Strategic Research and Innovation Agenda

ETIP-DG
European Technology & Innovation Platform on **Deep Geothermal**

www.etip-dg.eu

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EXECUTIVE SUMMARY

The present and the coming decades are some of the most critical in human history. Humanity and its industrial and social development continue to place the planet under increasing pressure, ultimately calling for a new understanding of sustainability and innovative approaches to achieving it. The decarbonisation of the energy sector, a step towards achieving the Paris objectives pursued by the EU, its member states and associated countries, will drive a switch in electricity and heat generation technologies from fossil fuels to renewables such as geothermal. Geothermal energy deals with complex systems that occupy the interface between our planet and society, underpinning an energy sector which is crucial to our prosperity and future well-being. Over the last 10 years, the European geothermal industry has matured and consolidated its position as a technological leader. Although the market has enlarged, there is still considerable resource potential in Europe which remains hidden and untapped.

The overall development of geothermal sector and its comprehensive contribution to a decarbonised and efficient European energy market require further research and innovation (R&I) actions. These actions are **presented and detailed in this Strategic Research and Innovation Agenda (SRIA)**. Successful accomplishment of the SRIA requires an increased and more coordinated allocation of private and public (EU, national and regional) funds.

Closely connected to the ETIP on Deep geothermal (ETIP-DG) Vision document, the SRIA addresses all of the issues judged by ETIP-DG members to be crucial to developing the use of deep geothermal energy resources, both as heat and electricity. The ETIP-DG forecasts highly ambitious development in the utilisation of geothermal energy in Europe, both for electricity and heat. However, in order to make our Vision a solid reality in the near future, we have to go beyond the business-as-usual approach and promote breakthroughs in all areas of technological and cross-cutting innovation while pursuing the long-term goals of the EU.

Following the SET Plan Declaration of Intent on Strategic Targets, defined in the context of an Initiative for Global Leadership in Deep Geothermal Energy in 2016 and its Implementation Plan adopted in 2018, geothermal potential will be unlocked through research and innovation focused on the improvement of technology and its incorporation into the energy system. These R&I actions must focus on achieving goals in terms of performance and cost-reduction.

Research and innovation will play a fundamental role in achieving these objectives. The present SRIA helps us to shape a strategic R&I plan and to define R&I priorities. The Vision for Europe's R&I on Deep Geothermal published in March 2018 is now reflected in this Strategic Research and Innovation Agenda. This SRIA document recommends that action focuses on addressing the following **key challenges**.

Technological challenges:

1. Prediction and assessment of geothermal resources
A better understanding of complex and deep geological processes will enhance the predictability of underground conditions; deep exploration technologies will have high-resolution imaging capacity and data modelling will be fully integrated; geothermal

resources beyond those already in development will be characterised in greater detail in order to optimise their use and increase energy production. The overall objective of R&I in exploration is to reduce the costs of exploration technologies and increase the probability of successfully characterising geothermal resources prior to drilling and during geothermal development.

2. Resource access and development

The extraction of heat from underground will be maximised thanks to improved well designs, new drilling technologies, new sensors and monitoring techniques, and safe and sustainable flow enhancement. In addition, reduced drilling costs will be possible as a result of new or high-performance drilling techniques. Another basic challenge is drilling deeper and/or reaching very high-temperature resources. There will be safe, rapid and automated technologies providing access below the ground.

The lifetime of boreholes and system components will be prolonged by using materials and pumps that are tailored for deep geothermal wells, as well as real-time monitoring and an in-depth understanding of reservoir and thermal loop processes. Geothermal energy storage will be efficient, fully integrated into energy systems, and responsive to demand.

R&I goals such as these, which will also be tied to environmental requirements, can serve as a reference for the majority of European geothermal reservoirs, which often occur in densely populated areas and are characterised by low-to-medium temperature conditions.

