GEOTHERM FORA

GEOTHERM-FORA Deliverable D3.3

Roadmap of Geothermal

Jan-Diederik Van Wees, TNO
Philippe Dumas, Giulia Cittadini, EGEC

Funded by
the European Union

Project Full Title:	Roadmap of Deep Geothermal
Project Acronym:	GEOTHERM-FORA
Title:	Roadmap of Deep Geothermal
Lead beneficiary:	TNO
Contributing beneficiaries:	EGEC
Related work package/ Related task(s):	3
Submission date:	31.08.2025
Security class:	Confidential/Public
Dissemination level:	All
Status:	Final version
DOI:	
License information:	It is recommended to use a Creative common license: https://en.wikipedia.org/wiki/Creative_Commons_license
Recommended Citation:	Roadmap of Geothermal
Related Data:	
ORCID:	Authors Orcid (or different Author Identifier)

Revision history	Author	Delivery date	Summary of changes and comments
Version 01	GC	11.07.2025	First draft compiling annual roadmap already published
Version 02	PD	11.07.2025	review
Final version	PD	18.07.2025	publication

Approval status				
	Name	Function	Date	Signature
Deliverable responsible	Giulia Cittadini, EGEC		11.07.2025	GC
WP leader	Jan-Diederik Van Wees	TNO		
Reviewer	Luca Xodo	Rete geotermica		
Project Coordinator	Philippe Dumas	Coordinator	18.07.2025	PD

Funded by the European Union from the Horizon Europe programme under the grant agreement n° 101075400.
Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

Contents

1. GEOTHERMAL ROADMAP 2022

ETIP DG Priorities for Horizon Europe Work Programme 2023-2024

1.1 TOPIC 1: Novel approaches for geothermal resource development

1.1.1 Specific challenges

The efficient resource development requires increasing or at least keeping steady the production of geothermal resources in the long run.
To achieve this result, some specific challenges need to be addressed:

- Topic 1 – Towards robot drilling technologies
- Topic 2 – Fast penetration rate technologies
- Topic 3 – Drilling fluids
- Topic 4 – Monitoring, Logging While Drilling and Geosteering in harsh environment
- Topic 5 – Production and stimulation technologies
- Topic 6 – Novel and optimised well architectures

The aim is for:

- Optimisation of the performance of the geothermal system
- Enhancement of production from a low-permeability reservoir.
- Improvement of the efficiency of geothermal fluid uplifting from the well bore.

1.1.2 Scope

- Improve the ability to control and predict reservoir performance and subsurface conditions and improve the sustainable management of the geothermal system by developing and testing of thermodynamic models coupled to the flow of heat/steam as well as models to evaluate coupled thermal, hydraulic, mechanical and chemical (THMC) processes in geothermal wells and reservoirs, accounting for subsurface structure and including the effects of long term production on the seismicity.
- Develop effective and safe technologies for increasing energy production from advanced well design, innovative procedures for permeability enhancement and new well completion technology (TRL 5 – 6 by 2023, TRL 7 – 8 by 2026, TRL 9 by 2030)
- Develop second-generation geothermal pumps/well bore designs with prolonged lifetime under aggressive fluid conditions, or alternative lifting technologies (e.g. gas lift) and avoiding mechanical erosion (TRL 6 – 7 by 2023, TRL 8 – 9 by 2026)
- Increase the ability to optimally design and operate the thermal flow and behaviour of geothermal reservoir, well field and heat (steam) network in order to improve the ability to control and predict the management efficiency of geothermal power and CHP plants.

1.2 TOPIC 2: Innovative approaches for the geothermal resource assessment

1.2.1 Specific challenges

In order to achieve this main objective, it is necessary that European countries agree and adopt harmonised protocols and pursue the assessment of geothermal energy stocks across Europe. This main objective is to be achieved via intermediate actions:

- Exploration technologies: imaging the resource
- Reservoir modelling: pre-drill assessment of resource performance
- Catalogues & geothermal database: harmonisation of data(bases) and data sharing
- Cutting edge & supercritical resources: extending the resource base
- Resources & reserves estimation: harmonised resources estimation and energy system integration

Numerous exploration techniques are used to characterise resources before, during and after the first wells are drilled in order to predict the resource, test the existence of a geothermal reservoir capable of sustaining commercial rates of fluid production and injection, and provide necessary data for sustainable management. Continuous effort as well as periodic RD&I opportunities are required in order to test and optimise developed technologies.

1.2.2 Scope and TRL

The main aim here is to characterise these resources and develop novel ways to use them, by:

- Developing advanced methods to estimate and forecast properties and coupled processes deep underground, and defining the abundance and techno-economic feasibility of resources in view of different applications by 2025 (TRL from 3 to 5)
- Demonstrating developed concepts by accessing resources and refining business models by 2030 (TRL 5 to 6).
- Mitigation of risks during the feasibility and operational phases of a geothermal project by maximising the probability of predicting physical (T, P, permeability, stress, thermal capacity, etc.) and chemical parameters as well as detecting fluid-bearing fractures and faults.

