EERA

EUROPEAN ENERGY RESEARCH ALLIANCE

Joint Programme on Geothermal Energy

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1 Summary

Geothermal energy is a non-carbon-based renewable energy source, able to provide peak and base load power for electricity and heat generation in many countries around the world. In Europe, the geothermal potential is estimated to be between 80-100 GW_e, however, only in Italy, Iceland, and Portugal it is harnessed for the generation of electricity (over 1.6 GW). In several European countries like Island, France or Germany, the geothermal power is used on a small or district scale, mainly for heating supply and heat/chill storage. In addition, the geothermal energy is used for industrial heating, mainly for agricultural purposes (greenhouses) and heating homes, offices. The development scenarios foresee about 5-6 GW of installed geothermal electric capacity within 2020 and between 15 and 30 GW within 2030.

To realize such an increase is beyond the scope of available mature technology and requires the development and market introduction of new cost-effective technologies for:

- significantly enhancing the production from already identified and utilized resources;
- exploring at large scale new untapped deep seated (up to 6 km) hydrothermal systems;
- making Engineered Geothermal ready for large scale deployment;
- accessing new extreme “high potential” resources such as Supercritical fluids and Magmatic systems;

Beside the technological challenges, other aspects of relevance for the further development of geothermal energy require to be addressed with innovative approaches and tools to:

- improve the risk assessment;
- control the quality of geothermal technologies;
- manage a reliable evaluation of the technical, environmental and economic sustainability of the projects;
- secure the social acceptance of geothermal projects by ensuring that potential site and technology specific side effects are relatively minor compared to the benefits;
- provide the guidelines to the Regulatory Authorities and Policy Makers for sustainable development of geothermal initiatives;

To face these challenges the EERA Joint Programme on Geothermal Energy (JPGE) aims at providing an outstanding contribution bringing together more than 30 leading European geothermal research institutions in a single strategically oriented Joint R&D Programme.

The goal of the JPGE is to contribute to the achievement of the European Strategic Energy Technology (SET)-Plan objectives, streamlining and coordinating national R&D programmes, accelerating the targeted development and maturing of next generation geothermal technology in order to provide industry with all the elements required for its large-scale and cost-effective deployment.

The JPGE operates mainly by facilitating and coordinating the cooperation and exchange between ongoing projects, both at the European and the national levels, and by the coordinated preparation of research proposals for European projects. In addition, the pool of experts from different research fields contributing to geothermal research provides input to strategic documents prepared at the European level and advises governments and the EC on questions regarding geothermal energy.

The main milestones of the JPGE are:

- *By 2020*: to achieve proof-of-principle technological milestones for the development of all technical elements needed for the deployment of geothermal systems for large-scale electricity and heat/chill production.
- *By 2025*: to develop demonstration projects, which will permit the testing of new technological solutions in preparation for their transfer into industry.

2 Introduction

2.1 Background

Geothermal energy is a valuable and local source of energy that can cost-effectively provide base-load/ dispatchable electricity, heat or a combination of both. With these features, it has the potential to provide real alternatives to replace fossil fuel based power plants not only in Europe but also globally, in particular, in some developing countries. In addition, geothermal reservoirs may also act as sites for geological storage.

Currently geothermal heat is directly used in a number of sectors, depending on its temperature, from bathing and swimming to industrial processes, agriculture and district heating and/or cooling (H&C). The last-mentioned sector is the most promising one for the large-scale uptake of geothermal heat. In Europe, there are 257 geothermal district H&C systems, with total installed capacity of 4.6 GW_{th} (2015 data published by EGEC[1]). Data on direct use is difficult to find and statistically not homogenous[2], yet the growing importance of geothermal heat as a local source of energy is evident. There is a great potential for the utilization of geothermal energy for H&C in Europe, including many countries that currently rely on fossil fuels for their heating needs. As an example, there are many cities in Eastern Europe like Košice in Slovakia with district H&C systems that can easily be adapted to use local geothermal resources instead of imported fossil fuels. This would increase energy security and price stability as well as independence from fossil fuel sources. In addition, there is also a potential for an increased use of geothermal heat in industry and agriculture. The unlocking of all of this potential will be enabled by research and innovation, which leads to the improvement of technology and its incorporation into the energy system.

According to the EGEC Market Report Update, the total installed capacity for geothermal electricity generation in Europe was about 2.2 GW_e in 2015, generated by 84 power plants (thereof, 0.95 GW_e in 51 plants in EU28). The total installed capacity is expected to reach 3.5 GW_e in 2018 including the rapidly growing Turkish market. In the world, the total installed capacity was 12 GW_e producing 76 TWh/y in 2013 and, according to IEA-GIA projections, it could increase to reach 1,400 TWh/y (equal to 3.5% of global electricity production) by 2050[3], half of it produced by EGS (Enhanced Geothermal System)[4] plants. The geothermal power market is particularly dynamic in the USA, Philippines,

[1] EGEC, Market Report 2015.

[2] According to the IEA-GIA 2013 report geothermal heat production reached about 150 TWh/yr in 2013 and it is projected to reach about 1,600 TWh/yr in 2050.

[3] IEA-GIA, Trends in Geothermal Applications 2013 and IEA, Technology Roadmaps - Geothermal Heat and Power, 2011.

[4] The EGS concept includes artificial improvement of the hydraulic performance of a reservoir with the goal to use it for an economical provision of heat or electric energy. The enhancement challenge is based on several nonconventional methods for exploring, developing, and exploiting geothermal resources that are not economically viable by conventional methods.

Indonesia, Mexico, Turkey and Kenya, and thus it could be invigorated soon in the EU if unconventional geothermal resources (non-hydrothermal or requiring innovative technologies to be economically exploitable) including EGS can be commercialised successfully under a wider range of geological conditions.

This target can be reached only through the application of new cost-effective technologies able to enhance the production of the already identified resources, to discover new untapped hydrothermal systems and to develop non-hydrothermal systems (EGS, Pressurized Geothermal Systems, Supercritical resources, magmatic, geo-pressurized, offshore hydrothermal etc.).

Like other renewable energy sources, geothermal energy development faces barriers and obstacles, such as the high upfront cost and risk associated with the resource assessment stage, the low efficiency of power conversion technology, the environmental acceptance and the lead-time from discovery to production. Moreover, with the actual technology only a part of the huge thermal energy confined at accessible depth may be utilized either for electricity generation or thermal energy uses.

For decades, geothermal energy has attracted only minor investments in the fast growing market of renewable energy. This has changed in the last years especially in continents other than Europe as demonstrated by the new geothermal initiatives from the USA and other countries, which are providing essential financial support for research and technological innovation. Europe requires major changes to its energy policy to avoid loosing the opportunity to develop this strategic resource whilst falling behind in the technological development in a worldwide market. Research organizations and industry must join forces in order to promote initiatives that stimulate immediate governmental intervention. The EERA initiative on geothermal energy serves this purpose.

2.2 Strategic leadership

The JPGE has the potential to provide an outstanding contribution to the growth of geothermal energy utilization in Europe and worldwide, bringing together all major European research organizations in a strategically oriented endeavor. As geothermal energy substitutes fossil energy provision at comparatively low environmental impact, the JPGE will represent a significant contribution to the deployment of a clean and efficient base-load power supply from an indigenous resource and provide the basis for the growth of an industry with attractive export potential.

The EERA Joint Programme on Geothermal Energy (JPGE) provides added value through strategic leadership and by speeding up the realization of the SET-plan goals[5]. A major group of strong research players performing a long-term collaboration will enhance networking activities and trust between all the participating partners resulting in a major virtual excellence centre. It is estimated that more than 40% of the European public research capacity is integrated into the EERA JPGE.

Speeding up the realization of SET-plan goals

The created synergies and the common reservoir of experienced researchers will speed up the implementation of new research ideas to matured developments, ready to be handed over to industry. Young researchers will be in contact with many excellent scientist profiting and learning from the experience of these experts.

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[5] HTTPS://SETIS.EC.EUROPA.EU/TOWARDS-AN-INTEGRATED-SET-PLAN

A better coordination between the member state funding organisations and the European Commission would further streamline the European industry and public research activities as a whole. A strategic research agenda of major European energy research organisations, adapted to the needs of the industry and implemented by a European council, representing the member state funding organisations and the European Commission will accelerate the development of new energy technologies.

2.3 Objectives

The overall goal of the JPGE is to expand the type, number and size of geothermal resources suitable for increasing electricity and heat/chill generation in the framework of the SET-plan to accelerate technology development. The main options are represented by:

- *enhancing the production from already identified and utilized geothermal field through*

  - enlarging the extent of productive zones and stimulating low permeability
  - accessing resources at depth greater than those exploited so far
  - increasing the performance of power systems improving the sustainability of the production and extending the lifetime of the systems
  - improving the processes for co-generation (of heat, power, hydrocarbon, ore and materials), and hybrid production;

- *exploring, accessing and developing new untapped hydrothermal resources (up to 6 km deep or offshore) at large scale in Europe;*
- *accessing and developing Engineered Geothermal Systems at large commercial scale;*
- *exploring, accessing and developing "high-potential" resources such as supercritical fluids, pressurized geothermal systems, and magmatic systems.*

To meet the overall goal, several challenges need to be faced and several research and technological innovation activities must be performed:

- application of innovative cost-effective exploration technologies and new modelling tools able to image the subsurface and define the reservoir characteristics and the accurate assessment of geothermal potential in different geological environment;
- predicting the geo-mechanical behaviour of fracture zones, with particular focus on reservoir performance evaluation and induced seismicity;
- development of new cost-effective drilling technologies specifically designed for very deep geothermal wells in extreme conditions of temperature and pressure monitoring of the dynamic processes in deep geothermal systems including supercritical fluid systems through the application of high-temperature down-hole tools;
- enhancing the viability of current and potential geothermal resources by improving thermodynamic cycles and optimizing power conversion;
- enhancing the net efficiency and performance of geothermal power plants for low-enthalpy power plant cycles (e.g. ORC, Kalina Cycle);
- optimization of heat transfer efficiency and development of new working fluids (supercritical fluids);
- design of very efficient systems for cogeneration of electricity and heat/chill;
- implementation of experimental test of materials and treatment to prevent or mitigate corrosion and scaling;

- assessment and improvement of hybrid application of geothermal heat with other energy source, other power generation systems (e.g., thermoelectric materials) and for direct applications;
- development of numerical simulators for coupled thermal-hydraulic-mechanical-chemical processes during exploitation of reservoir;
- improvement of methods to enhance reservoir performance and to study the processes of long-term geothermal exploitation;
- delineation of the impact of in situ geothermal fluid chemistry and microorganisms on lifetime and specification of system components;
- improvement of risk mitigation or risk sharing mechanisms during the early stage of development;
- improvement of project sustainability by risk management and the socio-economic acceptability.

Case studies, natural laboratories and test sites will be made available to confirm the results of the research and to test new tools, material and procedures.

The milestones described below (see chapter 4), meet these challenges and are targeted towards a comprehensive and coherent development of cost-effective geothermal technologies, which can successfully be applied under the different practical conditions. They are expected to be realistic since they are based on previous and/ or ongoing research efforts.

The joint programme incorporates experiences from several plants in operation under different geological environments. Combining the forces of the major European geothermal R&D institutions and considering the SET-Plan, the JPGE aims at a significant acceleration of the development for providing reliable and highly efficient technology for the use of geothermal energy from low enthalpy systems for heating, cooling, and electrical power generation.

2.4 JP structure

Different thematic areas of focus are set out in seven subprogrammes (SP) of JPGE, which will be explained in detail below in chapter three:

SP1 Assessment of Geothermal Resources

SP2 Exploration of Geothermal Reservoirs

SP3 Constructing Geothermal Wells

SP4 Reservoir Engineering

SP5 Energy Conversion Systems

SP6 Operation of Geothermal Systems

SP7 Sustainability, Environment and Regulatory Framework

3 Overview of subprogrammes

3.1 SP1 – Assessment of Geothermal Resources

Background

A most thorough knowledge about the subsurface geothermal reservoir is a crucial point both at the beginning of a geothermal project and during its exploitation phase. The main goal is to minimize the exploration risk and the cost for reservoir development on one hand, and to maximize the profitability and the reservoir sustainability on the other hand. Promising areas have been typically selected largely on the basis of observations of high near-surface temperature gradients derived from surface heat flow values (e.g., volcanic areas such as Iceland, regions of Italy and European ultra-peripheral islands) and/or relative high temperatures proven in deep boreholes drilled mainly for hydrocarbon exploration and production (e.g., Paris Basin or Upper Rhine Graben). Other areas result from near-field exploration (e.g. Landau, Insheim, Rittershoffen) based on local successes such as Soultz-sous-Fôrets and far field exploration in deep sedimentary basins (Mol – Donk, Belgium).

An accurate estimation of the geothermal resource potential is essential to take the right business decision at the right economic moment. Such a geothermal potential estimation has to be based on multi-parameters, e.g. geological processes, depth temperature, or techno-economic needs. In addition, data and information related to these components have to be accessible as easily as possible at a European scale to enhance the R&D efficiency.

This subprogramme focusses on aspects of resource assessment and geothermal prospective from continental to regional scales and is related to various past and current European projects (e.g. TOPO-EUROPE, GEOELEC, IMAGE, Geo ERA-NET or GEMex), and to national initiatives (e.g., VIGOR and Atlante Geotermico del Mezzogiorno[6], Italy; SALK[7], Belgium).

Objectives

In order to improve resource assessment and evaluation of the economic sustainability of geothermal projects, the subprogram has three main objectives:

1) Innovative insights and process modelling to improve in-depth knowledge;
2) Assessment of resource potential;
3) Advanced methodologies and tools to share, disseminate, and capitalize on data and information on a European scale.

Meeting these challenges will save significant time and expense in the very costly drilling process and will guarantee an optimized use of the resource, reducing environmental impacts by forecasting possible problems and finding solutions beforehand. Critical earth system properties and processes include: permeability, temperature, thermal conductivity, stress, rock-fluid interactions, chemical signature, (regional variation in) strength of existing fractures, history, cements, porosity type, and regional hydrogeology.

The knowledge gained through the past 50 years of exploration for hydrocarbon, geothermal and mineral resources, allows a-priori definition of several prospective areas in Europe: Priority targets for EGS, for example, are deep geological formations under favourable thermal conditions, in which permeability can be enhanced to produce an engineered geothermal system.