3. Heat and electricity generation and system integration

When it comes to energy conversion processes, geothermal plant surface systems and the integration of geothermal heating, cooling and electricity supply into the energy system, the challenge is maximising generation at the lowest lifetime cost. The net efficiency, performance and cost-effectiveness of production systems are to be optimised, extending the temperature range of different geothermal energy applications. The conversion of heat to electricity and cooling will only be constrained by physical laws and production will be sustainable and fully responsive to demand. Hybrid, multi-source and multipurpose high-efficiency systems embedding geothermal technology will become the European standard.

Cross-cutting challenges:

4. The shift from R&I to deployment (environmental, regulatory, market, policy, social, human deployment)

The aim is to develop regulatory, financial, political and social solutions that can be implemented in order to overcome barriers obstructing the deployment of innovation in the sector, the broad deployment of geothermal energy solutions, and increased uptake all over Europe. This must be done in parallel to the technological research described above if geothermal energy is to become one of the main contributors to European climate and energy targets. This includes supporting the establishment of a legislative framework that will sustain geothermal deployment, penetration and profitability while guaranteeing that resources are properly managed. This framework should also provide low environmental impact technologies, define economic evaluation criteria (including technical and economic risk assessment), and foster partnerships between companies and consumers by strengthening mutual trust as a result of ethics and security.

5. Knowledge sharing (data harmonisation and coordinated organisation of data and information, shared research infrastructures)

Establishing an open-access policy to geothermal information (including standard exchange formats) will ensure open and easy access to data and information. This should be achieved through the progressive harmonisation of national data in order to facilitate data discovery and data mining. It is also vital that demonstrations of capacity building, industrial technology transfer, and scientific and academic partnerships based around joint expertise take place throughout Europe, with the shared goal of developing high quality, competitive and sustainable geothermal energy projects.

Information, communication and analytical capabilities will receive large-scale support. The amount and types of underground data available will be expanded, globally organised and made easily accessible. Terms of reference for reporting and computing geothermal potential, production and capacity will be harmonised; data sharing will improve scalability and the extrapolation of information, improving the ability to forecast techno-economic parameters and influencing energy planning.

Solving these challenges will grant the geothermal sector enormous capability with regard to the key societal challenges of our energy future, and will significantly improve our ability to maintain the safety, security, wealth, and prosperity of Europe. The overall Mission of the Research, and Innovation Agenda is to elevate the Deep Geothermal sector so that it might contribute to the Clean Cities and Communities of the Future, where a combination of renewable energy sources (including geothermal) provide for local electricity, transport, and heating/cooling supply for both tertiary and industrial buildings, with underground thermal storage facilities and electric vehicles integrated into the system.

EDITORIAL

Geothermal is a key renewable energy source in the European low-carbon energy mix, able to provide a substantial share of electricity, heating and cooling in 2030 and beyond. Geothermal power production has been traditionally used as base load capacity, though it has a significant potential to both meet the needs of a changing flexible power system as well as stabilise energy grids.

Europe has pioneered the exploitation of geothermal resources for over a century, and the EU still maintains a leading role due to the development of new technologies. For example, smart district heating and innovative plant systems such as Enhanced Geothermal Systems (EGS) are a breakthrough technology which has already been demonstrated. These systems allow for the production of geothermal power as well as heating and cooling everywhere. However, there is a significant need to considerably increase the amount of research and innovation being carried out in order to harness the huge amount of deep geothermal resources which remain untapped in Europe and worldwide.

The European Technology and Innovation Platform on Deep Geothermal (ETIP-DG), together with the other members of the SET Plan Implementation Working Group on Deep Geothermal, aims to elevate the position of deep geothermal resources. Following the publication of the ETIP-DG Vision document in March 2018, this Strategic Research and Innovation Agenda (SRIA) has been drafted based on extensive collaboration from the Working Group.