This action includes the following:

- Developing advanced exploration, investigation and monitoring technologies to reduce the cost of surveys and improve the resolution of underground imaging by 2025 (from TRL 3 to 6)
- Developing an integrated approach by improving the multidisciplinary aspect of exploration methods, using joint modelling, specialised data and computationally advanced exploration, investigation and monitoring technologies by 2030 (from TRL 3 to 6 with an extended demo)
- Improving well logging and logging-while-drilling tools and methods, building upon those used in geothermal and the oil and gas sectors so as to withstand harsh geothermal conditions (in particular, high temperatures) (from TRL 3 to 6).
- Developing innovative processes, materials and technologies able to improve the integrated management of the resources, well field and power plants in harsh environment.

1.3 TOPIC 3: Enhancing geothermal energy integration in the energy system

1.3.1 Specific challenges

On Heating and Cooling

- **Underground Thermal Energy Storage** (innovative seasonal techniques): realization for high temperature and deep storage systems, also combined with DH
- **Integration** of geothermal into existing District Heating and Cooling Networks in terms of technical aspects and economics with focus on the connection between subsurface and surface components: subsurface target for the demand
- **Transformation of grids from the 2nd Generation to 5th Generation of DH**
- **Geothermal Heat supply to industry** (High temperature applications; open points for geothermal h&c uses (DH and industrial)

On Electricity and Combined Heat & Power

- **Advanced Binary Plants & Binary cycle exploitation**
  The first objective is to develop advanced low-to-medium temperature (usually 100-180°C) binary plants by 2030 (from TRL 5-6 to 8). This must notably address the need for flexible heat/cold and electricity supply from binary cycles, including upscaling capacity from the binary plants. The improvement of plant performance should focus on the working fluid and on specific components (improved heat exchangers with higher effectiveness and lower pressure drop, material selection, surface structure and coating, hybrid cooling) of the binary cycle (from TRL 4-5 to 6-7 and then 8).

1.3.2 Scope &TRL

Among the major targets and KPIs related to generation technologies, this action refers to:

- Maximising electrical and thermal generation and subsurface storage efficiency by 10% by 2030 (from an average conversion efficiency of geothermal binary plants of 12% in 2019)
- Reducing the production costs of various applications by 15% (with respect to specific technologies) by 2030
- Demonstrating the technical and economic feasibility of responding at any time to commands from a grid operator to increase or decrease output, ramping up and down from 20% to 110% of nominal power.

Other specific KPIs for this action are to:

- Reduce the surface part of power plant costs by 15 % by 2030:
- KPI: Manufacturing cost of a custom design 5 MWe ORC turboexpander, which
- stands at one million euros in 2019.
- Upscale binary plants:
- KPI: Plants with a capacity higher than 30 MWe, including for EGS (currently the
- largest is 25 MWe).

1.4 TOPIC 4: Novel materials and equipment for smart operation of geothermal plants

1.4.1 Specific challenges

Alternative materials for Scaling & Corrosion

Development of effective and environmentally benign measures to prevent and control scaling and corrosion (TRL 6 – 8 by 2023, TRL 9 by 2026)

Development of safe and environmentally benign measures to remove scaling (TRL 6 – 7 by 2023, TRL 8 – 9 by 2026)

Development of materials that are resistant to corrosion and/or have anti-scaling properties. Such materials can help to reduce costs and downtime due to workovers and increase the lifetime of components such as submersible pumps and tubing (TRL 5 – 7 by 2023, TRL 8 – 9 by 2026)

Equipment

Development of second-generation geothermal pumps with prolonged lifetimes under aggressive fluid conditions or development of alternative lifting technologies (e.g. airlift) (TRL 6 – 7 by 2023, TRL 8 – 9 by 2026

Development of innovative efficient Heat pumps: challenges with heating systems coupled with HP

High Temperature sensors & tools

Development of electronics and sensors to be used in high-temperature geothermal wells during drilling operations. This will lead to better control of the drilling process, reducing the risk of wellbore instability and lost-in-hole incidents.

Development of data communication or telemetry technologies allowing fast and reliable data transfer under high-temperature conditions

Develop electronics and sensors that can withstand temperatures up to 350°C by 2030. • Develop data communication technologies that can withstand temperatures up to 350°C by 2030

Eco-friendly chemicals

Development of eco-friendly drilling fluids that are stable under high-temperature and high-pressure conditions and that effectively protect drilling equipment against corrosion
(TRL 4 – 5 by 2023, TRL 6 – 7 by 2026, TRL 8 – 9 by 2030)

Eco-friendly materials

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. Focus will be on:
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);

1.4.2 Scope & TRL

Action aims to prolong the lifetime of geothermal wells, piping and equipment by making the materials used more resistant to the detrimental effects of temperature, fluid chemistry and flow.
This can be done in a number of ways, either through materials research, the use of environmentally benign chemicals, or effective design and operating protocols.