However, an integrated approach for a comprehensive characterisation of such reservoirs and for the assessment of their geothermal potential at different depths is still lacking. It is one of the major goals of this SP to enable the compilation of a database of potential geothermal sites that includes

[6] HTTP://WWW.VIGOR-GEOTERMIA.IT AND HTTP://ATLANTE.IGG.CNR.IT
[7] HTTP://WWW.LIMBURG.BE/LIMBURG/SALK

characterisation information for different types of geological settings to facilitate data integration and exchange, and to harmonize the estimation of geothermal resources potential in Europe.

3.1.1 Work Package 1: Geothermal Assessment

Various complementary criteria have to be taken into account to assess geothermal resources. The main ones are the geological framework, the heat flow, and the stress field. Improvements in the assessment will be made not only by a better understanding of these single criteria but also by the ability of analysing them in an interdisciplinary way to produce integrated geothermal mapping.

Task 1.1 Geological processes

Out of the many fracture systems co-existing in many rocks, those activated by the current in-situ stress field serve as the main conduits for fluids. The interaction of active fault-fracture zones and the geological environment, their combined influence on the in-situ stress field and the resulting geomechanical, fluid flow and geochemical processes are not well understood, but are critical for assessing the geothermal resource. This task will develop new conceptual and numerical models to assess the impact of different geological settings on the geothermal resource.

Targets:

- Conceptual models to assess the impact of different geological settings on the geothermal resource.
- Numerical models to assess the impact of different geological settings on the geothermal resource.

Task 1.2 Heat flow

The terrestrial heat flow (HF) is the most critical factor governing the computation of temperature-depth profiles. The HF is a parameter obtained from the combination of two directly measured parameters, i.e. temperature gradient and rock thermal conductivity. The HF provides temperature models for geothermal assessments. The existing values of continental HF in parts of Europe are no longer conform to the state of the art for heat-flow determinations and thus no longer meet the required quality standards. Work has to be done under the umbrella of the International Heat Flow Commission (IHFC) to set-up standards and methodologies for a re-evaluation of existing heat flow data. In addition, an access to the Global Heat Flow Data Base is important for R&D on geothermal resource and needs to be available through the European Geothermal Information System/Platform (see WP3 of SP1).

Targets:

- Standards and methodologies for HF evaluation.
- Access to the Global Heat Flow Data Base via the European Geothermal Information System/Platform.

Task 1.3 Stress field

Developing stress field characterization and linking geomechanical modeling to novel stress and geomechanical lab measurement are key approaches for geothermal resource assessment. From these models stress maps will be drawn for various depth levels and for the important interfaces for particular prospective settings (e.g. the natural laboratories and surrounding regions in relation with WP3 of SP2). Integration with natural seismicity catalogues will help to define possible zonation in risks for induced seismicity. Paleo- and current stress maps will also be used in distinguishing between open or closed pathways. Integrated approaches in surface neo-tectonic, geochemical and hydrological mapping and near surface geophysical methods (e.g. high resolution seismic, radar etc.), allows the improvement of subsurface models for EGS in active tectonic zones (e.g. natural analogs of WP1-3 of SP2).

Targets:

- New stress field characterization approaches.
- Updated stress maps.

Task 1.4 Integrated Geothermal mapping

The aim of this task is to develop innovative methodologies and tools to integrate various sources of information and data to build comprehensive and consistent 3D geothermal models at the regional scale. In particular, the approach is fed by geological processes, heat flow, and stress field investigated in the tasks above. In addition, regional geophysics takes an important place in the process for constraining the mapping at depth. A close attention is to be paid to cross-fertilization with the oil and gas industry especially for sedimentary contexts. However, a large range of geological contexts is to be investigated to take in account the full range of geothermal frameworks. The regional models derived from the task are an essential component for the geothermal potential estimate developed in the next work package.

Targets:

- Methodologies and tools for multi-source data integration for 3D mapping at regional scale.
- New 3D models in various geological contexts at regional scale.

3.1.2 Work Package 2: Potential estimate

The geothermal potential estimation aims at quantifying the amount of energy. To perform such a quantification, geometry and petrophysical properties of the rocks need to be known and combined with temperature estimation of the underground. On top of that, the geothermal potential has to be considered in a techno-economic context to evaluate the interest the resource.

Task 2.1 3D Temperature model

The knowledge of temperature at depth is a fundamental factor for geothermal potential estimation. The work achieved in WP1, especially regarding heat flow and geology, is the cradle for temperature estimation at depth. Innovative approaches need to be explored to take into account the complexity in the combination of the various elements governing the temperature estimation. Furthermore, a 3D perspective is required to consider the spatial variability of the components. As the processes involved have large wavelengths, the estimation of temperature will be done at continental to regional scale. However, it could be refined on smaller areas depending on the accuracy of the data and on the objective of the estimation. As a result, 3D temperature maps (e.g. voxets) will be delivered.

Targets:

- Innovative methods for temperature estimation.
- 3D maps of temperature at depth for various scales.

Task 2.2 3D Temperature – rock properties model

Beside temperature, the geothermal potential assessment requires the subsurface representation of rock properties. The required geological parameters depend on the type of geothermal resource. Starting from an estimate of reservoirs geometries and permeability required for hydrothermal systems, other kinds of information are required to establish the occurrence of favourable conditions for geothermal resources. Based on the volume method, the geothermal potential is nowadays computed for hydrothermal resources and has been proposed for EGS systems, but a comprehensive set of methods is not well established. In conjunction to WP1 and Task2.1, this activity aims at defining reference methodologies and provide 3D maps to be used as input to Task 2.3.

Targets:

- Innovative methods for estimating technical geothermal potential of non-conventional systems.
- Harmonized maps throughout Europe of technical geothermal potential of different geothermal systems for various scales.

Task 2.3 Techno-economic estimation

This task aims at providing a base line for resource potential estimates for various geothermal play systems. Methodologies for the estimation have to be based on the work conducted in Task 2.2. Performance assessment tools as well as workflows will be developed for resource assessment and will extent the approaches defined by the IGA (International Geothermal Association). Moreover, integrated modelling comparing the local geothermal potential with the local heat & power demand (e.g. coming from industry process) and providing the optimal solution to satisfy the energy requirements will be developed. These activities aim at delivering a probabilistic techno-economic evaluation methodology that will be used to predict portfolios of potential prospects in each region, in conjunction to SP5.

Targets:

- Probabilistic techno-economic methodologies for geothermal resource evaluation.
- Performance assessment tools and workflows.

3.1.3 Work Package 3: Implementation of European Geothermal Information System/ Platform

This platform intends to help stakeholders of the geothermal sector to access geothermal information and data at the European level. It is planned to act as a Web portal, where information can be retrieved and queried. Beyond pure data sharing, the way information and data are displayed, examined, and compared has to participate to the harmonization and structuration of the European geothermal sector.

Task 3.1 Architecture and data model

The system is aimed at data access, retrieval, storage and visualization of both key parameters such as temperature, hydraulic properties, stress condition and relevant stratigraphic units at depth levels, as well as information about geothermal use (power plants, well, spas and spring location, concession areas) and statistics about power, heat production and consumption for further re planning concepts. In agreement with the INSPIRE European directive, data and information have to be stored at the national level, i.e. countries remain owner of the data and responsible of their update. A user committee of stakeholders will be set up to participate to the definition of the capabilities and to the development and tests.

Targets:

- Definition of the needs in relation with stakeholders.
- EGIS/P data model.

Task 3.2 Web services

The web services are responsible for the transport and exchange of data of every description via internet, based on open standards defined by OGC (Open Geospatial Consortium) such as WFS, WPS, WCS, WMS and CSW. This approach supports the efforts to meet the needs of the international data suppliers and GIS users for data access, retrieval, storage and visualization. The development will take into account the developments in the Geothermal ERA-NET.

Targets:

- EGIS/P Web services

Task 3.3 Portal

The portal is the front door to the information. This is the place where data and knowledge from the involved countries are aggregated and displayed. The portal needs to be able to access national database to retrieve information and data through the web services developed in Task 3.2. However, the portal is not only a passive tool. This is the place for computing calculations based on the available data. A set of computations or workflows will be developed to meet the stakeholders' requirements, such as statistics on a given parameter at the European scale or at a regional scale, or comparative analysis of national actions regarding the geothermal use.

Targets:

- EGIS/P portal.
- A set of workflows and computations to achieve stakeholders' needs.

Milestones of SP1

Nr	Title	Measurable Objectives	by
M1.1	3D modelling	Understanding the processes and properties that control the spatial distribution of critical exploration parameters at European to local scales. The focus will be on the prediction of temperatures, in-situ stresses, fracture permeability and hazards which can be deduced from field analogues, public datasets, predictive models and remote constraints	2017[8]
M1.2	EGIS-European Geothermal Information System	Definition of features and capabilities of the European Geothermal Information System (EGIS) and of the universal data format (EML).	2016 (partial) [9] 2018[10]
M1.3	Protocol for resource assessment	Standardized European protocol for resource assessment and supporting models	2017[11]

3.2 SP2 – Exploration of Geothermal Resources

Background

After the large-scale structural situation is defined (cf. background of SP1), with the contribution of all fields of geophysics, geochemistry and structural geology, a more detailed description is mostly given by, under favourable circumstances, information from boreholes, and by geophysical surveys such as seismic, geoelectric and magnetotelluric data. These geophysical methods have been established for a long time, but their specialized use for the assessment of geothermal reservoirs has not. Therefore, the derivation of reservoir parameters like permeability, temperature, stress, structural interpretation,

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[8] HTTP://WWW.IMAGE-FP7.EU
[9] HTTP://WWW.GEOTHERMALERANET.EU
[10] PROJECTS TO BE IDENTIFIED
[11] HTTP://WWW.IMAGE-FP7.EU

rock fluid and chemistry is not established yet. Often, geothermal projects have been carried out with the use of few methodologies, and in most cases, a comprehensive picture coming from the integration of different methods is lacking.

This subprogramme looks at reducing mining risks for site exploration and relates to various past and current projects at the European (e.g. I-GET, IMAGE, DESCRAMBLE or GEMex) and national level (e.g. SALK in Belgium, UDG in the Netherlands).

Objectives

The subprogram focuses on three main objectives:

1) Novel geothermal mapping techniques and process models for site exploration, to improve pre-drill site assessment of the reservoir rock physics.
2) Development of innovative, cost-effective geophysical imaging technologies for reservoirs at depths between 500 and 6000 m including borehole surveys (core, logs, down-hole instrumentation, VSP, Walk-away, cross-hole geophysics) and surface surveys, reducing the cost footprint and reducing exploration uncertainty, and associated joint field acquisition and data assimilation technologies including development of novel high T tracers.
3) Case studies showcasing added value for particular geothermal plays and tectonic setting in so called “natural laboratories”.

Meeting these challenges will save significant time and expense in the very costly drilling process and will guarantee data coverage and quality to properly optimize the use of the resource, reducing environmental impacts by forecasting possible problems and finding solutions beforehand. Critical earth-system properties and processes include: permeability, temperature, thermal conductivity, stress, rock-fluid interactions, chemical signature. Strength, existing fractures, history, cements, porosity type, and hydrological regimes.

Targeted resources are conventional geothermal resources as well as low permeability reservoirs exploitable with Enhanced Geothermal Systems technology, to cover all geological contexts: deep sedimentary basins, volcanic contexts, crystalline rocks.

Major breakthroughs in conceptual insights and imaging technology reducing uncertainty and lowering cost for exploration in natural laboratory areas/particular settings are to be expected within the next five years. The resource potential for the brownfield areas will be significantly improved. Exploration drilling pilot projects defined through insights of brownfields will be executed in greenfield natural laboratory settings. In 10 years’ time methodologies and concepts shall be refined and exported to other regions in Europe, and abroad.

3.2.1 Work Package 1: Geothermal models for site exploration

Reduction of mining risk can benefit strongly from predictive models capable of addressing temperature, stress, fluid flow and chemical evolution at appropriate spatial site scale and geological timescales, in order to predict critical exploration parameters. Furthermore, insights Outcrop studies, and catalogues of rock properties are of key importance to develop and constrain conceptual models of geothermal reservoirs. In addition state of the art 3D mapping approaches are required including capability to integrate in depth insights of geological processes in geothermal site mapping.

Task 1.1 Geological process models for site exploration

At site scales, geological processes and properties are marked by complex interaction (e.g. temperature and fluid flow) and structural complexity (of the reservoir and its geological embedding). Reduction of mining risk benefits strongly from predictive models capable of addressing temperature, stress, fluid flow and chemical evolution at appropriate spatial site scale and geological timescales, in order to predict critical exploration parameters. Coupled model approaches, capable to honor structural and evolutionary complexity are key. To this end, this task will develop new conceptual and numerical models and workflows. These models embed in model components of relevance developed in WP1 on stress and temperature. The mapping component is covered in Task 1.3 of WP2.

Of particular importance is the assessment of the evolution of primary permeability and fracture related fluid pathways. The relationships between fluid pathways, fracture formation and the geological environment, the influence of the in-situ stress field and the interacting geomechanical, thermal, fluid flow and geochemical processes are not well understood, but critical to targeting and exploiting many geothermal resources. (Note synergy with elements of Tasks 1.1 and 1.3 of WP1).

Targets:

- Conceptual models to assess the impact of different geological settings on the geothermal reservoir at site scale.
- Numerical models to assess the impact of different geological settings on the geothermal reservoir at site scale.

Task 1.2 Outcrop studies and rock physic properties

Outcrop and lab analysis investigations are needed to provide conceptual insights and rocks physics catalogues respectively. Outcrop studies allows to identify pertinent processes. Structural tectonic studies at the micro-meso-macro scales (including 3D seismic attributes) in outcrops and petrographic-mineralogical-geochemical studies and fluid inclusion data will provide useful information on the characteristics (fluid temperature, mineral precipitations/dissolutions processes, fluid recharge) of reservoirs similar to that of active geothermal systems and systems at depth. Lab analysis of multiple key properties at different sample scales allows to develop petrology-specific physical or empirical relationships and to improve parametrization of site predictive models and the interpretation of geophysical imaging methods.

Targets:

- Reservoir analogue conceptual models – insights in fracture fabric and rock properties, to improve pre-drill reservoir performance prediction.
- Rock property database for conceptual and geophysical imaging methods.