The research and innovation actions described in the SRIA will enable geothermal technologies to play a more important role in the energy sector:

- Unlocking the potential of new geothermal resources as affordable, sustainable and secure sources of energy across large areas of European countries
- Achieving a significant reduction in the costs of the development and O&M for geothermal projects by improving the performance of technologies and developing new energy conversio processes and concepts
- Increasing social acceptance of geothermal energy and improving the quality of life of the local Community
- Maintaining and even strengthening European leadership in the geothermal industry sector and continuing to export know-how and technologies worldwide.

"Research, Innovation and Competitiveness" are key for ensuring energy security, energy efficiency and the decarbonisation of the EU economy. Geothermal energy for heating and cooling and electricity generation is significant resource within the energy system of the future and will contribute to making Europe the global leader in renewable energies."

Fausto Batini
President of the ETIP-DG

INTRODUCTION:
DESIGNING THE FUTURE OF GEOTHERMAL ENERGY

Renewable, secure, clean, versatile, distributed, predictable: the energy future that we imagine for human societies in Europe is firmly grounded upon geothermal energy. Boasting a long tradition of electrical power production, first developed in Italy at the dawn of the 20th century, as well as district heating, used in Iceland for almost a century, geothermal has been a backbone of the renewable energy system in Europe. Nonetheless, alongside its numerous and diversified applications, there are still abundant opportunities for further development in the geothermal sector.

This is the principal focus of the **Vision of the European Technology and Innovation Platform on Deep Geothermal (ETIP-DG)**. Anchored within the current status of geothermal production in Europe and presented as an overview, the Vision lays out the challenges ahead with regard to increasing social welfare by fully and responsibly deploying novel technologies and unlocking geothermal potential.

By 2030, almost 60 per cent of the world's population will live in urban areas and the way in which cities are organised will play an increasingly significant role in terms of the social, environmental and economic sustainability of human societies. The Vision presents an ideal "City of the Future": a combination of renewable energy sources providing local electricity and heating/cooling supply at house level, either with or without storage facilities, along with electrical cars integrated into the system. It envisions large heating and cooling networks fed by geothermal heat, with intelligent energy exchanges between houses and the major supply pole. It will be a city using 100% renewable energy sources for its electricity, heating/cooling and mobility needs, with zero impact on the environment (no pollution, no GHG emission, no long distance transportation of fossil fuels), where citizens will act as "prosumers" in a smart, clean, renewable and sustainable system.

The Vision aims at covering a large part of domestic heat and electrical power requirements in Europe by using geothermal energy. It also goes beyond urban areas, exploring the numerous applications already in operation and producing heat for industrial and agricultural processes, balneology and health spas all over Europe.

It explains that the Levelised Cost of Electricity, LCoE, (with no additional system costs) is one of the lowest in the entire renewable energies sector, and that heat applications largely contribute to energy efficiency. If we compare the potential of geothermal energy with the potential of fossil fuel, we find that 1% of the amount of thermal energy contained within our planet is 500 times greater than the energy accumulated within all of the oil and gas reservoirs worldwide. From this perspective, we could alternatively state that if we are to start "looking up" towards the future, it would also be worthwhile to start **"looking down"**. Beyond this wordplay, a cultural shift is absolutely fundamental if the potential of geothermal energy is to be unleashed

In Europe, where the **heating and cooling sector** represents nearly 50% of energy demand, the 280 geothermal district heating plants already in operation in 24 countries are using only a minimal fraction of geothermal potential. Given the 160+ plants under construction or investigation in 2016, the heating capacity from deep geothermal sources in Europe is expected to grow significantly, and the same goes for industrial and other applications (i.e. food industry, bio-refineries, tourism etc.).

As scientific knowledge and technological developments move forward, improving the accuracy of resource assessment as well as the development, management and efficiency of plants, the geothermal community is also expanding. Thanks to continuous innovation, geothermal resources that previously were out of reach will be explored and developed. New technologies will make it technically and economically feasible to deliver hot fluids even in areas with an average or low geothermal gradient by enhancing heat extraction, going deeper, or by relying upon heat pumps to raise the temperature. With every new well drilled, our knowledge of the subterranean landscape improves, leading to better forecasting of underground conditions and improved performance from geothermal applications.