1.5 TOPIC 5: Demonstration of mineral (lithium) production exploitation from geothermal sources

1.5.1 Specific challenges

Lithium & other minerals exploitation

- Selective extraction technologies: Contaminant removal, Upscaling
- Production technologies
- Concentration enrichment technologies
- Products to be produced in the GEOpp and to be integrated with the market chain
- Different minerals: Lithium, Silica, Magnesium…
- Ensure reinjection compatibility (for sustainable reservoir management)

1.5.2 Scope

The objective is to develop novel and potentially disruptive technological solutions that can help satisfy European needs for energy and strategic metals as well as other economical non-metallic materials in a single interlinked process. This means increasing the selectivity and efficiency of the separation techniques used for minerals and geothermal brines, as well as developing new, potentially disruptive technologies to separate and transform the chemical components of geothermal brines into more valuable products.

Demonstration sites for technologies for metal extraction: (from TRL 4-5 to 7-8, 2020-2023 and 2023-2026 periods)

Several pilot plants worldwide have been built to extract salts, silica, lithium and specific metals from brines, but industrial production has only taken place at a few locations and has been limited to the production of silica, Li, Br, J and Sn. Geothermal plants can optimise the production of both energy and metals/materials according to market demands by exploiting deep geological formations. The exploitation of mineral production can also help geothermal plants become more economically competitive.

2 GEOTHERMAL ROADMAP 2023

ETIP Geothermal priorities for Horizon Europe Work Programme 2025

2.1 TOPIC 1: Novel approaches for geothermal resource development

2.1.1 Specific challenge

The efficient resource development requires to increase or at least keep steady the production of geothermal resources in the long run. To achieve this result, some specific challenges need to be addressed:

- Towards drilling technologies with fast penetration rate technologies using Artificial Intelligence (AI) driven resource development
- Drilling fluids leading to enhanced wellbore cleaning, stability and integrity post cementing (including High Temperature cementing)
- Monitoring, Logging While Drilling and Geosteering in harsh environment
- Production and stimulation technologies
- Novel and optimized well architectures

The aim is for:

- Optimization of the performance of the geothermal system
- Enhancement of production from low-permeability reservoir
- Improvement of the efficiency of geothermal fluid uplifting from the well bore.

2.1.2 Scope

- Improve the ability to control and predict reservoir performance and subsurface conditions and improve the sustainable management of the geothermal system by developing and testing AI-driven thermodynamic models coupled to the flow of heat/steam as well as models to evaluate coupled thermal, hydraulic, mechanical and chemical (THMC) processes in geothermal wells and reservoirs, accounting for subsurface structure and including the effects of long term production on the seismicity
- Develop effective and safe technologies for increasing energy production from advanced well design, innovative procedures for permeability enhancement and new well completion technology (from current TRL 5 – 6 to TRL 9 by 2030)
- Develop second-generation geothermal pumps/well bore designs with prolonged lifetime under aggressive fluid conditions, or alternative lifting technologies and avoiding mechanical erosion (from TRL 6 – 7 today to TRL 8 – 9 by 2027)
- Increase the ability to optimally design and operate the thermal flow and behaviour of geothermal reservoir, well field and heat (steam) network in order to improve the ability to control and predict the management efficiency of geothermal power and heat plants.

2.1.3 Required budget

40 million € (4 projects with 10 million € budget each)

2.2 TOPIC 2: Innovative approaches for the geothermal resource assessment

2.2.1 Specific challenge

One of the major roadblocks for accelerated deployment of geothermal installations in many parts of Europe is the lack of available or accessible subsurface information. It is therefore of paramount importance to upscale data acquisition and exploration efforts, given the rapid development of new technologies, analytical tools and advanced modelling approaches to overcome limitations of data scarcity or subsurface uncertainties. In order to achieve this main objective, it is necessary that European countries agree and adopt harmonised protocols and pursue the assessment of geothermal energy stocks across Europe. This main objective is to be achieved via intermediate actions:

- Exploration technologies > imaging the resource
- Reservoir modelling > pre-drill assessment of resource performance
- Catalogues & geothermal database > harmonization of data(bases), public availability and data sharing across EU
- Resources & reserves estimation > harmonized resources estimation and quantify reserves

Numerous exploration techniques are used to characterise resources before, during and after the first wells are drilled in order to predict the resource, test the existence of a geothermal reservoir capable of sustaining commercial rates of fluid production and injection, and provide necessary data for sustainable management. Continuous effort as well as regular RD&I opportunities are required in order to test and optimise developed technologies and better assess resources potential.