Task 1.3 Integrated geothermal site mapping

Research in integrated geothermal mapping is focused on developing methodologies and software solutions for 3D mapping, integrating in-depth insight in geological processes, petro- and geophysical data and probabilistic approaches for sedimentary, fault and hard rock settings. In deep sedimentary basins, 3D modeling of aquifer reservoirs (limestones or clastic type) will be improved (such as permeability, temperature), based on state of the art data and methodologies developed in the oil and gas industry. In hard rock settings, particular attention is paid to 3D mapping of faults and fractures and the emplacement of magmatic bodies such as granitic plutons, which often produce pathways for the migration of hot fluids in geothermal fields, and the relationship between lithological layering (metamorphic) and hydrological layering. Burial and uplift history is also important for predicting the thermal resource as well as the permeability and recharge systems.

Targets:

- Methodologies and tools for multi-source data integration for 3D site mapping
- New 3D models in various geological contexts

3.2.2 Work Package 2: Geophysical Imaging and Inversion

Deep geothermal reservoir characterization is in need of cost effective imaging, processing and interpretation techniques. Low cost sensor techniques, high computation power and big data analytics approaches provide important possibilities to enhance the resolution while lowering the cost of geophysical techniques, joint interpretation and inversion to in view of multiple data constrains.

Task 2.1 Application of advanced geophysical technologies

Novel cost-effective acquisition and imaging techniques for assessing reservoir structure and properties will be developed, including improved imaging between wells for near field development, such as VSP and micro gravity, and novel methods including ambient noise fibre optics, novel tracers (especially for high T and P) and remote sensing (e.g. INSAR) and integrated techniques for analysis,, providing valuable information on rock-fluid interactions, rheology and stress characterization, risks for induced seismicity and interaction with subsurface tectonic fabric. Interpretation techniques for airborne geophysics and remote sensing will be developed and tested for geothermal applications. Advances in reprocessing of vintage data originally collected by the hydrocarbon industry is of key importance for basement-sediment settings.

Best practice workflows for geophysical acquisition will be developed for particular tectonic settings. Further methods to determine heat flow at surface and heat flow and temperatures at depth will be improved to consistent process oriented models.

Targets:

- Novel geophysical imaging techniques,
- Advanced reprocessing of vintage data from hydrocarbon E&P,
- Best practice workflows for geophysical acquisition.

Task 2.2 Joint field acquisition and inversion

Imaging methods will be significantly improved by joint acquisition and inversion, resulting in an increase in reliability of subsurface interpretation as part of methodologies to update existing reservoir characterization based on real-time (production) observations. Low-power instrumentation and information technology and data assimilation systems are crucial for capturing and analyzing instantaneous and long-term information. Data to be monitored include production, INSAR data, well-log data, surface resistivity and seismic data etc. New receivers will be developed in order to jointly (with the same layout and shared sensors) acquire data using different geophysical methodologies (MT, IP, SP and ERT) to reduce bias and improve imaging. Further joint inversion is aimed at taking full advantage of data collected by hydrocarbon industry (seismic, well, temperature, conductivity) in mature oil and gas basin settings.

Targets:

- Advanced joint acquisition and forward model/interpretation approaches,
- Joint inversion methods and workflows.

3.2.3 Work Package 3: Natural laboratories

The conceptual and technological advances need to be tested, progressively improved and validated in field applications. To this end SP2 focusses on selected sites and regions, serving as natural laboratory for representative geothermal system environments including deep sedimentary and basement settings, and magmatic settings. For various novel techniques access to wells or other subsurface infrastructure is required, for test and validation. In addition the natural laboratories serve as platform for multidisciplinary integration of different geophysical techniques and conceptual approaches.

Task 3.1 Deep basement-sediment systems

Integrated mapping methodologies for deep subsurface structures in sedimentary basins developed in task 2.1.3 will be applied to prospective countries (e.g. Sweden, Norway, Germany, UK, Netherlands) and stored and shared through innovative data repository and visualization systems, developed in task 1.3. In prospective areas, new (3-D) seismic reflection surveys, and advanced processing of existing oil and gas data will be performed. In addition several exploration techniques (e.g. ambient noise seismics but also electromagnetics) will be tested which are dedicated to peri-urban areas in sedimentary contexts. Integrative numerical modelling approaches will be used to improve prediction of deep thermo-mechanical and structural characterization, temperature, and fluid flow.

Targets:

- Integrated reservoir characterization for basement-sediment systems
- Show cases of multidisciplinary geophysical and modelling techniques

Task 3.2 Magmatic systems

In particular work will focus on the modalities of magma migration and emplacement and their mutual relationships with active faults and stress field. Particular attention is paid to the study of faulting and fractures development related to the emplacement of granitic plutons and related intrusives. Studies will be performed on the island of Elba, a natural analogue to Larderello hydrothermal system, and studying the Larderello and Amiata geothermal fields by means of magnetotelluric data, fluid inclusion and mineralogical data.

Targets:

- Test and validation of conceptual models for magmatic reservoir formation

Task 3.3 Deep well research infrastructure

Existing operations for (Enhanced) geothermal systems in deep basement and clastic rocks (e.g., Soultz-sous-Forêts/France, Grimsel/ Switzerland, Larderello/ Italy, Groß Schönebeck/ Germany, Lavrio/ Greece) provide excellent settings to test and validate the benefits of novel imaging and mapping methodologies at reduced cost and exploration risk. For Carbonate rocks, the Balmatt[12] (Mol - Donk) geothermal site can be used as a natural lab. Complementary to analogue sites, other investigation programmes such as nuclear waste storage, capture and geological storage of CO_2 and oil and gas field development will provide useful information and experiences. Low-permeability, deep sedimentary reservoirs– with special attention to deep carbonate reservoirs – will be the target.

Targets:

- Demonstration of imaging and mapping techniques for near well characterization;
- Prediction of key subsurface parameters for soft stimulation.

Milestones of SP2

Nr	Title	Measurable Objectives	by
M2.1	Spatial distribution of critical exploration parameters	Understanding the processes and properties that control the spatial distribution of critical exploration parameters at site scales. The focus will be on the prediction of temperatures, in-situ temperature, stresses, fracture permeability and hazards which can be deduced from field analogues, public datasets, predictive models and remote constraints incl. rock property catalogues and predictive models of super-critical resources	2017[13]
M2.2	Improved exploration techniques	Radically improving well established exploration techniques for imaging, detection and testing of novel geological, geophysical and geochemical methods to provide reliable information on critical subsurface exploration parameters. Methods include: a. Geophysical techniques such as ambient seismic noise correlation and magnetotellurics with improved noise filtering, b. fibre-optic down-hole logging tools to assess subsurface structure, temperature and physical rock properties; advanced reprocessing of	2017[14] 2018[15]

[12] HTTP://WWW.DIEPEGEOTHERMIE.BE/NL/
[13] HTTP://WWW.IMAGE-FP7.EU AND HTTP://WWW.DESCRAMBLE-H2020.EU
[14] HTTP://WWW.IMAGE-FP7.EU AND HTTP://WWW.DESCRAMBLE-H2020.EU
[15] HTTP://WWW.LIMBURG.BE/LIMBURG/SALK

		vintage data from hydrocarbon industry; the development of new tracers and geothermometers.	

3.3 SP3 – Constructing Geothermal Wells

Background

Extraction of underground resources requires the establishment of a communication channel between the underground resource and surface. To extract heat from the underground for generation of electricity, it is generally required to go deep to achieve a sufficiently high temperature. Geothermal wells are often constructed by penetrating hard formations.

The cost of drilling for geothermal resources is a major challenge in many cases. The fraction of the investment spent on wells could be up to 75 % of the total investments in a geothermal plant. A target of 25 % reduction of well construction cost within 2020/2025 is given by the European Geothermal Energy Council.

Objectives

Improvements within construction of geothermal wells could be achieved along two main areas:

1) New methods for drilling and improvement of existing technologies for penetrating the formation, and
2) Improvements within well construction and design, including e.g. completion, annular seals, well logging etc. suitable for high-temperature applications.

Improvements within this technology area are believed to reduce construction cost, improve the integrity and reliability of geothermal wells, and enable efficient large-scale utilization of deep geothermal resources.

3.3.1 Work Package 1: New drilling methods

It is recognized, that the major impact on the cost of a geothermal power plant is connected to the drilling cost especially because deep wells are needed to reach temperatures, which are reasonable to produce a minimum of electricity (i.e. > 150°C). This requires in many places well depths of 4 km and more. With conventional mechanical drilling methods one reaches drilling speeds of around 1-6 m/h, meaning that rock breaking and rock removal should be greatly improved to reduce the cost of drilling.

This WP deals with methods for construction of a well to ensure communication between the surface and the geothermal reservoir. However, new and improved methods for stimulation to improve production could be valuable for the WP. Stimulation is primarily treated in SP-4. Of particular interest is probably the SURE project, dealing with radial jet stimulation technology. Results from this could be useful regarding fundamentals of rock removal.

Task 1.1 Hybrid thermal drilling

Hybrid drilling involves using a combination of mechanical (assisted) drilling and a thermal process, e.g. a flame, plasma, spallation, or Laser induced process. Thereby, thermal energy as heat via the above-mentioned techniques is used to stress the hard rock base material in such a way that small particles, so called spalls, are being created. Subsequently, if needed, the spalls and weakened rock structure are being further mechanically crushed, and finally being flushed out of the hole. First lab tests with a combination of mechanical and a thermal method, in this case hydrothermal flames or Laser, do show remarkable increase in drilling speed ROP. The objective of this task is to develop a prototype drill Head / BHA for an all new thermally based drilling process, including first experiments to be conducted in granite or similar hard rock in large scale experimental set-ups under atmospheric / ambient as well as reservoir conditions (e.g. autoclave system iBOGS at GZB). Further Investigations in rock laboratories including thermomechanical tests – related to rock as well as bit materials – under in-situ HP / HT conditions, and on test sites to be defined.

Efforts within different thermal drilling are ongoing and funded by national projects (Bochum / GZB, ETH Zürich, TU Dresden). These are described briefly below.

At GZB in Bochum, a LASER supported drilling method is under development. The drilling system to be built within the LaserJetDrilling project aims at increasing both ROP and service life of the drilling tools by use of laser technology. A high power industrial laser source of 30 kW is being used to transfer energy to the bit face in order to ease the process of rock destruction by provoking thermal spallation as well as thermal weakening of the rock. By transferring the laser beam onto rock's surface, using a water jet to guide and protect laser optics, the compressive strength of hard rocks is significantly reduced. Thus, a combined Laser + mechanical drill bit can easily crush and remove the weakened rock and remaining particles, which are being flushed out with regular drill mud. Only little weight on bit (WOB) and low torque through the drill string are required. According to first lab results, drilling at much higher ROP and with minimal tool wear seams possible.

A proof of concept type field test under real drilling conditions at GZB in Bochum is scheduled for the last quarter of 2017.

Contact person: Volker Wittig, GZB, volker.wittig@geothermie-zentrum.de.

In Zürich at ETH, a combustible medium / "fuel" is being pumped down the drill string in order to be ignited and burned within the especially designed BHA, thus raising the temperature enough in order for spallation to occur. The rock flakes / spalls are being flushed out using drill mud. This method, called "Flame-jet drilling", uses low thermal conductivity and resulting thermal stresses induced by local heating, to burst incompressible (i.e. crystalline) rocks rapidly into fragments (spalls). It essentially breaks the rock by tension which is inherently more efficient than crushing (roller cones) and shearing (fixed cutters). Lab tests and literature show the efficiency of this drilling technique to increase with depth, and spallability of a formation is inversely proportional to its drillability.

A proof of concept field test under real drilling conditions is scheduled for the last quarter of 2017.

Contact person: Philipp Rudolf von Rohr, ETHZ, philippr@ethz.ch.

Another quasi "thermal" drilling method is the so-called EI drilling, which is a zero-contact rock destruction method without any mechanical support. Electric Impulse Technology (EIT) is based on the effect of electric discharges inside the rock. A high voltage electrode (up to 500 kV) and a ground electrode are placed on the rock via the BHA. Rock and electrodes are surrounded by a liquid (water, drilling mud, etc.), which acts as an insulator for very fast rising times of the electrical voltage. Thus, the electrical discharge occurs inside the rock. Very high pressures and temperatures are generated in the plasma channel, which leads to failure of the rock structure. The biggest advantage of this technology is its significantly lower specific energy demand by working against the tensile strength of the rock, which is about 1/10 of the compressive strength. Furthermore, no mechanical force is needed to destroy the rock, which makes an almost wear free removal of the rock possible because the electrodes only need a loose contact to the rock. The electrodes can be designed in such a way that no relative motion to the rock is necessary.

This drilling method is under investigation at TU Dresden and also scheduled for a field test later in 2017 / 2018.

Contact person: Erik Anders, TU Dresden, erik.anders@tu-dresden.de.

Targets:

- new technology to drill faster and cheaper in hard rocks.
- design rules for a hybrid drilling system based on thermally induced stresses theory (model) and practical experiments (prototyping),

Task 1.2 Fluid-assisted drilling

The overall goal of ThermoDrill[16] is the development of an innovative drilling system based on the combination of conventional rotary drilling with water jetting that will allow at least 50% faster drilling in hard rock, a cost reduction of more than 30% for the subsurface construction and a minimized risk of induced seismic activity.

Contact: Karin Rehatschek, Uni. Leoben, Austria (karin.rehatschek@unileoben.ac.at)

Targets:

- enhanced water jet drilling technology for borehole construction and replacement of fracking;
- HT/HP crystalline rock jetting and drilling fluids;
- systematic redesign of the overall drilling process, particularly the casing design and cementing;
- evaluation of drilling technologies and concepts in terms of HSE (health, safety and environmental) compliance.

Task 1.3 Hard rock drilling improvements

The INNO-Drill project is funded by the Norwegian Research Council and industry, 2016-2020, ca. 3 Mio EUR. The project proposes to extend, demonstrate, and make available a research-based technology platform to enable new and significantly more cost effective drilling tools and systems for deep geothermal wells in hard rock formations.

[16] HTTP://THERMODRILL.UNILEOBEN.AC.AT/

Contact: Pascal-Alexandre Kane, SINTEF, Pascal-Alexandre.Kane@sintef.no.

Targets:

- extend, demonstrate, and make available a research-based technology platform to enable new and significantly more cost effective drilling tools and systems
- analytical and numerical model of hard rock chip removal

3.3.2 Work Package 2: Well construction and completion

Construction of geothermal wells poses a number of issues related to e.g. high temperatures, temperature cycling, corrosive environment and fractured rock. The challenges are associated with all phases of the well life cycle, including drilling, running casing/completion cementing, production, workovers and permanent plugging and abandonment.