The development of early-stage and new generation technologies is fundamental to unlocking the potential of geothermal energy as an affordable, sustainable and secure energy resource across large areas of Europe. Some geothermal energy technologies are still at an early stage in their development. We have to start bringing these new energy conversion solutions, new concepts and innovative uses to a higher level of technological readiness. Moreover, now that the past energy growth model has shown its shortcomings, geothermal energy is being called upon to increase social welfare in Europe, improving quality of life and the environment and favouring social inclusion, cohesion and solidarity within and among European countries.

As international competition increases, maintaining European technological leadership is key to preserving our competitive advantage in the sector. None of the ambitions listed above stand a chance of becoming reality without a collective commitment.

It is for this reason that all of the stakeholders involved in the SET Plan Declaration of Intent on Strategic Targets in the context of an Initiative for Global Leadership in Deep Geothermal Energy, as well as in the Implementation Plan adopted in 2018, and now all the members of the Implementation Working Group, have agreed to ambitious targets in an endeavour to maintain global leadership in the sector, putting forward their best efforts while coordinating between public and private sectors and jointly addressing all relevant issues in order to attain these targets.

As we have learned in recent decades, energy transition is not only a matter of techno-scientific innovation, but also of cultural habits, social issues and political choices, all of which are strongly interconnected. In order to redesign European energy systems and move towards a sustainable future, it is therefore fundamental to establish an interdisciplinary, open, and comprehensive approach which includes the heat flowing beneath our feet. If you would like learn more about our ambitions regarding this renewable and indigenous energy in Europe, look to the ETIP-DG Vision on Deep Geothermal.

A. PREDICTION AND ASSESSMENT OF GEOTHERMAL RESOURCES

Comprehensive knowledge of subsurface geography is crucial when choosing the most promising areas for detailed exploration and potential geothermal development, and indeed throughout the life of a geothermal project. Improved knowledge of the underground landscape and the geological processes at play contributes to minimising the risk posed by unconfirmed resources and the cost of reservoir development, while also optimising the profitable, sustainable and environmentally-friendly management of reservoirs in place.

The knowledge gained over the past 50 years of exploration seeking hydrocarbon, geothermal and mineral resources allows for a priori definition of several prospective areas in Europe based on well data, survey information and their geological interpretation. However, a multi-disciplinary approach integrating geoscience disciplines is required for the comprehensive characterisation of such reservoirs and for the assessment of their geothermal potential at different depths. The prediction and assessment of geothermal resources must embrace an integrated, whole-Earth perspective in both theory and practice, recognising the true complexity of our planet. By developing new technologies and pursuing data-driven advances in key areas of study and modelling, geosciences will increase knowledge, solve challenges, and offer ways to sustain resource discovery, use and remediation. Currently the underground thermal regime of many areas where wells are not available can only be extrapolated, and the related potential may turn out to have been underestimated. There is still a long way to go before geothermal energy provision and thermal energy demand for industrial and civil processes (including those for urban areas) are in balance, and too often energy planning misses the real contribution that geothermal energy may provide.

Geothermal exploration technologies have made advancements in recent years, taking advantage of the progress of individual methodologies and opportunities to develop and test integrated geoscientific approaches. In addition to accompanying the development of the most promising resources, exploration has progressively targeted areas with limited surface manifestations (e.g. in magmatic areas) or sedimentary basin structures which cannot rely on existing subsurface data, such as wells and seismic information in mature oil and gas basins. As a result, innovative surface measurement, remote sensing, and imaging and monitoring techniques at surface and borehole level are required to detect reservoirs and characterise deep thermal, hydrogeological and geological regimes. The overall objective of R&I in exploration is to reduce the costs of exploration technologies and increase the probability of successfully characterising geothermal resources both prior to drilling and during geothermal development.