2.2.2 Scope & TRL

The main aim here is to characterise these resources and develop novel ways to use them, by:

- Developing advanced methods to estimate and forecast properties and coupled processes deep underground, and defining the abundance and techno-economic feasibility of resources in view of different applications by 2028 (TRL from 3 to 5)
- Demonstrating developed concepts by accessing resources and refining business models by 2030 (TRL 5 to 6).
- Mitigation of risks during the feasibility and operational phases of a geothermal project by maximising the probability of predicting physical (T, P, permeability, stress, thermal capacity, etc.) and chemical parameters as well as detecting fluid-bearing fractures and faults.

This action includes the following:

- Developing advanced exploration, investigation and monitoring technologies to reduce the cost of surveys and improve the resolution of underground imaging by 2028 (from TRL 3 to 6)
- Developing an integrated approach by improving the multidisciplinary aspect of exploration methods, using joint modelling, specialised data and computationally advanced exploration, investigation and monitoring technologies by 2030 (from TRL 3 to 6 with an extended demo)
- Improving well logging and logging-while-drilling tools and methods, building upon those used in geothermal and the oil and gas sectors so as to withstand harsh geothermal conditions (in particular, high temperatures) (from TRL 3 to 6).
- Developing innovative processes, materials and technologies able to improve the integrated management of the resources, well field and heat and power plants in different geological settings (TRL 6-9)

2.2.3 Required budget

40 million € (4 calls with 10 million € budget each)

2.3 TOPIC 3: Enhancing geothermal energy integration in the energy system

2.3.1 Specific challenge

ON HEATING AND COOLING

- **Underground Thermal Energy Storage:** Demonstration of new generation of Underground thermal storage systems (UTES), with subsurface system development and planning.
- **Solutions and demonstration of geothermal integration** in the coupling of the energy system for the heating and cooling sector **and Transformation of grids** from the 2nd Generation to 5th Generation of DH retrofitting of existing DH networks and building efficiency improvement
- **Geothermal Heat and cold supply to industry:** High temperature applications; open points for geothermal H&C industrial uses

ON ELECTRICITY AND COMBINED HEAT & POWER

- **Advanced Binary Plants & Binary cycle exploitation**
  The first objective is to develop advanced low-to-medium temperature (usually 100-180°C) binary plants by 2030 (from TRL 5-6 to 8). This must notably address the need for flexible heat/cold and electricity supply from binary cycles, including upscaling capacity from the binary plants. The improvement of plant performance should focus on the working fluid and on specific components (e.g. improved heat exchangers with higher effectiveness and lower pressure drop, material selection, surface structure and coating, hybrid cooling) of the binary cycle (from TRL 4-5 to 6-7 and then 8).

2.3.2 Scope

Among the major targets and KPIs related to generation technologies, this action refers to:

Underground Thermal Energy Storage:

- Subsurface characterization of suitable formations (mainly for High Temperature Aquifer Thermal Energy Storage (HT-ATES)), identification of potential. Impact / water quality effects / water treatment. Coupled temperature water quality changes, desorption of heavy metals
- New BTES configurations to allow an efficient high temperature heat storage at diurnal or seasonal timescale
- Development of PCM based concepts to allow enhanced borehole heat exchanger BUTES applications for District Heating (DH) systems
- Optimization of recovery efficiency
- Integration with district heat network. Optimisation with well types / well placement.

Solutions and demonstration of geothermal integration and transformation of grids

- Smart integration in DH networks: Develop technical solutions and optimization, and implement a demonstration in different urban environments
- Integration of seasonal heat underground storage
- Resource management in dense installation environnent (from TRL 6 to 9)

Geothermal Heat and cold supply to industry

- Integration of geothermal heat supply at low and medium temperature
- Cooling supply
- Combined heat, cold and power supply for a base load profile

Advanced Binary Plants & Binary cycle exploitation

Maximising electrical and thermal generation and subsurface storage efficiency by 15% by 2030 (from an average conversion efficiency of geothermal binary plants of 12% in 2019)

- Reducing the production costs of various applications by 15% (with respect to specific technologies) by 2030

- Demonstrating the technical and economic feasibility of responding at any time to commands from a grid operator to increase or decrease output, ramping up and down from 20% to 110% of nominal power (flexible power generation).

Other specific KPIs for this action are to:

- Reduce the surface part of power plant costs by 15 % by 2030:
  - KPI: Manufacturing cost of a custom design 5 MWe ORC turboexpander, which stands at one million euros in 2019.
- Upscale binary plants:
  - KPI: Plants with a capacity higher than 30 MWe, including for EGS (currently the largest is 25 MWe).