In the following, relevant ongoing projects are listed, each with their objectives and targets.

The H2020 DESCRAMBLE[17] "Drilling in dEep, Super-CRitical AMBient of continentaL Europe" project proposes to drill in continental-crust, super-critical geothermal conditions, and to test and demonstrate novel drilling techniques to control gas emissions, the aggressive environment and the high temperature/pressure expected from the deep fluids.

To achieve this target, the first drilling in the world in an intra-continental site at a middle-crustal level will be performed. The test site is an existing dry well in Larderello, Italy, already drilled to a depth of 2.2 km and temperature of 350 °C, which will be further drilled to 3-3.5 km to reach super-critical conditions unexpectedly experienced, and not controlled, in a nearby well in 1979.

Contact: Ruggero Bertani, ENEL, ruggero.bertani@enel.com

Targets:

- Improved drilling concepts in deep crustal conditions,
- New drilling materials, equipment and tools,
- Physical and chemical characterization of deep crustal fluids and rocks.

GeoWell[18] (Innovative materials and designs for long-life high-temperature geothermal wells) aims at developing reliable, cost effective and environmentally safe technologies for design, completion and monitoring of high-temperature geothermal wells. This is strongly needed to accelerate the development of geothermal resources. GeoWell will address cement and sealing technologies, materials and coupling of casings, temperature and strain measurements in wells using fibre optic technologies to monitor well integrity, and development of risk assessment methods. The technology developed will be tested in laboratories and partly in real geothermal environment.

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[17] HTTP://WWW.DESCRAMBLE-H2020.EU/
[18] HTTP://WWW.GEOWELL-H2020.EU/

Contact: Árni Ragnarsson, ÍSOR, Arni.Ragnarsson@isor.is.

Targets:

- Improved cement and sealing technologies
- Materials, drilling fluids and coupling of casings
- Tools for logging temperature and pressure, long-lasting in very harsh conditions
- Temperature and strain measurements in wells using fibre optic technologies to monitor well integrity
- Development of risk assessment methods (in connection with SP 7)

The DeepEGS[19] (Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business) project is funded through Horizon 2020.

The DEEPEGS project will be testing stimulating technologies for deep EGS development, and intends to deliver new innovative solutions and models for wider deployments of EGS reservoirs for significant amounts of geothermal power across Europe. The project will demonstrate the capabilities of EGS for widespread exploitation of enthalpy systems, by testing the deep roots beneath the existing hydrothermal field at Reykjanes, with temperature up to 550°C, and in very deep hydrothermal reservoirs in sedimentary basins at Valence and Vistrenque in France with temperatures up to 220°C.

Contact: Guðmundur Ómar Friðleifsson, HS Orka, gof@hsorka.is.

Targets:

- The deep well at Reykjanes, IDDP-2, is expected to be completed in 2016. A 2.5 km deep production well will be deepened to 5 km by HS Orka, Statoil and IDDP.
- After drilling the well it will be extensively tested for injectivity and connection to the overlying conventional hydrothermal field, and subsequently flow tested for fluid chemistry and production properties.

The HYDRA[20] (Hydraulics modelling for drilling automation) project is a Marie Skłodowska-Curie project. The scientific objective of HYDRA is to develop a framework for multi-phase hydraulic modelling and model complexity reduction for drilling operations, delivered in software directly usable in industry.

Contact: Eindhoven University of Technology

Targets:

- The main training objective is to launch 3 doctoral students into future leading scientific positions with an intersectoral network to support them throughout their careers.
- The developed models uniquely combine high predictive capacity and low complexity enabling their usage in both virtual drilling scenario testing and drilling automation.

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[19] HTTP://DEEPEGS.EU/
[20] HTTP://CORDIS.EUROPA.EU/PROJECT/RCN/199790_EN.HTML

Milestones of SP3

Nr	Title	Measurable Objectives	by
M3.1	Laser-supported drilling development	A proof of concept type field test under real drilling conditions.	2017
M3.2	Flame-jet drilling	A proof of concept field test under real drilling conditions.	2017
M3.3	El-drilling	Field test.	2017/ 2018
M3.4	High pressure fluid jet	This combination of fluid jetting and rotary drilling is expected to at least double the rate of penetration.	2018[21]
M3.5	Drilling and completion technologies for high temperatures	New drilling technologies and concepts for increasing the number of economically viable geothermal resources, including in hard rock and high temperature/pressure conditions, and have a demonstrably smaller environmental footprint by comparison to existing drilling methodologies.	2018[22] 2018[23]
M3.6	Demonstration of EGS	Demonstrate the capabilities of deep EGS for widespread exploitation of high enthalpy systems.	DEEPEGS

Future plans and opportunities of SP3

Drilling technology development:

- Modelling of thermal effects during the drilling operation in high enthalpy (even supercritical) wells, e.g. drillstring behaviour, hydraulics

Geothermal well construction:

- Analyse and test high temperature/pressure wells;
- Statistical assessment of well integrity issues for low and high temperature (geothermal and O&G) wells (sustained casing pressure/surface casing vent flow/gas migration);
- Cooperation with other nations worldwide on critical developments, like superhot geothermal wells (e.g. GEMex project). Potential partners: New Zealand, US, Japan, Ring of Fire-Countries;
- Super critical geothermal wells, e.g. casing expansion during thermal transients;

[21] HTTPS://WWW.THERMODRILL.UNILEOBEN.AC.AT/EN/PROJECT/
[22] HTTP://WWW.DESCRAMBLE-H2020.EU/
[23] HTTP://WWW.GEOWELL-H2020.EU/

- Cost effective methods of increasing temperature rating of existing logging tools, e.g. wireline cable and telemetry system rated to more than 320°C.

3.4 SP4 – Reservoir Engineering

Background

Producing geothermal energy requires reservoir-engineering technology for commercial and sustainable reservoir development. In particular, resources lacking sufficient fluid and/or permeability require the use of specialized engineering technology. The subprogram gathers expert research groups with expertise ranging from basic modelling and experimental studies through analysis of field data and development of demonstration projects.

Objectives

The subprogramme will focus in particular on the following:

- The improvement of reservoir engineering technology for the development of commercially viable geothermal reservoirs;
- The optimal resource utilization through utilization of combined reservoir engineering concepts.

3.4.1 Work Package 1: Engineering a geothermal system

Commonly engineered systems are only considered to mean so-called enhanced geothermal systems (EGS), where “enhanced” refers to the enhancement of permeability by hydraulic, thermal, and/or chemical (soft) stimulation. However, there are other ways in which the subsurface may be engineered to result in a geothermal energy resource, where before such engineering, an energy resource was not accessible or economically speaking not present. In case of EGS, permeability is enhanced to be able to access and extract, by advective heat transfer, the geothermal heat that is present at considered depths. In contrast, by exchanging the subsurface working fluid, for example carbon dioxide (CO_2) for water, thereby approximately doubling the energy-to-electricity conversion efficiency so that much lower subsurface temperatures can be economically utilized, a previously unusable, low-temperature condition is turned into an engineered geothermal system, i.e., one that is economically usable to generate electricity – without permeability enhancement. A third example is to combine geothermal heat energy extraction (i.e., geothermal preheating) with subsequent heating of the fluids (water or CO_2) produced from the low-temperature “geothermal reservoir.” In this way, an otherwise, for electricity production unusable geothermal “resource”, may be turned into an economically usable, where the engineered hybrid power plant (combining geothermal with other energy resources), under the right conditions, has higher efficiencies, i.e., produce more power, than the sum of the separate (geothermal and auxiliary) power plants alone. In an extreme case, the geothermal power plant alone would not be economically viable at all. All of these examples constitute engineered geothermal systems.

Task 1.1 Geomechanical behaviour of fractures and fracture zones (EGS)

The internal architecture and geomechanical properties of fracture zones are particularly important for modelling the permeability enhancement processes in EGS and will be studied in considerable detail. Intermediate-scale experiments will be performed in underground laboratories to simulate and monitor fracturing and shearing of existing fractures under in-situ conditions. Geological and wireline data will be used to produce a geological model of the reservoir with its fracture structures, and waveforms of microseismic emissions used to illuminate the active structures and place constraints on the nature of the failure processes occurring within them. Models to explain the observed changes in physical properties associated with fracturing and/or shearing of (existing) fractures will be developed from measurements recorded in observation boreholes: With the use of Digital Rock Physics and Laboratory experiments (thermal cracking / stimulation as potential support for hydraulic stimulation in EGS (predestinated crack initiation and propagation) using THETIS and HECTOR) characterize the effective elastic properties on the micro-scale will be characterized. With an upscaling-procedure larger fractures at the meso-scale will be implemented. With high-performance wave propagation simulations parameter studies on the field-scale to determine the expected signals at observation boreholes will be performed (ETHZ, GZB).

It is also planned to study scaling relationships between the variation in stress orientation within a rock mass as derived from wellbore failure and b-value of micro-seismicity. Numerical studies will be conducted to assess whether the scaling of both parameters is controlled by a fracture size distribution that scales similarly. Moreover, it is known, that fracture zones are low-velocity zones. In those low-velocity zones elastic energy can be concentrated and may stimulate further fracture growth. The importance of this effect will be evaluated.

For a long-term operation of a geothermal installation (power/heat) it is necessary to study dissolution and precipitation processes in detail as a coupled thermo-hydro-mechanical-chemical process acting in pores and fractures. Such chemical processes have not only an impact on the productivity of a reservoir but can also influence induced seismicity due to a change of the rocks mechanical properties.

With reactive flow experiments in thermo-triaxial cells the alteration of different porous and fractured rocks due to the geothermal operation will be studied under reservoir conditions and parameters for reservoir models will be derived. By using numerical THMC simulators the processes can be generalized to the reservoir scale. For this respective upscaling approaches are necessary and have to be derived.

Targets:

- Improved understanding of the hydro-mechanical response of fracture zones to injection (ETHZ, GZB, UoB)
- Evaluation of the relationships between b-values of induced seismicity, stress variations and fracture size distribution within the reservoir (ETHZ, GZB)
- Demonstration of multi-stage and cyclic hydraulic fracturing design in intermediate-scale experiments
- Evaluation of the long-term behaviour of an engineered reservoir (TUDA)

Task 1.2 Stimulation: Development and demonstration of multi-stage and cyclic hydraulic fracturing combined with thermal-chemical treatments (EGS)

Horizontal multi-stage hydraulic fracturing is the process by which multiple fractures are created along a horizontal section of the wellbore in a series of consecutive operations. This provides a better access to geothermal reservoirs, since horizontal wellbores allow for much greater exposure to a formation to develop a down hole heat exchanger with an appropriate size for extraction of heat. The individual stimulation is carried out stepwise in isolated intervals from the bottom (toe) to the end (heel) of the horizontal part of the well. This can be achieved by perforating the intervals of interest. One crucial aspect is the right distance between the perforation intervals to avoid any interference. This depends on the rock properties and the state of stress and needs to be simulated in advance. A special focus in this respect is the stress shadow effect, which impairs the propagation of adjacent fractures and in addition, can be also applied to control the direction of propagation.

As an added value of multiple fracturing, the individual stimulation treatment could be more moderate, which reduces the risks of seismic events above a tolerable level. Furthermore, suitable stimulation schemes may include cyclic stimulations with varying flow rates (so-called soft/fatigue stimulation) to reduce the risk of unwanted seismic events with large magnitudes. To obtain a sustainable opening of the fractures after stimulation, adding of gel and proppants (like meshed sand or high strength ceramics) shall be a suitable option.

Depending on the state of stress and the rock properties different fracturing modes can be applied: hydro-fracturing (mode 1), hydro-shearing (mode 2) or a combination of both. Mode 1 is ascribed to the creation of new tensile fractures, whereas mode 2 is related to the reactivation of already existing fractures. Mode 1 could be favorable in multi-stage fracturing in conjunction with supporting proppants to avoid any interference of the individual treatments. Mode 2 scenarios are best suited in natural fractured environments if the natural fractures are favorable oriented (high slip tendency).

In addition to a pure hydraulic stimulation, it can be combined with a chemical treatment and/or thermal fracturing (i.e. cold water injection). In carbonate environments or environments with sealed pre-existing fractures a combination of chemical treatment and hydraulic stimulation can be considered to lead to a better access to the reservoir. Cold water injection can support the stimulation by creating of thermal induced fractures perpendicular oriented to the hydraulic fractures. Another option in case of formation damage is the drilling of so-called deep radials into the formation to penetrate the radius of the damage zone and which subsequently should be stimulated with acid (e.g. HCl) to overcome the damage zone.

The ultimate goal is to demonstrate the feasibility of the concepts mentioned above in field experiments. All scenarios have to be evaluated regarding the site-specific geological requirements to optimise the performance of the reservoir regarding geothermal heat extraction and simultaneously reduce the risk of unwanted seismic nuisance and environmental impact.

Targets:

- Concepts and demonstration for multi-stage designs in hydro-thermal and petrothermal environments to demonstrate the feasibility to generate sufficiently large heat exchangers at depth,
- Concepts and demonstration for cyclic stimulation designs in hydro-thermal and petrothermal environments to demonstrate the reduction of seismic risk (soft/fatigue stimulation),

- Recommendation for hydro-fracturing (mode 1) and/or hydro-shearing (mode 2) stimulation design based on specific site conditions,
- Demonstration of combined hydraulic and/or chemical and thermal treatments to optimize the stimulation performance,
- Concepts and demonstration for drilling deep radials in conjunction with chemical stimulation treatments to overcome formation damage zones.

Task 1.3 Stimulation: Development of a novel productivity enhancement concept based on radial water jet drilling technology

The radial water jet drilling (RJD) technology will be investigated as a method to increase inflow into insufficiently producing geothermal wells thus enabling a more sustainable utilisation of geothermal resources. RJD uses the power of a focused jet of fluids, applied to a reservoir rock in order to create several horizontal holes. These laterals from an existing well into the reservoir aim to drain initially not connected high permeable zones to the main well. As the possible length of the drilled laterals is currently up to approximately 100 m, the RJD technology has a potential benefit in highly heterogeneous reservoirs, where strong and eventually even anisotropic permeability variations can be observed in the vicinity of the main bore. These can be either fracture, fault or karst systems not connected to the main bore or highly permeable matrix structures as can be found, for example in channel structures in sandstones.

