology Plan (SET-Plan)**
European plan for accelerating the development and deployment of low-carbon technologies. It seeks to improve new technologies and bring down costs by coordinating national research efforts and helping to finance projects. The SET-Plan promotes research and innovation efforts across Europe by supporting the most impactful technologies in the EU's transition to a low-carbon energy system. It promotes cooperation amongst EU countries, companies, research institutions, and the EU itself.

**European Technology and Innovation Platforms (ETIPs)**
Open platforms created to support the implementation of the SET-Plan by bringing together EU countries, industry, and researchers in key areas. These platforms promote the market uptake of key energy technologies by pooling funding, skills, and research facilities.

**Flash steam system**
A type of geothermal plant that uses geothermal fluids in the vapor phase to drive a turbine and produce electricity (see Binary system).

**Greenhouse gases**
Any gaseous compound in the atmosphere that is capable of absorbing infrared radiation, thereby trapping and holding heat in the atmosphere.

**Hybrid systems**
Two or more modes of power generation combined together, usually using renewable technologies.

**Heat pump**
A device that moves thermal energy in the opposite direction of spontaneous heat transfer by absorbing heat from a cold space and releasing it to a warmer one.

**Levelised Cost of Energy (LCoE)**
The ratio between the cost of generating an asset during its whole lifetime and the electricity produced. Representing the total costs, it can be used to compare different technologies that have unequal lifespans, project sites, capacities, capital, operating costs and revenues.

**Prosumers**
People that both consume and produce energy.

**Quality of life**
A broader concept than economic production and living standards, including the full range of factors that influence what people value in life beyond purely material aspects.

**Public engagement**
Envisions impacts and reflects upon underlying assumptions, values, and purposes to better understand how R&I shapes the future. This yields valuable insights and increases our capacity to act upon what we know.[3]

**Reinjection**
Underground injection of geothermal fluids, cooled after heat extraction, typically close by the extraction area.

3 https://www.rri-tools.eu/about-rri

**Research and development and innovation (R&D&I)**
Promoting R&D&I is an important European Union objective laid down in Article 179 of the Treaty, which states that "[t]he Union shall have the objective of strengthening its scientific and technological bases by achieving a European research area in which researchers, scientific knowledge and technology circulate freely, and encouraging it to become more competitive, including in its industry, while promoting all the research activities deemed necessary".[4]

**Responsible Research and Innovation (RRI)**
According to this approach, societal actors work together during the whole research and innovation process in order to better align both the process and its outcomes with the values, needs and expectations of European society.[5]

Sustainable development
Meeting the needs of the present whilst ensuring future generations can meet their own needs. It has three pillars: economic, environmental and social. In order to achieve sustainable development, policies in these three areas must work together and support each other.[6]

**Turbine**
A device that converts kinetic energy into mechanical energy and, when combined with a generator, electrical energy.

4 Official Journal of the European Union 27/6/2014, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.C_.2014.198.01.0001.01.ENG

5 "RRI. Europe's ability to respond to societal challenges", EU Commission, 2012, https://ec.europa.eu/research/swafs/pdf/pub_rri/KI0214595ENC.pdf

6 EU trade policy and sustainable development http://ec.europa.eu/trade/policy/policy-making/sustainable-development/

# TERMS & ABBREVIATIONS

**CCHP**
Combined Cool, Heat and electrical Power

**DH**
District Heating

**DHC**
District Heating and Cooling

**EU**
European Union

**GEODH**
Geothermal District Heating

**GHG**
GreenHouse Gases

**GSHP**
Ground Source Heat Pump

**H&C**
Heating and Cooling

**HT-UTES**
High Temperature Underground Thermal Energy Storage

**LCOE**
Levelised Cost of Energy

**O&M**
Operation and Maintenance

**R&I**
Research and Innovation

**RES**
Renewable Energy Source

**RRI**
Responsible Research and Innovation

**SHGS**
Super-Hot Geothermal Systems

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ETIP Geothermal
European Technology & Innovation Platform on Geothermal

The European Technology & Innovation Platform on Geothermal (ETIP-G) is an open stakeholder group, endorsed by the European Commission under the Strategic Energy Technology Plan (SET-Plan), with the overarching objective to enable deep geothermal technology to proliferate and reach its full potential everywhere in Europe.
The primary objective is overall cost reduction, including social, environmental, and technological costs.
The ETIP-G brings together representatives from industry, academia, research centres, and sectoral associations, covering the entire deep geothermal energy exploration, production, and utilization value chain.

For more information on its activities visit www.etip-geothermal.eu

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