2.3.3 Required budget

60 million € (4 calls with 15 million € budget each)

2.4 TOPIC 4: Novel materials and equipment for smart operation of geothermal plants

2.4.1 Specific challenge

Alternative materials for Scaling & Corrosion

- Development of effective and environmentally benign measures to prevent and control scaling and corrosion (TRL 6 – 8 by 2028, TRL 9 by 2033)
- Development of safe and environmentally benign measures to remove scaling (TRL 6 – 7 by 2028, TRL 8 – 9 by 2033)
- Development of materials that are resistant to corrosion and/or have anti-scaling properties at HT. Such materials can help to reduce costs and downtime due to workovers and increase the lifetime of components such as submersible pumps and tubing (TRL 5 – 7 by 2030, TRL 8 – 9 by 2035)

Equipment

- Development of second-generation geothermal pumps with prolonged lifetimes under aggressive fluid conditions or development of alternative lifting technologies (TRL 6 – 7 by 2030, TRL 8 – 9 by 2035
- Development of innovative efficient high-temperature (industrial) heat pumps: increase temperature range to >200°C with COP>2.

High Temperature sensors & tools

- Development of electronics and sensors to be used in high-temperature geothermal wells during drilling operations. This will lead to better control of the drilling process, reducing the risk of wellbore instability and lost-in-hole incidents.
- Development of data communication or telemetry technologies allowing fast and reliable data transfer under high-temperature conditions
- Develop electronics and sensors that can withstand temperatures up to 350°C by 2030.
- Develop data communication technologies that can withstand temperatures up to 350°C by 2030

Eco-friendly chemicals for HT environment

Development of eco-friendly drilling fluids that are stable under high-temperature and high-pressure conditions and that effectively protect drilling equipment against corrosion
(TRL 4 – 5 by 20268, TRL 6 – 7 by 2030, TRL 8 – 9 by 2030)

Eco-friendly materials

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. Focus will be on:

- Development and laboratory testing during the period 2025 – 2030 (TRL 5 – 6)
- Testing under realistic conditions and in the field during the period 2026 – 2028 (TRL 7 – 8)
- Application in one or two demonstration projects by 2030 (TRL 8 – 9);

2.4.2 Scope & TRL

Action aims to prolong the lifetime of geothermal wells, piping and equipment by making the materials used more resistant to the detrimental effects of temperature, fluid chemistry and flow.
This can be done in a number of ways, either through materials research, the use of environmentally benign chemicals, or effective design and operating protocols.

2.4.3 Required budget

40 million € (4 projects with 10 million € budget each)

2.5 TOPIC 5: Demonstration of mineral (CRM) production exploitation from geothermal sources

2.5.1 Specific challenge

CRM and other minerals production

- Selective extraction technologies: Contaminant removal, Upscaling
- Production technologies
- Concentration enrichment technologies
- Products to be produced and to be integrated with the market chain
- Different minerals: Lithium, Silica, Magnesium, Potassium…
- Ensure reinjection compatibility (for sustainable reservoir management)

2.5.2 Scope

The objective is to develop novel and potentially disruptive technological solutions that can help satisfy European needs for energy and strategic metals as well as other economical non-metallic materials in a single interlinked process. This means increasing the selectivity and efficiency of the separation techniques used for minerals and geothermal brines, as well as developing new, potentially disruptive technologies to separate and transform the chemical components of geothermal brines into more valuable products.
Demonstration sites for technologies for metal extraction: (from TRL 5-7 to 8-9, 2024-2026 and 2027-2030 periods)
Several pilot plants worldwide have been built to extract salts, silica, lithium and specific (CRM) metals from brines, but industrial production has only taken place at a few locations and has been limited to the production of silica, Li, Br, J and Sn. Geothermal plants can optimise the production of both energy and metals/materials according to market demands by exploiting deep geological formations. The exploitation of mineral production can also help geothermal plants become more economically competitive.

2.5.3 Required budget

50 million € (4 projects)
• Develop technical solutions to extract minerals: 20 M€
• Test solutions in demonstration sites: 30 M€

3 GEOTHERMAL ROADMAP 2024/2025

ETIP Geothermal priorities for Horizon Europe Work Programme 2026-2027

3.1 TOPIC 1: Increase sustainable production of geothermal in Europe

3.1.1 Specific challenges

Efficient resource development requires increasing or sustaining the production of geothermal resources in the long run. To achieve this, some specific challenges need to be addressed:

1. *Advancing drilling technologies*
   - Developing high-penetration-rate drilling using AI-driven resource development
   - Enhancing drilling fluids for improved wellbore cleaning, stability, and integrity, including high-temperature cementing
   - Improving monitoring, logging while drilling, and geosteering in harsh environments
2. *Optimising production and well design*
   - Innovating production and stimulation technologies to enhance extraction efficiency
   - Developing novel and optimised well architectures to improve geothermal system performance
   - Encouraging advanced well designs to extend the lifespan of geothermal projects and reduce operational costs, increasing competitiveness
   - Incorporating AI-driven optimisation to enhance efficiency and boost production in low-permeability reservoirs