The suitability of the RJD technology will be investigated for deep geothermal reservoir rocks at different geological settings such as deep sedimentary basins or magmatic regions. A characterization of the parameters influencing the jet-ability of different rock formations will be necessary. In addition, advanced modelling will help understand the actual mechanism leading to the rock destruction at the tip of the water jet.

RJD is likely to provide a much better control of the enhanced flow paths around a geothermal well compared to established stimulation methods. The technological concept furthermore aims to significantly decrease the environmental footprint of a stimulation treatment by reducing simultaneously the amount of applied fluid volumes, the number of applied chemicals with environmental impact, and the risk of induced seismicity. Special focus will be on the comparison of RJD with the established stimulation treatments concerning benefits and drawbacks on issues such as flow performance of the well prior to and after the stimulation, sustainability of the productivity increase in terms of the thermal breakthrough and hydraulic properties, environmental footprint of the necessary technical equipment for the stimulation treatment, and the necessary time and budget to perform an operation.

Targets:

- Understanding of the parameters influencing the jet-ability of relevant reservoir rocks
- Report on RJD stimulation at a sedimentary and a magmatic site
- Evaluation of the productivity increase from an RJD stimulated geothermal well
- Evaluation of environmental impact of an RJD stimulation compared to a conventional stimulation treatment concerning induced seismicity, volume and toxicity of released fluids as well as land use and noise generation during operation

Task 1.4 Induced microseismicity (EGS)

The detailed monitoring of induced seismicity during hydraulic stimulation is not only a requirement for assessing and mitigating the seismic nuisance and potential hazard, but also a rich source about the reservoir creation and evolution with time. This analysis is relevant not only for understanding permeability enhancement in EGSs, but also for seismic hazard assessment in any scenario where fluid pressures are disturbed through re-injection (CO2 storage, disposal of waste liquids, hydraulic fracturing).

The importance of accurately knowing the stress field deep in the subsoil can be crucial for calculating the response of the porous medium during fluid injection and withdrawal. The calculation of the focal mechanisms with first motion or inversion techniques can provide the orientation of the 3 principal stress axes and, hence, the possibility to map (vertically or horizontally) the variations of the stress field. Furthermore, with the inversion of the full moment tensor not only the deviatoric part of the tensor but also its volumetric part can be extracted. A contribution to the localization of microseismic activities that can be observed during hydraulic stimulation of a reservoir can be offered by the know-how on hydrocarbon reservoirs. Information regarding the behavior of the rock, including the potential identification of the opening of new fractures that can modify the fluid flow, can also be provided. With time reverse techniques, we will also localize and characterize microseismic events. Especially for multiple events in highly anisotropic media this can lead to an enhanced understanding of the source mechanism.

Induced seismicity has been studied in the GEOTHERM project using data from Basel, Soultz and Cooper basin, and more widely within the framework of the GEISER project using additional data from Groß Schönebeck, Icelandic sites, Latera/Italy (provided by Enel within the GEISER project), and The Geysers/USA. These projects have greatly advanced the understanding of the statistical and physical processes governing induced seismicity. A first generation of models is able to forecast the evolution of induced seismicity during the reservoir creation, forming the baseline of hazard mitigation strategies such as advanced traffic light systems. In a next step, such systems must now be calibrated and validated with independent data, while at the same time further improving the underlying physical models. One important aspect of the future work will be to simultaneously model and eventually optimize on the fly the permeability creation and the induced seismicity, rather than simply minimising induced seismicity. In addition, the role of aseismic creep and numerous micro-earthquakes below the detection threshold in permeability creation will need to be better understood. Finally, an important goal will remain to be able to forecast with confidence the induced seismicity response to injection prior to the expensive drilling phase, based on geological/geophysical measurement and analogues. Use of OGS experience in gas storage monitoring, to distinguish between natural earthquakes and induced seismicity.

Targets:

- Validated risk mitigation strategies coupled to permeability creation.

Task 1.5 CO_2-based geothermal energy extraction and auxiliary heating of geothermally preheated geofluids – alternative engineered geothermal systems

As mentioned in the introduction to this SP, aside from EGS, where enhancing or engineering refers to increasing a potential reservoir's permeability, there are other ways to engineer a geothermal system. Two such approaches are mentioned here: 1) using a subsurface working fluid other than water (e.g.,

CO_2 or N_2) as the heat and pressure energy extraction fluid and 2) auxiliary heating of geothermally preheated fluids.

The former approach uses an alternate subsurface working fluid, such as CO_2, that results in an approximate doubling of the energy-to-power conversion efficiency, compared to water, so that much lower subsurface temperatures (and also much lower reservoir permeabilities) are economically viable than when standard water is employed. This approach can be coupled with carbon capture and storage (CCS) resulting in a carbon capture utilization and storage (CCUS) approach, but not necessarily so, as alternatively, (partially) depleted oil and gas reservoirs could be used. In the case of oil, this would constitute an enhanced oil recovery system. However, if the CCUS version is employed, the result is a CO_2-sequestering geothermal power plant, which can have a negative carbon footprint, if the captured CO_2 comes from bio-energy (BE) utilization with CCS, i.e., BECCS, or from direct air capture.

The auxiliary heating of geothermally preheated fluids (water, CO_2, N_2, ...) approach enables utilization of low underground temperatures, as the subsurface is essentially used as a geothermal preheater. During this approach, the underground-preheated fluids are produced to the surface and are auxiliary-heated, ideally with a renewable energy resource, such as solar-thermal or bio-energy, but possibly instead with a fossil-energy resource such as natural gas. Because the temperature of the working fluid, entering the turbine, is higher than those of the two separate systems' fluids, the resultant fluid entering the turbine has a higher thermodynamic quality than if the separate fluids with their respective lower temperatures were used separately. The result is a higher power generation efficiency, to the point, where in an extreme case, the geothermal resource alone could not be used at all to produce electricity in an economically viable fashion. Consequently, geothermal preheating and subsequent auxiliary heating of fluids to generate power is a way to use low/moderate geothermal energy resources, that would, if used alone, be too low in temperature for economic power generation. As each energy input to the power generation can easily be determined, it is possible to declare how much of the power is the result of geothermal energy utilization, which is useful for taking advantage of geothermal feed-in tariffs and similar regulations.

Both of the above alternate geothermal-system engineering approaches do not necessarily require hydraulic stimulation, with its potential seismic and environmental risks, but can be coupled with EGS if desired, thereby combining the advantages (but also the disadvantages) of the involved approaches. One could even envision a CO_2-based EGS with auxiliary heating, i.e., a triple-engineered system that increases the efficiency by enhancing permeability, using CO_2 as the subsurface heat extraction fluid, and auxiliary-heating the produced fluid before it enters a heat exchanger or a turbine. In that way, it may be possible to utilize particularly low-temperature geothermal resources at moderate depths (e.g., of 1-2 km) that are otherwise unthinkable to be considered.

Targets:

(ETHZ, Geothermal Energy and Geofluids Group; Swiss Competence Center on Energy Research – Supply of Electricity (SCCER-SoE)

- Numerical models of 1) CO_2-based geothermal systems alone, 2) of hybrid systems of geothermally preheated and then auxiliary heated fluids alone, and 3) combinations of (1) and (2) – all non-EGS-based.
- Numerical models of (A) combined with EGS.
- Numerical models of power (both electricity and heat) generation for (A) and (B).
- Economic models of (C)

- Longer-term: first pilot and demonstration systems of any one of the above, perhaps at St. Gallen, Switzerland.

The first four targets above would be reached with one or more simulators discussed under Task 1.6 of this subprogramme.

Task 1.6 Simulators

Thermo-Hydro-Mechanical-Chemical (THMC) as well as (electricity/heat) power plant process (P) simulator for several geothermal and EGS systems (e.g. Soultz-sous-Forêts) will be developed to define appropriate reservoir exploitation strategies, e.g. to optimise test durations and performance and multi-well layout planning. Based on these comprehensive models, e.g. thermo-mechanical impacts on the evolution of the flow path during long-term circulation will be investigated. Transport properties of fractured porous media addressed include convection-dispersion of passive and reactive fluids, dissolution and precipitation processes as well as thermal properties, which is important for the characterization of fractured porous reservoirs. Several numerical codes are under development (here we can list the specific codes we are providing), each focused on simulating different aspects of hydrothermal, petrothermal (i.e., EGS), CO_2-geothermal, and related power plant systems.

- One set of codes is concerned with the real-time, statistical and physics-based prediction of the maximum seismic event size in systems undergoing hydraulic stimulation.
- Another suite of models is expanding the CSMP++ platform to model fluid-rock interactions in realistic geological structures.
- The third set is the new and the continued development of a THMC-coupled EGS reservoir simulators with a modular structure that includes the essential physics for simulating hydraulic and thermal stimulation, as well as the long-term changes in system performance arising from fluid-rock interaction. The new simulator development includes surface (electricity/heat) power plant process (P) simulations, resulting in a THMCP simulator, that enables estimation of power (electricity) generation as well as more complex couplings between power or heat supply, fluid injection, subsurface heat energy storage, and power grid demands. Coupled with a geothermal system economics (E) simulator (such as US DOE's GETEM), this could be extended to a THMCPE simulator.
- A fourth type of code addresses the long-term performance of the reservoir, the quantification of uncertainty in data assimilation and parameter estimation, and the use of high-performance parallel computing for high-resolution, large models of single- or multiple-phase reservoirs.
- A fifth type of code addresses THMC processes with an emphasis on dissolution and precipitation processes in pores and fractures. Using appropriate upscaling techniques experimental results will be transferred on the reservoir.
- Workflows for modelling and data analysis: Due to the complexity of geothermal reservoir modelling, the development of workflows including data integration, forward process simulation and inversion as well as visual data analysis is envisaged. These workflows will also support interoperability between different workflow components.

Targets:

- Proof of reliability of THMC reservoir models for several sites, benchmarking (UFZ).
- Code for real-time prediction of seismicity during stimulation (ETHZ).

- Full multiphase, parallelized THMC reservoir simulators including hydraulic, thermal, and chemical stimulation as well as plant process (P) and possibly economics (E) simulations, resulting in THMCP and THMCPE simulators, respectively (several groups at ETHZ).
- Fully hybrid MPI/OpenMP-parallelized, multi-phase-, multi-component THC-code for prognostic forward simulations (UFZ) and inverse parameter estimation (RWTH/E.ON ERC).
- Code for simulation of induced seismicity in reservoirs structurally dominated by complex 3D fracture networks, based on coupling of flow, fracture deformation models (including proper friction laws), and geomechanics (UoB).
- Development of upscaling processes for handling deformation of fine-scale fractures in simulation of induced seismicity (UoB).
- THMC code for simulation of dissolution and precipitation using advanced HPC.

Milestones of SP4

Nr	Title	Measurable Objectives	By
M4.1	Soft Stimulation	Demonstration EGS for European sites with treatments for increasing the reservoir's transmissivity or long-term productivity at minimising the level of induced seismicity and environmental impact	2018[24], 2019[25]
M4.2	Roadmap for application of soft stimulation	Scenarios with the aim to provide a public acceptance and cost optimized roadmap for a reliable future application and further development of soft stimulation technique.	2019[26]

3.5 SP5 – Energy Conversion Systems

Background

An increasing exploitation of geothermal energy in a rapidly evolving context requires technologies that can efficiently and flexibly convert heat taken from different kinds of geothermal sources into electricity and possibly other valuable products.

Several drivers will affect the evolution of power plants technology:

- the concern for the environmental impact,
- the trend towards higher efficiency and economics.
- the request for reliability and operation flexibility, relevant in a context of increasing power generation from non-predictable, intermittent renewable sources and,

[24] HTTP://CORDIS.EUROPA.EU/PROJECT/RCN/199917_EN.HTML
[25] HTTP://WWW.DESTRESS-H2020.EU
[26] HTTP://WWW.DESTRESS-H2020.EU

- the convenience for joint exploitation of geothermal energy together with other energy sources, by means of hybrid plants, where the geothermal source is exploited in parallel to another (possibly renewable) source;

Actually, the technology of binary power plant is expected to be a key technology in the near future, and the SP5 efforts will therefore concentrate mainly on binary plant technology.

Objectives

This subprogramme looks at designing plants with increased performance and widespread application and focuses on these main objectives:

- Minimizing the environmental impact, aiming at zero-emission plants, with total reinjection of the exploited geothermal fluid, and least use or no use of cooling water;
- Increasing plant performance, both from the thermodynamic and economic point of view, for single purpose and multi-purpose plants, co-producing electric energy, heat, chill, and possibly mineral extraction.
- Increasing reliability and operation flexibility.
- Developing concepts for hybrid multi-source, multi-purpose plant.

3.5.1 Work package 1: Heat transfer process and plant engineering

The efficient production of heat, chill and electricity from geothermal energy plays a major role for the economic sustainability of any geothermal power project. To enhance the net efficiency of geothermal power plants all components and aspects have to be considered. This subprogramme addresses improvements in heat transfer from geothermal fluid to the energy conversion system and the development of new, more efficient binary power systems. In addition, cross-sectional tasks as geothermal water chemistry, corrosion etc. will be taken into account by the development of new materials at lower cost. These developments will be integrated in new power loop components.

Task 1.1 Heat transfer process

Numerical tools, laboratory and on-site tests will be performed for the design of improved heat exchangers. All aspects of the heat introduction process will be considered. Moreover, the investigation will assess the feasibility and performance of an innovative heat rejection option for the binary cycle, i.e. the adoption of a condenser cooled by shallow groundwater, which could be very attractive when such an aquifer is available. The selection of material, surface structure and coating is also a key aspect in order to enhance the heat transfer and minimize scaling, thus realising an enduring and efficient heat transfer process.

Targets:

- Experimental assessment of heat exchanger performance operating with geothermal fluid
- Performance evaluation of different coated materials in contact with the geothermal fluid

Task 1.2 Design and operating of power conversion systems

In the range of 50 KW new binary power conversion systems will be tested, to be able to offer low-maintenance, reliable small-scale solutions for remote areas without access to a power distribution grid. Such a unit will be shipped to Indonesia commissioned and tested for further on-site use. Larger power stations (approx. 1 MW) will be set up and tested at Groß Schönebeck and in Indonesia to provide sustainable base-load power and test different power plant layouts for optimised net-power output.

Above all, in the context of European applications, combined heat and power generation (CHP) as well as trigeneration increases the cost-efficiency of geothermal energy conversion systems. In this context, most suitable power plant configurations and operation strategy will be identified depending on the power unit (e.g.: standard ORC, double-stage ORC, Kalina cycle), the characteristics of the reservoir and the heating network (supply temperature and capacity). Partial load performance and operational flexibility during the whole plant life constitute also an important issue. Furthermore, thermodynamic analyses based on real power plant data are preformed to identify inefficiency of the binary cycle and develop appropriate optimization approaches. In this context, operational parameters of the ORC power plants Kirchstockach (double-stage ORC) and Traunreuth (standard ORC) are available and will be analysed in detail. At the same time, the investigation for the development and improvement of the binary plant technology will focus on innovative cooling techniques, and innovative cycles like the Misselhorn process, the trilateral flash cycle or the organic flash cycle, which will be adapted to geothermal applications and evaluated. In addition, the possible exploitation of hotter or unconventional resources will require the investigation of suitable binary cycle arrangements and working fluids.

Finally, coupling the geothermal heat source with an alternative, renewable energy source is another promising optimization approach to increase the power output of binary cycles. Such hybrid power plants will be examined for low- and medium-enthalpy resources.

Targets:

- Development and testing of small-scale binary power plant units for remote areas;
- Identification of efficient geothermal CHP systems based on transient simulations;
- Creation of synergies by coupling geothermal resources with alternative, renewable energy sources in form of hybrid power plants.

3.5.2 Work Package 2: Storage and provision of heating and cooling

The performance and economics of CHP and tri-generation plants can be boosted by the adoption of an underground thermal energy storage (UTES) system, allowing a more flexible operation. Producing heat or cooling for a district H&C system has consequences for the electrical power cycle due to the seasonal fluctuations. Depending on the conditions of the geothermal fluids, like mass flow and temperature, and urban surrounding, geothermal reservoirs offer the opportunity to store thermal energy in the subsurface so that the geothermal power system can be designed and operated considering not only provision but also storage of heat or chill.

Task 2.1 Underground storage for heating and cooling purpose

Technology of borehole thermal energy storage (BTES) and low-temperature aquifer thermal energy storage (ATES) systems will be improved for their performance optimisation for the assessment of the environmental impact of densely assembled fields during regular operation and in case of failure. Medium-temperatures aquifer storage systems (up to approx. 90°C) still face operational problems including heat losses, clogging and precipitation, corrosion and impacts on the groundwater system. High-temperature systems have not been yet been implemented and require conceptual design. Recommendations for regulatory frameworks will be done.

Targets:

- Evaluation of operational performance of medium temperature aquifer thermal energy storage systems
- Concepts for high temperature aquifer thermal energy storage systems

Task 2.2 Provision of heating and cooling

In the next future geothermal combined heat and power plants both for conventional resources and Enhanced Geothermal Systems will be developed, and, at the same time, innovative heating and cooling supply systems will be required. Promising areas are the development of "smart thermal grids" by means of new district heating & cooling networks (Geothermal District Heating & Cooling) which will face a variety of different heat and cooling demand from different kind (new and old) of buildings and thermal users. Simultaneously, the economic feasibility and energetic efficiency of geothermal district heating systems could be increased by the adoption of low supply temperatures. An optimal interaction of heating and cooling in the context of the demand characteristics will increase the economic conditions of district H&C system considerably. Furthermore, the use of a district heating system as a buffer system could increase the flexibility of the power unit in periods with low residual load. Investigation will mainly focus on operating strategies for the optimization of new and existing DHC networks.

Targets:

- Performance evaluation and monitoring of different types of borehole heat exchangers supplying a GSHP system used for heating and cooling;
- Development of simulation codes for design and optimization of heating and cooling supply networks;
- Understanding of the parameters influencing the performance of Geothermal District Heating & Cooling Networks and evaluation of the applicability range.

Milestones of SP5

Nr	Title	Measurable Objectives	by
M5.1	Geothermal power research test site	High temperature binary power plant demonstrated	2017[27]
M5.2	Underground storage of heat & chill	Case studies: Paris Basin and German parliament, TU Berlin	2018[28][29]
M5.3	Heat transfer efficiency	Identification of advanced technologies, materials, and solutions for the improvement of heat transfer efficiency in power plant cooling	2019
M5.4	Efficient CHP-concepts	Provision of a planning instrument concerning geothermal CHP systems for low-enthalpy resources	2019[30]

3.6 SP6 – Operation of Geothermal Systems

Background/ Objectives

Major problems hampering the economically viable and sustainable operation of EGS systems are

- realisation (see SP4) and permanent maintenance of economically viable flow rates without inducing sensible seismicity,
- well stability and safety,
- scaling, i.e. precipitation of minerals in the reservoir, below and aboveground installations,
- accelerated corrosion of materials due to aggressive fluids in consideration of minimal environmental impacts and ecological sustainability.

To overcome these bottlenecks, profound system knowledge based on complex coupled numerical models and experiments from the laboratory to the field scale and a close cooperation with industry are necessary.

[27] HTTP://WWW.GFZ-POTSDAM.DE/SEKTION/GEOTHERMISCHE-ENERGIESYSTEME/PROJEKTE/GENIE/
[28] HTTP://EDOK01.TIB.UNI-HANNOVER.DE/EDOKS/E01FB13/737502312.PDF
[29] HTTP://WWW.GFZ-POTSDAM.DE/SEKTION/GEOTHERMISCHE-ENERGIESYSTEME/PROJEKTE/ATES-BERLIN/
[30] WWW.MSE.TUM.DE/GAB/

3.6.1 Work Package 1: Sustainability, chemical and biological processes of geothermal resources and lifetime of boreholes and system components

The sustainable use of geothermal energy requires a thorough understanding of the processes occurring during the operation of the system. Reliable reservoir models, intelligent design of surface installations, careful selection of system components, operation methods and maintenance schemes are the most important factors for success.

Task 1.1 Improvement of sustainability of geothermal resources

Sophisticated THM models will be developed based on the experience gained at existing and successfully stimulated reservoirs such as Soultz and Groß Schönebeck to predict the performance of geothermal reservoir under different operation conditions.

These models will be complemented by laboratory measurements on rock cores and analogue materials. In addition, surface and down-hole monitoring methods will be applied to observe and detect changes occurring during the exploitation stage. Such monitoring will be performed at Groß Schönebeck, Soultz and at some high temperature wells in Iceland.

Targets:

- State-of-the-art numerical implementation and simulations of multiphysics geothermal applications across scales using a high-performance computing infrastructure;
- Validation and calibration of numerical results by means of natural data sets → improvement of the reliability of numerical tools;
- Improvement of the physical understanding of coupled THMC processes operating in hot and fractured geothermal reservoirs at various scales and time frames;
- Assessment of the response and performance of geothermal reservoirs → transfer to related research areas.

Task 1.2 Chemical and biological processes in reservoirs and surface installations

Scaling and precipitation of salts will be monitored in wells as well as by numerical and laboratory testing. Long-term fluid-rock interaction experiments at simulated in-situ condition in the laboratory will provide insight into the processes and rates of change in the permeability development of reservoir rocks. For biological communities in closed native systems an ecological balance has often been developed and established over a geological time scale. Any change in temperature, chemical composition of fluids, pH or pressure, nutrient availability etc. may have significant impact on microbial growth and activity. Stimulation of microbial growth in porous systems may affect injectivity and water flow. Bio plugging in porous systems will be studied in laboratory models, with the aim of developing mathematical models describing establishment of biofilm at pore scale and Darcy scale – with an overall aim of future field scale models describing biofilm build-up and regulation in reservoirs.

Targets:

- Analysis of scalings and fluids from operating sides → Geochemical and mineralogical analytics → Investigation of scaling formation mechanism and improvement of process understanding;
- Quantification of scaling forming processes → Numerical approaches (THC modelling) → Scaling potential assessment in early stages of project development for failure risk mitigation;

- Development of inhibition methods → Laboratory experiments under in-situ conditions and numerical studies → Lifetime prolongation of production facilities and plant components;
- Investigation of production related reservoir processes (development of injectivity, thermal reservoir behaviour and reservoir clogging → Fully coupled reactive transport modelling (THC) from mirco to macro scale → Development of sustainable exploitation strategies.

Task 1.3 Prolonged lifetime of boreholes and system components

Corrosion and scaling are major problems when geothermal water flows through pipes, pumps and heat exchangers. To reduce these effects, detailed knowledge of local concentrations of salt, scale and minerals at each point in the cycle will be improved as well as the knowledge of chemical processes for material selection and for the prevention of corrosion. Materials and tools will be developed to withstand corrosive conditions in geothermal wells and tested at the Groß Schönebeck site within the joint programme.

Targets:

- Creation of a data base to determine *in situ* properties of thermal water for specific adaptions of power plant components and process modifications;
- Investigations of the electrochemical processes and the weight loss of the starting material → Development of simulation methods to investigate the electrochemical phase transformations during corrosion;
- Simulation of corrosion-induced microstructural changes of materials for various saline solutions and fluid properties.

Milestones of SP6

Nr	Title	Measurable Objectives	by
M6.1	Numerical simulation instruments	Coupled thermo- hydraulic- mechanical- chemical modelling techniques; Validation with production data of a geothermal plant, scaling deposits, incl. turbulent fluid flow	2018[31]
M6.2	High-temperature geothermal well completion	Geothermal well completion solution for longer-term lifetime of high-temperature geothermal wells through strongly improved well design, casing connectors, cement and materials used and monitoring.	2018[32] 2018[33]

[31] Projects to be identified
[32] http://www.geowell-h2020.eu/
[33] http://matching-project.eu/

M6.3	Co-production of energy and metals	Technology for exploitation from metal-bearing deep geological formation	2018[34]

3.7 SP7 - Sustainability, Environment and Regulatory Framework

Background

Geothermal power generation faces different kinds of barriers, obstacles and risks associated to different phases of a single project. Therefore, the ability to identify, assess and mitigate these barriers and risks is crucial. For the investors, the most relevant risks are related mainly to the uncertainties in assessing the resource during the exploration phase and to predict the production performance during the project life. However, the environmental sustainability and social acceptance represent potential hurdles as well. In particular, social acceptance will be analyzed by taking account all contextual (negative and positive) factors.

The assessment of the hazard has been the focus of past research and should be the starting point here. Risk as the production of hazard, its exposure and vulnerability, is generally the more meaningful parameter to consider. In addition to the safety of an operation and risk of accidents, the financial risk to the operators and investors is critically important. Besides assessing risks, establishing appropriate risk governance for deep geothermal projects is a key requirement for advancing the technology, and for promoting market uptake. Regulatory compliance and public acceptance demand transparent, state of the art risk governance, including the assessment of technological risk (e.g., blow-out, induced seismicity, ground deformation), environmental impact assessment (e.g., ground water pollution, noise etc.) and social value chain management.

Since geothermal energy has attracted only minor investments in the fast growing market of renewable energy during recent years, great efforts must be made to bring geothermal technologies to full commercial scale and to allow for widespread harnessing of geothermal energy. A critical aspect is related to the interplay between social acceptance, financial and economic dimensions in geothermal installations. In fact, geothermal installations (for electricity generation or large thermal energy uses) are characterized by high CAPEX in exploration and drilling and the plant construction phases, but low OPEX and high capacity factors, which highly exposes investments to a delayed rise of criticism. Moreover, social and environmental dimensions should be promptly assessed and managed in order to remove information asymmetries between investors and stakeholders, which might affect the implementation of geothermal projects. Some detractors could even take advantage of asymmetries and lack of information for creating the perception of danger – motivated only by the presence of the geothermal project itself – and for impeding the development of geothermal projects. Then, investors should be fully aware of the potential opportunities and challenges inherent in participating in geothermal projects. To this end, the development and implementation of socio-economic and environmental evaluation methodologies and related management practices is a priority to share information, engage stakeholders and reduce tensions.

[34] HTTP://WWW.CHPM2030.EU

This subprogramme is related to past and current European projects such as GEOELEC, GEMex, but also to national initiatives[35][36], which will offer real test cases (i.e. the opportunity to test solutions in different physical, environmental, technological and socio-economic, conditions).

Objectives

The subprogram focuses on three main objectives:

1) Improving project sustainability by risk management and the socio-economic acceptability.
2) Developing socio-economic and environmental assessment of geothermal installations' performances.
3) Development of practices and guidelines to manage such risks and social acceptance issues.

Meeting these challenges will foster the development of geothermal projects by improving social engagement, communication methodologies, and strategies. Breakthroughs are to be expected in the improvement of risk assessment and social acceptance associated with geothermal installations by providing evidences from crucial case studies. Long-term methodologies and concepts shall be refined and exported to other regions in Europe, and abroad.

3.7.1 Work Package 1: Risk assessment, mitigation, and regulation

Risks can be considered the more meaningful parameter to be taken into account when developing geothermal projects. Risks comprehend financial, operational, technical risks, and they should be managed according to appropriate risk governance strategies. In addition, such strategies need to be compliant with the regulatory framework, aimed at licensing geothermal site development and preventing possible impediments to their development, and to strengthen by social acceptance that supports removing information asymmetries between investors and stakeholders.

Task 1.1 Risk assessment and mitigation

This task aims at improving the ability to assess and mitigate risks associated to geothermal installations. Risk assessment and mitigation concepts need to be enveloped such that they allow minimizing any potential negative impact of the technology to levels as low as reasonably possible (Assigned Risk Adjustment Programme). These strategies need to be adopted not only for various geological contexts, but also for different regulatory and socio-economic and cultural contexts.

Targets:

- Conceptual models to assess risks associated to geothermal installations
- Risk assessment in different kinds of geothermal installations
- Definition of a systemic approach to manage the assessed risks

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[35] HTTP://WWW.VIGOR-GEOTERMIA.IT AND HTTP://ATLANTE.IGG.CNR.IT

[36] AN ITALIAN INITIATIVE WAS PROMOTED BY MINISTERO DELLO SVILUPPO ECONOMICO, REGIONE TOSCANA, PROVINCIA DI PISA, UNIVERSITÀ DI PISA, SCUOLA SUPERIORE DI STUDI UNIVERSITARI E DI PERFEZIONAMENTO SANT'ANNA, CONSORZIO PER lO SVILUPPO DELLE AREE GEOTERMICHE - CO.SVI.G., ENERGEA S,C.R.L, AGENZIA ENERGETICA DELLA PROVINCIA DI PISA, ACQUE S.P.A. THAT HAVE SIGNED A WORKING PROTOCOL ON JULY 2014 TO FOSTER THE USE OF GEOTHERMAL ENERGY FOR SPACE HEATING IN PISA, TOSCANA.