3.1.2 Aim

The aim is for:

- Optimisation of the performance of the geothermal system for long-term sustainability
- Enhancement of production from low-permeability reservoir through innovative stimulation and well-completion techniques
- Improvement of the efficiency of geothermal fluid uplifting from the well bore.
- Increase cost-efficiency and competitiveness by integrating AI-driven optimisation and innovative drilling solutions

3.1.3 Scope

To address these challenges, the following actions are necessary:

1. *Reservoir performance and sustainable management*
   - Develop and test AI-driven thermodynamic models that simulate the flow of heat/steam and THMC (thermal, hydraulic, mechanical, chemical) process in geothermal wells and reservoirs
   - Improve subsurface characterisation to enhance the predictability of reservoir behaviour and seismicity impacts
2. *Advanced well design and production technologies*
   - Develop effective and safe technologies for increasing energy productions through:

i. Advanced well designs,
ii. Innovative permeability enhancement procedures,
iii. New well completion technologies (Target: TRL 5-6 to TRL 9 by 2030)

3. *Next-generation geothermal pumps and lifting technologies*
   - Design second-generation geothermal pumps with prolonged lifetimes under aggressive fluid conditions,
   - Develop alternative lifting technologies to prevent mechanical erosion

- Target technological readiness from TRL 6-7 today to TRL 8-9 by 2027

4. *Optimised thermal flow and energy management*

- Enhance the ability to design and operate thermal flow systems in geothermal reservoirs
- Improve the efficiency of geothermal power and heat plants by integrating advanced modelling and operational strategies.

3.1.4 Required budget

40 million € (4 projects with 10 million € budget each)

3.2 TOPIC 2: Innovative approaches for the geothermal acceleration areas

3.2.1 Specific challenges

One of the major roadblocks for accelerated deployment of geothermal installations in many parts of Europe is the lack of available or accessible subsurface information. It is therefore of paramount importance to upscale data acquisition and exploration efforts, given the rapid development of new technologies, analytical tools and advanced modelling approaches to overcome limitations of data scarcity or subsurface uncertainties. In order to achieve this main objective, it is necessary that European countries agree and adopt harmonised protocols and pursue the assessment of geothermal energy stocks across Europe.
This main objective is to be achieved via intermediate actions:

1. *Advancing exploration technologies*
   - Improving resource imaging techniques to enhance subsurface characterisation
   - Developing AI-enhanced reservoir modelling for accurate pre-drill assessment of geothermal resource performance
2. *Standardising data and resource assessment*
   - Establishing harmonised geothermal databases for publicly accessible and shared data across the EU
   - Implementing standardised resource and reserves estimation methods to enable a uniform approach to geothermal assessment
3. *Ensuring sustainable geothermal management*
   - Enhancing predictive capabilities to assess reservoir sustainability before and after drilling
   - Encouraging continuous R&D innovation to refine technologies for better resource characterisation
4. *Enhancing economic viability and sectoral integration*
   - Strengthening EU competitiveness in geothermal exploration through standardised data-sharing protocols and technological advancements
   - Expanding geothermal integration in agri-food sectors to create sustainable energy applications

3.2.2 Aim

The objective of these advancements is to:

- Improve geothermal resource identification and prediction before drilling
- Harmonise and share geothermal data across the EU to enable wider adoption
- Increase cost-efficiency and reduce exploration risks through advanced monitoring and modelling
- Optimise well placement and reservoir management for long-term sustainable use

3.2.3 Scope & TRL

To address these challenges, the following actions are necessary:

1. *Innovative subsurface characterisation and forecasting*
   - Develop advanced methods to estimate and forecast subsurface properties and define the techno-economic feasibility of resources by 2028 (TRL 3 to 5)
   - Demonstrate developed concepts through resource access and business model refinements by 2030 (TRL 5 to 6)
   - Mitigate feasibility and operational risks by improving predictions of temperature, pressure, permeability, stress and thermal capacity, and detecting fluid-bearing fractures and faults
2. *Enhanced exploration and monitoring technologies*

- Develop cost-efficient exploration and underground imaging technologies to enhance resolution and reduce survey costs (TRL 3 to 6 by 2028)
- Improve multidisciplinary exploration approaches, integrating joint modelling and advanced computational techniques by 2030 (TRL 3 to 6 with an extended demo)
- Enhance well logging and logging-while-drilling methods, leveraging best practices from the oil and gas sector to withstand high-temperature geothermal conditions (TRL 3 to 6)

3. *Integrated resource and energy system management*

- Develop innovative processes, materials, and technologies to enhance the management of geothermal resources, well fields, and heat/power plants across different geological settings (TRL 6 to 9).
- Promote geothermal applications in agri-food, including greenhouse heating and food processing.

3.2.4 Required budget

40 million € (4 calls with 10 million € budget each).