Task 1.2 Regulatory framework

This task aims to develop a systematic decision tool that will be used to examine and measure the likely benefits, costs and effects of new or existing regulation, with special attention to the impact on the interlocked relations between sustainability and innovation trajectories. The enforcement and compliance strategies will be defined for each developed scenarios, including an evaluation of their effectiveness and efficiency. Within this framework, an evidence-based comparison between innovation eco-systems will be developed to improve the opportunity for all stakeholders to participate in the regulatory process and to support their investment decisions for geothermal installations.

Targets:

- Impact assessment on geothermal policies
- Guidelines for regulatory bodies for the licensing of geothermal site development
- Stakeholder engagement in regulatory process

Task 1.3 Social acceptance

This task aims to develop an integrated model towards coping with social acceptance in the development of geothermal projects. This model using technical, economic, environmental and social information about geothermal projects and related context conflict lines (e.g. citizen protests or opposing public interests) will foster the development of the strategy for communication and the consultation process for public engagement in order to remove information asymmetries between investors and stakeholders (e.g. citizens, companies in the county, local authorities, etc.) regarding expected benefits.

In turn, investors and stakeholders should become more aware of the potential opportunities and challenges inherent in actively participating in geothermal projects. This sharing of information can create a favourable environment for social acceptance, which might result in innovative business models, reducing the possibility of opportunistic behaviour and tensions.

Targets:

- Stakeholder identification and identification of possible contextual factors, classification and mapping;
- Definition of the business case for social acceptance;
- Integrated model for managing social acceptance and promoting public engagement.

3.7.2 Work Package 2: Socio-economic and environmental evaluation of geothermal projects

The development of geothermal projects need effective evaluation methodologies, such as Life Cycle Analysis (LCA) and Life Cycle Costs (LCC), economic evaluation and multi-criteria evaluation adequately support the decision-making process. In particular, these methodologies provide the assessment of social, economic and environmental impacts associated to geothermal projects (LCA, LCC and economic evaluation) and represent coalitions of interests among stakeholders (multi-criteria evaluation).

Task 2.1 Total Life Cycle Analysis – LCA

This task aims to provide a conceptual framework to use social, economic and environmental impacts associated to geothermal installations through total LCA for the improvement of decision-making process of investors and other stakeholders involved in geothermal development. Total LCA includes traditional LCA, which is an established decision support tool with risk analysis and life cycle costs (LCC). The integration of all these tools overcomes the limitations of tradition LCA by including social and economic factors necessary for the sustainable use of a geothermal resource. This approach will be refined for existing systems in operation and be applied for the planning of new operations.

Targets:

- Conceptual model for the integration of total LCA in the investors' decision-making process.
- Integration of total LCA in communication with stakeholders.

Task 2.2 Economic evaluation methodologies

This task aims at facilitate the interpretation and adoption of the economic evaluation of geothermal projects that allows a suitable comparison with other renewable energy initiatives in a life cycle costing perspective to improve relationship and communication with local communities and public authorities. The results of the economic assessment will be analysed in order to provide reliable economic values and/or indices that will take part of local dialogue among stakeholders.

Targets:

- Development of economic communication strategy.

Task 2.3 Multi-criteria evaluation

This task aims to integrate the evaluation of potential geothermal project that takes into account sources of investment, ownership structures, the process of stakeholder engagement, overall business model adopted for delivering the service, public opposition and environmental concerns, as well as the process to support and involve public authorities and private investors in the replication of successful geothermal initiatives (i.e. see previous sub tasks). Since all these dimensions are incommensurable, multi-criteria evaluation tools will be developed and tested to improve the capabilities to represent the coalitions of interests from different stakeholders that might derive from a geothermal project.

Targets:

- Set up and testing of a multi-criteria evaluation approach for geothermal projects
- Guidelines for interpreting coalitions of interest and, consequently, taking action

Milestones of SP7

Nr	Title	Measurable Objectives	by
M7.1	Stimulation risks	Identification and quantification of risk mitigation measures with respect to stimulation treatments based on relevant technical and nontechnical key factors	2018[37]
M7.2	Regulatory framework	Guidelines for regulatory bodies for the licensing of geothermal site development and for mitigating environmental impact in particular the seismic hazard.	2019[38]
M7.3	Social acceptance	Integrated model for managing social acceptance and promoting public engagement	2019[39]
M7.4	Economic and environmental life cycle assessment	LCA-Parameter of plants in different alternative areas and with different technological components	2018[40]

4 Management of the Joint Programme

The JP on geothermal energy will interact with the following existing and emerging initiatives:

- It has been conceived in close collaboration with the Services of the European Commission and geothermal organizations such as ETIP[41] and/or EGEC[42] and it is open to other research organizations, which can provide a significant contribution and agree to share instrumentation and resources. The JPGE Coordinator has a permanent seat in the steering committee of ETIP accompanied by elected further representatives of JPGE.
- It aims at liaising with European industries for fostering their strong involvement in the huge emerging market of world-wide geothermal project development, well beyond the indigenous European potential.
- It regularly informs European and National Authorities represented by ERANET[43] or by participants defined by those authorities about the overall progress in achieving the main objectives.

[37] HTTP://WWW.DESTRESS-H2020.EU
[38] HTTP://WWW.DESTRESS-H2020.EU
[39] PROJECTS TO BE IDENTIFIED
[40] PROJECTS TO BE IDENTIFIED
[41] HTTP://WWW.GEOELEC.EU/ETIP-DG/
[42] HTTP://WWW.EGEC.ORG/
[43] HTTP://WWW.GEOTHERMALERANET.IS/

Considering the benefit provided by the JPGE to industries and utilities, it is expected that financial support can accrue from these sectors.

- Several participants of the EERA JP on geothermal energy are active in a technology platform accredited by the EC on renewable heating and cooling.

The management structure of the JP was set up in accordance with the guidelines in "EERA Joint Programme Governance". Members of this JP will include Participants as well as Associates. The JP is coordinated by the Joint Programme Coordinator (JPC), and consists of several subprogrammes, which have separate research objectives and milestones for the planning period and comprise a number of joint projects or activities. Each subprogramme is coordinated by a subprogramme Coordinator (SPC).

4.1 EERA JPGE Participants

4.1.1 Participants and Human Resources

Nr	Country	Participant / Institution	Short Name
1	Belgium	Flemish Research Institute for Technological Research	VITO
2	France	Bureau des Recherches géologiques et minières	BRGM
3	France	University of Strasbourg, École et observatoire des sciences de la terre	EOST
4	Germany	RWTH Aachen University, E.ON Energy Research Center	RWTH/E.ON ERC
5	Germany	Helmholtz Centre Potsdam GFZ German Research Centre for Geoscience	GFZ
6	Germany	International Geothermal Center Bochum	GZB
7	Germany	(LTTT & ZET) University Bayreuth	LTTT/ZET
8	Germany	Karlsruhe Institute of Technology	KIT
9	Germany	Leibniz Institute for Applied Geophysics	LIAG
10	Germany	Technische Universität Darmstadt - Institute of Applied Geosciences	TUDa
11	Germany	Helmholtz Centre for Environmental Research	UFZ
12	Greece	Centre for Renewable Energy Sources and Saving	CRES
13	Iceland	Iceland GeoSurvey	ISOR
14	Italy	Consiglio Nazionale delle Ricerche – Istituto di Geoscienze e Georisorse	CNR-IGG
15	Italy	Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile	ENEA
16	Italy	ENERGEA	ENERGEA
17	Italy	Istituto Nazionale di Geofisica e Vulcanologia	INGV
18	Italy	Politecnico di Milano, Dipartimento di Energia	POLIMI
19	Italy	Politecnico di Torino	POLITO
20	Italy	Università di Bari, Dipartimento di Scienze della Terra e Geoambientali,	UNIBA
21	Italy	Università di Torino	UNITO
22	Italy	Università di Trieste and Istituto Nazionale di Oceanografia e Geofisica Sperimentale	UNITS-OGS

23	Netherlands	Netherlands Organization for Applied Scientific Research	TNO
24	Netherlands	Utrecht University, Department of Earth Sciences	UU
25	Netherlands	Technical University of Delft	TUDe
26	Norway	CMR	BERGEN
27	Norway	CIPR	BERGEN
28	Norway	Uni Research, Bergen	BERGEN
29	Norway	Institute for Energy Technology	IFE
30	Norway	International Research Institute of Stavanger	IRIS
31	Norway	SINTEF	SINTEF
32	Portugal	Laboratório Nacional de Energia e Geologia	LNEG
33	Switzerland	Swiss Federal Institute of Technology - Zürich	ETHZ
34	Turkey	TÜBITAK	TÜBITAK
35	UK	British Geological Survey - Renewables & Energy Security Team	BGS

4.1.2 Infrastructures and facilities

Short Name	Infrastructure: technical characteristics	Type of access
BGS	Public research organization. National databases for onshore and offshore UK: geothermal, geological, geophysical (e.g. gravimetry, magnetotelluric, heat flow), geochemical (surface waters, ground waters, stream sediments, gases). National repository of core material. Laboratory facilities: elevated pressure/temperature geochemistry to supercritical conditions, fluid flow, mechanical properties of rocks, fluid chemistry, mineralogy, isotopes, microbiology. Range of field equipment including: gas monitoring, surface geophysics, down hole geophysics. Modelling: fluid chemical, fluid flow, 3D geological visualisation.	for joint efforts
BRGM	Database on French territory.	public access
CNR	Geothermal Information Platform of Italy. Geophysical (gravimetry, magnetotelluric, heat flow and thermal conduction), geochemical (fluid, gas and isotope geochemistry), experimental mineralogy, petrology, fluid inclusion, tectonic modelling equipments and laboratories. Remote sensing tools. Software packages: TOUGH2 and THOUGH-REACT, Petrel, WinGLink, COMSOL MultiPhysics. Public library. Rock samples.	for joint efforts
CNRS	Public research organization, geological, geophysical, geochemical instruments and laboratories.	for joint efforts
CRES	Natural laboratory for testing EGS exploration and exploitation technology: CRES RES park in Lavrio, Attica; Software packages: EASY genetic evolution optimisation code, TOUGH2 with the PETRASIM; will use the software package "SimaPro 7".	for joint efforts
ENEA	Public research organization. Environmental Geochemistry, Seismology and earthquake engineering: seismic microzoning, vulnerability analysis. Support to public administration in the normative field.	for joint efforts
ETHZ	High pressure laboratory, pilot and laboratory facility for spallation drilling with supercritical water (with optical access), laboratory for chemical analysis and particle analysis, CFD- software, public library; Shallow borehole logging equipment.	for joint efforts

GFZ	Geothermal Research Platform Groß Schönebeck (doublet 4200 m; thermal water loop installation for well-logging, monitoring, geophysical testing, and material testing); ATES Research Platform TU Berlin; Geophysical Instrument Pool Potsdam (GIPP); Borehole measurement facilities; High pressure laboratories available with simulation of in-situ conditions for rock testing and experiments	for joint experiments
GZB	Multi-scale core facility: in-situ Laboratory (research, observation and production wells; > 500 m, >35 in total); Mobile dual drive drilling rig (60t; hp-pumps, mud cleaning and auxiliary equipment); i.BOGS: in-situ Borehole and Georeservoir Simulator for testing of drilling technologies under in-situ reservoir conditions and large scale fluid/rock experiments (L=300cm/D=50cm; 180°C/1200bar); Seismic monitoring equipment; Borehole logging (e.g. natural gamma, acoustic televiewer, full waveform sonic, flowmeter, temperature / conductivity, caliper, NIMO-T, deviation, EGRT); 3D-surface roughness analysis and microscopy; Hard-rock laboratory: rock physical characterization (Vp/Vs, porosity, density, thermal conductivity), thermo-triaxial testing system for mechanical tests under reservoir conditions up to 5 km depth, high-pressure high temperature equipment for µCT-scanning (225 kV) and in-situ flow-through experiments; geochemical analysis (e.g. ICP-OES, MIP-GC, spectrophotometre); Heat-Pump Laboratory with Geo.Star (BHA 20x200m; incl. glasfibre-monitoring); Numerical Simulation Laboratory.	for joint efforts
IRIS	Full-scale (offshore type) drilling rig with access to seven wells. Testing and qualification of equipment, training of personnel etc.; Tension and compression testing of tubulars; Flow loop for drilling fluid testing, testing of down hole equipment, erosion testing, etc.; High pressure/high temperature test site capable of testing at full-scale dimensions and extreme energy levels whilst fulfilling extensive safety requirements; Plug & abandonment test site under establishment. Barrier verification, pressure/leakage testing, cementing testing, sealant materials; Virtual Arena – drilling simulator for research, technology development, testing and training/education. Remote (web based) access; Petroleum laboratories for special core analysis, petrophysical measurements and improved oil recovery.	for joint efforts
ISOR	Various geophysical instruments for prospecting; many test sites of different physical state with deep boreholes where results of geophysical exploration can be compared with borehole data; Admittance to numerous boreholes and power plants as tests sites covering reservoir temperatures up to 340°C and borehole depths up to 3 km IDDP well in Krafla; Admittance to numerous reservoir monitoring systems; Admittance to fields and plants with variable chemical composition of geothermal fluid; 5 logging trucks and various logging equipment; owns specialized chemical laboratory for analysis of geothermal substances.	common projects within international cooperation
KIT	Thermal and fluid-dynamic laboratory; corrosion loops instruments and laboratories, public library.	public access to partners, but at no costs for KIT
LIAG	Logging Truck (10t) for geothermal logging with 6000 m / 3000 m cable winch, 4 conductor cable, temperature resistant up to 240 °C, several sensors, laboratory facilities. Database on German territory.	for joint efforts
LTTT/ ZET	Small-scale ORC test rig (1 kWel) for simultaneous measuring of heat transfer coefficients and power output; Software packages for transient and steady-state simulation of geothermal power plant systems	for joint efforts

OGS	Public research organization. Geophysical, Geothermal, CCS research activity, seismology, geological interpretation, marine geology. Borehole geophysics facility (wells), surface and borehole seismic instrumentation (shallow and up to 2000 m depth) and monitoring. Seismic sources (vibro, air gun). Seismological monitoring network. Gravimetry and remote sensing. Surface seismic and borehole data acquisition and processing (imaging and inversion). Rock physics research and seismic wave propagation numerical modelling in hot rocks (including melting and supercritical).	for joint efforts
RWTH/E.ON ERC	Slimhole logging equipment up to 1.5 km (P/T/Sal, Caliper, Gamma and spectral Gamma; Induction, Neutron-Porosity, Sonic); instrumented borehole heat exchanger array (41 boreholes, 100 m each); parallelized, high-performance simulation code with (supercomputer access) for single/multi-phase flow, species and heat transport, and geochemical reactions between fluid and rock; petrophysical lab for measuring thermal and hydraulic rock properties (thermal conductivity, spec. heat capacity, porosity, permeability); collaboration with RWTH Geotechnical institute with triaxial cell for acoustically monitored hydraulic fracturing experiments on samples of dimension 30×30×45 cm^3.	available for joint projects or consulting work
SSSUP (ENERGEA)	Geothermal Database of Tuscan territory (Italy).Software and database for LCA, LCC and SMCE (Bousted and Ecoinvent for LCA, Gabi4 for LCC, Musiasem for SMCE).Technical and logistic support to primary data investigation (including in-field case study analysis).	for joint efforts
TNO	Database on Netherlands territory; Data assimilation techniques for reservoir modelling; analytical fast models for fracture formation and subsidence; Techno-economic performance tools (EGS-DSS).	for joint efforts
TUDa	International PetroPhysicalProperty Database; Hydrothermikum: lab for measuring petrophysical, thermal, hydraulic and mechanic rock properties (thermal conductivity, thermal diffusivity, spec. heat capacity, rad. heat production, porosity, permeability, uniaxial and triaxial strength) and hydrochemical fluid properties (AAS, ICPMS). High pressure, high temperature labs available with simulation of in-situ conditions for rock testing and experiments; Parallelized, high performance simulation code for BTES systems and multiple commercial codes for heat and mass transport simulations (with supercomputer access).	for joint efforts
Uni CIPR	Lidar, photogrammetry and hyperspectral outcrop analysis hardware and software. Thermal conductivity*, VpVs, spectral gamma, tiny perm, microscopy including fluid inclusion*. Flow Laboratories for (petroleum) special core analysis, high P&T core, Petrophysical measurements, core & slab X-ray under flow, rock-fluid interaction, flow-front progression. Biological processes in reservoirs. Basin & reservoir modelling and fluid flow simulation software. Seismic recorders, land cables* & geophones* (* through UiB).	for joint efforts
UNITO	Fully monitored Living lab on underground heat storage (www.gtes.unito.it); Analogic thermal box aimed at simulation of soil behaviour at heat perturbations; near surface geophysical monitoring and investigations; petro-physical characterization; modelling porous and fracturing rock mass (Feeflow, Comsol, Tridec, …) at different P-T conditions, living lab on public acceptance aimed at environmental impact minimizing and human comfort maximization.	for joint projects or consulting work
UU	Integrated analogue – numerical modelling facilities for crustal and lithosphere deformation, stress analysis and thermal evolution; Analytical facilities for high-resolution dating in low-temperature geochronology	for joint efforts
VITO	Balmatt geothermal site open for testing innovative exploration, monitoring techniques.	for joint research

4.2 JPGE Committees and Boards

The JPGE is structured into several bodies, whose tasks and purpose are detailed below.

- Steering committee (JP-SC), comprising a representative of all JP participants
- Joint Programme Management Board (JP-MB) including the Joint Programme Coordinator (JPC) and the Programme Secretary (JPS). Two participants of each subprogramme, including the SPCs represent the subprogrammes.

Participation in and contribution to the JPGE is open to new members. Participants have to join the EERA either as full participants (*Participants*) or as *Associates*. Details of the membership status are explained and fixed by the EERA aisbl for all EERA joint programmes (for more see: www.eera-set.eu for more information).

The admission of a new *Participant* or *Associate* to the JPGE follows the following procedure:

- After an informal application with the JPC, the applicant has to fill out a questionnaire, prepared to collect information on the applicants' areas of expertise, current activities and their potential contributions to the JPGE. The applicant should deliver back the filled out questionnaire to JPC within three weeks.
- Recommendations about the approval are made by the JP-MB; final decisions about approval can be made via e-mail voting by the JP-SC.
- After the JP-MB and the JP-SC approve of the information, applicants will be invited to present their institutions at a JPGE meeting. After their presentation, the JP-SC will vote on the accession of the applicants to the JPGE.

Voting and managerial rights are limited to Participants. Both, participants and associates in the JPGE have a collective responsibility for the accomplishment of the programme objectives, must sign the Joint Programme Letter of Intent and pay a contribution to the costs of joint programme coordination. The fees are € 1200 per year for participants and € 600 per year for associates.

4.3 EERA Officers of JPGE

Joint Programme Coordinator (JPC)

The Joint Programme Steering Committee (JP-SC) selects the Joint Programme Coordinator, who must be approved by the EERA Executive Committee.

The JPC coordinates the JP, hairs the JPMB, hairs the JP-SC and reports to EERA ExCo.

Task and Responsibilities:

- Coordination of the scientific activities in the joint programme and communication with the EERA secretariat.
- Monitoring of progress in reaching targets and milestones in each subprogramme.
- Reporting on scientific progress and unexpected developments to the EERA secretariat and the EERA ExCo.
- Coordination of the overall planning process and progress reporting.

- Interaction with relevant industry and scientific initiatives (the ETIP deep geothermal energy, KICs, etc.)
- Representation of the EERA JPGE in the steering committee of the European Technology and Innovation Platform on Deep Geothermal Energy (ETIP deep geothermal)

The JPC is assisted by a joint programme secretary (JPS) from a joint programme participant. A Joint Programme Office (JPO) at the JPCs institution supports the JPC and the joint programme management board (JP-MB).

Subprogramme Coordinator (SPC)

The JP-SC selects Subprogramme Coordinators (SPC), who are responsible for the coordination of a subprogramme and reporting to the JPC.Task and Responsibilities:

- Coordination of the scientific activities in the subprogramme to be carried out by the participants according to the agreed commitment. The SPC communicates with the contact persons to be assigned by each participant;
- Monitoring progress in reaching the sub-programme´ targets and milestones;
- Reporting progress to responsible programme co-ordinator of the joint programme;
- Propose and coordinate scientific plans for the subprogramme for the planning period;
- Monitor scientific progress and report unexpected developments in terms of depleting financial means or technical or scientific bottlenecks.

4.4 Bodies of EERA JPGE

Steering Committee (JP-SC)

The JP-SC has the responsibility to take all collective decisions necessary for the functioning of the JPGE and accomplishment of its objectives. Any decisions are taken when requested or proposed by a Participant or by the JPC.

Composition: the Steering Committee (JP-SC) comprises a representative of all Participants and Associates.

Appointment: New Participants and Associates are appointed by the JP-MB and have to be approved by the JP-SC.

Decisions in the JP-SC are taken by voting of all participants present at the meeting, as long as a minimum of 60% of all participants are present. Approval or rejection of recommendations by the JPMB can also be done by e-mail voting. If a vote is not cast within two weeks, approval of the recommendation is assumed.

Tasks and responsibilities:

- Approval of the JPGE's
  - Annual work plan, budget and allocation of resources of participants to the joint programme
  - Annual progress report

- Modifications of the work programme

- Platform for annual JPGE conference, networking between Participants and Associates, and discussion of new proposals to be submitted to the Management Board (JP-MB) convenes on a yearly basis unless circumstances require exceptionally a shorter interval.

Joint Programme Management Board (JP-MB)

The Management Board (JP-MB) is responsible for all management aspects of the joint programme. The JP-MB is chaired by the project Coordinator (JPC) flanked by a Programme Secretary (JPS).The JP-MB is assisted by the Joint Programme Office, which is directed by the JPC. In addition, the JP-MB has the responsibility to safeguard the scientific quality, and societal and industrial relevance of the joint programme.

Composition: The JP-MB consists of the JPC, the JPS, appointed representative of the *Subprogramme Coordinators* (SPC) and additional selected participants. To maintain a geographical balance, a maximum of two participants per country can be represented in the JPMB.

Appointment: Members of the JP-MB are appointed for periods of two years by the JP-SC, which should strive for a unanimous decision. At the start of the JPGE the JP-MB was constituted by the founding Participants.

Tasks and responsibilities:

- financial and contracts management,
- pursuing implementation of IPR, enforcing the EERA IP guidelines, following the best practice of EU framework programmes (FP7, H2020),
- scientific coordination and joint programme progress control,
- planning on programme and sub-programme level,
- appointment of new participants subject to confirmation by the JP-SC,
- internal communication (reports, workshops, proposals etc.),
- dissemination and promotion actions of the EERA-JPGE towards 3 targeted audiences: (1) Partners & Associates, (2) Decision Makers & Companies, and (3) Public audience.

Subprogramme management team (SPMT)

The SP management team (SPMT) is responsible for the execution of an individual JPGE subprogramme.

Composition: The SP management team consists of the WP leaders and is headed by the SPC.

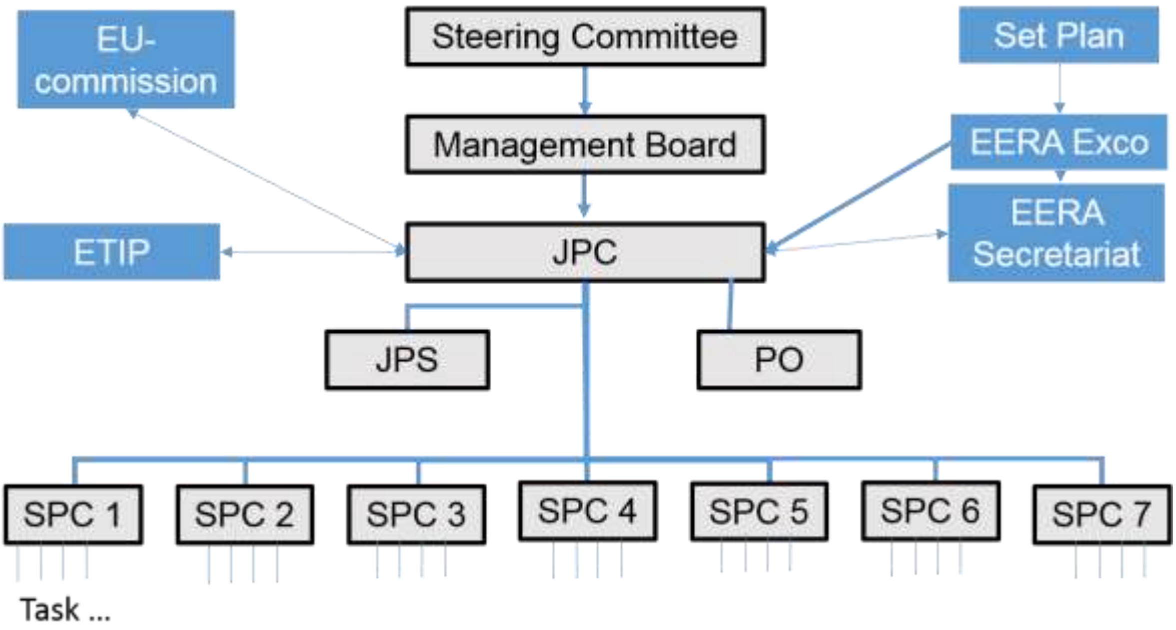
Appointment: The SPMT is decided upon by the JP-MB.

Tasks and responsibilities:

- elaboration of proposals of annual work plans,
- execution of annual work plans,
- reporting to JP-MB,

- adjustment of work plan, based on internal progress and recommendations by JP-MB.
- Convenes: when necessary

ORGANIZATION CHARTS



The scientific discussion and interaction will be facilitated through several thematic workshops, which may be opened for participation of selected institutions or individuals that are not part of the consortium or to generally interested participants. These workshops will be organised on a regular basis.

5 Risks

In general, there are two types of risks, the geothermal joint programme could potentially face. The first type is inherently involved in scientific work and includes failure of experiments, unexpected results and breakdown of equipment etc. The other type of risk is associated with the organisation and structure of the joint programme in general, as the commitment of partners may decrease, leading to a loss of synergies and competitiveness, or the required national support may not be equally available for all partners and legal and financial ways and means to fine and/or correct such shortcomings are limited.

The scientific risks for the subprogrammes are addressed there and include the following:

- SP1: The standards required for a trans-European data exchange system may not be supported by all national authorities who own the data. Data acquisition in the field may not be successful.
- SP2: Lack of public acceptance and hindering of geophysical campaigns.
- SP3: Drilling projects incorporate high financial and technical risk.

- SP4: Demonstration projects may not be successful; public acceptance may erode because of induced seismicity; stimulation treatments may not result in sufficient increase of productivity.
- SP5: The main risk is associated with the reduction of auxiliary power necessary for the development of low-enthalpy reservoirs.
- SP6: There may be problems in finding suitable materials for completion and components in highly corrosive geothermal environments.
- SP7: no major risks envisaged.

The general risk of decreasing partner commitment will be addressed at the management meetings of the JP. Generally, this risk is perceived as fairly low, as all partners have collaborated in various European projects (including GEMex, IMAGE, DESTRESS, DeepEGS, GEISER, ..) partly to define the objectives addressed by this JP. In addition, the interest in the scientific community in the EERA geothermal programme is already large, such that the loss of one partner may be compensated by admitting (a) new partner(s). The main way to deal with this risk, however, is the communication culture established at the programme management level, which involves frequent meetings and the potential to rotate or change responsibilities within the JP.

The risk of failing national support is perceived as relatively small at this stage, as large parts of the programme are based on already funded activities. However, part of the benefits of an EERA JP are seen in supporting partners towards the national agencies, such that the erosion of national support should not become an issue or could be compensated by the interaction within the JP. Joint Calls in the frame of ERA-NET projects (GEOTHERMICA and Geo ERA-NET recently submitted) will also be of support.

6 Intellectual Property Rights of the JP

We follow the default procedures made available by the EERA secretariat.

The EERA policy on intellectual property rights is accepted based on seven principles:

1. Ownership of results and inventions remain with the inventing institutions.
2. Results must be protected where appropriate.
3. Background knowledge should be available to EERA projects.
4. Access to project generated knowledge should be available to other EERA projects.
5. Licensing should generally be non-exclusive.
6. Joint commercialisation should be pursued where possible.
7. EERA aims for commercialization in a global energy technology arena.

Imprint

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