3.3 TOPIC 3: Enhancing geothermal energy integration in the energy system

3.3.1 Specific challenges

ON HEATING AND COOLING

1. *Underground thermal energy storage (UTES)*
   - Demonstration of next-generation underground thermal storage systems, including subsurface system development and planning
   - Optimisation of high-temperature Aquifer Thermal Energy Storage (HT-ATES) for efficient energy storage and water quality management
   - Integration of UTES in district heating and cooling (DHC) to enhance energy system flexibility.
2. *Geothermal district heating and cooling*
   - Transforming 2nd to 5th-generation DH networks through retrofitting, grid coupling, and improved building efficiency
   - Smart integration of geothermal energy in dense urban environments for optimised seasonal storage and distribution
   - Expanding geothermal district heating solutions for residential applications, reducing dependency on fossil fuels
3. *Industrial and agri-food applications*
   - Expanding the use of geothermal heat and cooling in industrial sectors requiring high-temperature applications
   - Developing solutions for combined heat, cold and power supply to serve baseload industrial and agricultural demands efficiently
   - Utilising geothermal heat for greenhouses and food processing to increase productivity and reduce operational costs.

ON ELECTRICITY AND COMBINED HEAT & POWER (CHP)

1. *Advanced Binary Plants & Binary cycle exploitation*
   - Develop advanced low-to-medium temperature (usually 100-180°C) binary plants to improve efficiency and scalability (TRL 5-6 to 8 by 2030)
   - Improve binary cycle performance through advanced heat exchangers, enhanced working fluids, material selection, and hybrid cooling technologies (TRL 4-5 to 6-7 and then 8)
   - Demonstrate the feasibility of flexible power generation, allowing geothermal plants to dynamically adjust output in response to grid demands.

3.3.2 Aim

The main objectives are to:

- Enhance geothermal energy integration into heating, cooling, electricity, and industrial processes
- Improve system flexibility and efficiency through technological advancements
- Reduce the costs of geothermal infrastructure and operations, making it more competitive
- Strengthen sectoral integration, ensuring geothermal energy plays a key role in housing, industry and agri-food applications.

3.3.3 Scope

Among the major targets and KPIs related to generation technologies, this action refers to:

1. *Underground Thermal Energy Storage (UTES):*
   - Subsurface characterisation and optimisation of recovery efficiency for HT-ATES
   - Development of new borehole thermal energy storage (BTES) configurations for high-temperature, diurnal, and seasonal storage

- Integration of phase change materials (PCM) to enhance borehole heat exchanger applications for DH
- Optimisation of UTES integration with district heat networks, including well placement and efficiency improvements

2. *Geothermal grid integration and transformation*
- Smart DH integration: develop and implement optmised solutions for urban environments
- Seasonal heat storage solutions for increased grid flexibility
- Resource management strategies for high-density installation areas (TRL 6-9)

3. *Industrial and agri-food sector applications*
- Integration of geothermal heat supply at low and medium temperatures for industries
- Expansion of geothermal-based cooling solutions
- Application of geothermal heating for greenhouse and food processing, ensuring stable and sustainable energy supply

4. *Advanced Binary Plants & Binary cycle exploitation*
- Increase geothermal power plant efficiency by 15% by 2030 (from 12% average in 2019)
- Reduce production costs by 15% across key applications by 2030
- Develop geothermal binary plants with capacities greater than 30Mwe, particularly for Enhanced Geothermal Systems (EGS)
- Support the cost reduction of surface power plant components, with a focus on ORC turboexpander technology

3.3.4 Required budget

60 million € (4 calls with 15 million € budget each).

3.4 TOPIC 4: Novel materials and equipment for smart operation of geothermal plants

To ensure the long-term sustainability and cost-effectiveness of geothermal energy systems, the development of advanced materials, equipment, and eco-friendly solutions is essential. Key challenges include improving resistance to scaling and corrosion, enhancing high-temperature sensor technology, and integrating eco-friendly chemicals and materials into geothermal applications.

3.4.1 Specific challenges

ON MATERIALS FOR SCALING AND CORROSION PREVENTION

1. *Alternative anti-scaling and corrosion-resistant materials*
   - Develop environmentally benign scaling and corrosion prevention technologies (TRL 6-8 by 2028, TRL 9 by 2033)
   - Design corrosion-resistant and anti-scaling materials for high-temperature applications to extend equipment lifespan and reduce downtime (TRL 5-7 by 2030, TRL 8-9 by 2035)
   - Develop safe and effective scaling removal solutions to maintain system performance (TRL 6-7 by 2028, TRL 8-9 by 2033)

ON EQUIPMENT AND HIGH-TEMPERATURE SOLUTIONS

1. *Next generation geothermal pumps and lifting technologies*
   - Develop second-generation geothermal pumps with extended operational lifetimes under aggressive fluid conditions (TRL 6-7 by 2030, TRL 8-9 by 2035)
   - Design alternative lifting technologies to optimise geothermal fluid extraction
   - Develop high-temperature industrial heat pumps capable of operating at >200°C with COP <2 to improve efficiency
2. *High-temperature sensors and monitoring tools*
   - Develop durable electronics and sensors for use in geothermal drilling operations to enhance wellbore stability and reduce operational risks
   - Create high-temperature data communications and telemetry technologies for real-time subsurface monitoring (TRL 6-9 by 2030)
   - Develop electronics and sensors capable of withstanding up to 350°C by 2030 to enable more reliable geothermal system monitoring

ON ECO-FRIENDLY SOLUTIONS FOR GEOTHERMAL SYSTEMS

1. *Eco-friendly drilling fluids and chemicals*
   - Develop high-temperature, high-pressure stable eco-friendly drilling fluids to prevent equipment corrosion and extend system longevity (TRL 4-5 by 2026, TRL 6-7 by 2030, TRL 8-9 by 2035)
2. *Advanced eco-friendly materials for geothermal applications*
   - Develop sustainable casing couplings and cements to improve heat transfer efficiency, well integrity, and resistance fatigue
   - Conduct laboratory testing (TRL 5-6 by 2025-2030) and transition to realistic condition field testing (TRL 7-8 by 2026-2028)
   - Apply materials in demonstration projects (TRL 8-9 by 2030)

3.4.2 Aim

The main objectives of these innovations are to:

- Extend geothermal well and equipment lifespan through advanced materials and corrosion prevention
- Improve geothermal efficiency and sustainability through eco-friendly solutions
- Enhance geothermal competitiveness by reducing maintenance costs and improving operational reliability

- Supporting different applications by ensuring geothermal energy remains a cost-effective and durable solution for heating, cooling and industrial use

3.4.3 Scope & TRL

1. *Advanced materials for long-term geothermal sustainability*
   - Improve heat transfer efficiency, durability, and scaling resistance of geothermal system components
   - Develop cost-effective solutions for reducing operational risks in geothermal wells
2. *High-temperature equipment and sensor technologies*
   - Increase geothermal pump lifetimes and efficiency in harsh fluid conditions
   - Enhance sensor durability and communication reliability for high-temperature environments
3. *Eco-friendly materials and chemicals for sustainable geothermal operations*
   - Develop non-toxic, high-performance drilling fluids to enhance well stability
   - Optimise geothermal cementing and casing materials to ensure long-term system integrity

3.4.4 Required budget

40 million € (4 projects with 10 million € budget each).

3.5 TOPIC 5: Demonstration of critical raw materials production made in Europe from geothermal sources

The development of critical raw materials (CRM) and other valuable minerals from geothermal brines presents an opportunity to support Europe's clean energy transition, economic competitiveness, and resource self-sufficiency. This requires overcoming challenges related to efficient extraction technologies, reinjection compatibility, and integration into market supply chains.

3.5.1 Specific challenges

1. *Selective extraction technologies*
   - Develop advanced contaminant removal and selective extraction technologies to improve purity and recovery rates
   - Optimise scalable and energy-efficient separation techniques for lithium, silica, magnesium and potassium
   - Ensure reinjection compatibility to maintain sustainable reservoir management and prevent environmental degradation
2. *Production and concentration enrichment technologies*
   - Develop innovative concentration and enrichment processes to increase the value of extracted minerals
   - Create cost-effective transformation technologies to convert geothermal brine components into market-ready products
3. *Geothermal brine product integration*
   - Identify new market opportunities for strategic materials derived from geothermal brines

3.5.2 Aim

The main objectives are to:

- Develop advanced mineral extraction technologies to enhance geothermal plant competitiveness.
- Improve the efficiency and sustainability of geothermal brine processing for CRMs and strategic minerals.
- Support EU self-sufficiency by reducing reliance on imported raw materials.

3.5.3 Scope

1. *Demonstration and validation of extraction technologies*
   - Develop TRL 5–7 pilot extraction technologies for lithium, silica, and magnesium (2024–2026)
   - Scale up TRL 8–9 production-ready technologies for commercial implementation (2027–2030)
   - Deploy demonstration sites to test large-scale metal extraction for market integration
2. *Optimising geothermal plant economics*
   - Improve geothermal plant flexibility by enabling combined energy and mineral production
   - Enhance economic competitiveness by aligning mineral extraction with market demands and supply chains
3. *Sustainability and reinjection strategies*
   - Develop solutions to minimise brine waste and optmise reinjection process
   - Conduct environmental impact assessments to ensure long-term reservoir stability
   - Implement life-cycle assessments to measure sustainability improvements in CRM recovery

3.5.4 Required budget

50 million € (4 projects): €20 M to develop technical solutions to extract minerals; €30 M to test solutions in demonstration sites.


GEOTHERM
FORA