Targets

- Improve accuracy and reliability and reduce the cost of survey-based and down-hole exploration technologies

- Improve analytical models and energy production forecasting and increase imaging capacity while characterising underground geological, physical and chemical properties throughout the life of geothermal projects

- Minimise the uncertainty associated with geothermal energy by increasing the probability of discovering productive (i.e. fluid-filled) fractures and faults to be used as drilling targets

- Improve resource and uncertainty reporting protocols, contributing to transparent and harmonised methods and instruments for technical and financial risk management, increased transparency for stakeholders, better assessment of energy stocks across Europe, and direct comparisons with other RES projects

- Investigate and characterise unconventional geothermal resources

TOPIC 1: IMPROVED EXPLORATION PRIOR TO DRILLING

Objective

Cost effective exploration methods contributing to improved imaging of geothermal reservoir structures (geometry and size) and rock and fluid properties (thermal, flow, chemical, mechanical) are critical to reducing exploration costs. Key innovations are novel methods capable of detecting size and properties, thus reducing uncertainty (risk).

Current status

Methods of exploration and investigation of geothermal resources are numerous and well described in literature (e.g. 'Best practices guide for geothermal exploration' by International Geothermal Association and International Finance Corporation[1]). Many projects funded by EU funding programmes in the last 10 years have tackled exploration techniques including single and integrated survey methods, logging, modelling, performance evaluation, resource assessment (DESCRAMBLE, DARLINGe, CHPM2030, GEMex, IMAGE[2], EoCoE, TRANSENERGY, I-GET, GEO-DH, GEOELEC, ENGINE).
Nonetheless, exploration risk remains high until the first exploratory well has been drilled and direct data can be obtained. The high-risk cost of drilling to confirm the existence of a viable geothermal resource remains one of the key challenges facing the industry. It is necessary to further develop methods of reducing the uncertainty of a given resource's location, size, and productivity characteristics.
This topic requires continuous effort as well as periodical R&D&I opportunities to test and optimise developed technologies.

Potential for technological development

Technological development options include:

- Reducing the cost of surveys and improving the resolution of underground imaging through the use of geophysical exploration techniques (e.g. gravity, electromagnetic, passive seismic, 2D-3D-4D reflection seismic) beyond industry standards

- Improving remote sensing techniques for detecting surface anomalies

[1]IGA-IFC (2014) Best Practices Guide for Geothermal Exploration, 2nd edition, 196 pp https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/publications/publications_handbook_geothermal-bp-2ed
[2]IMAGE Project Final report (2017) http://www.image-fp7.eu/reference-documents/deliverables/IMAGE-D2.05-2017.11.02-IMAGE-final-book-public.pdf

- Further developing an integrated approach by improving the multidisciplinarity of exploration methods (geological, geophysical, geochemical) as well as by using specialised data and computational science

- Advanced fluid pathways, heat flow and stress assessment

- Methods to assess reservoir temperature, chemistry and flow properties, seismicity, joint field acquisition and enhanced numerical joint inversion

- Technologies to evaluate seismogenic condition during the exploration stage

TOPIC 2: ADVANCED INVESTIGATION AND MONITORING TECHNOLOGY

Objective

The aim is to improve the characterisation of reservoir performance before, during and after geothermal development.

Current status

Numerous exploration techniques are used to characterise resources during and after the first wells are drilled in order to test the existence of a geothermal reservoir capable of sustaining commercial rates of fluid production and injection. These can be used during drilling in order to predict and reduce drilling risks (e.g. Logging While Drilling (LWD) and Measurement While Drilling (MWD)). Various technologies applied at surface/airborne and borehole level provide input to numerical models for forecasting the performance of the geothermal reservoir during future production. By using geophysical and geochemical methods, it is also possible to monitor underground physical and chemical changes during production, which is essential for optimal and sustainable operation of the resource.
All methods require further improvement in order to mitigate risks during the feasibility and operational phases of a geothermal project.

Potential for technological development

Technological development options include:

- Enhancing reservoir information from time-lapse analysis of field data

- Improving the quality (or cost-effectiveness) of borehole-based geophysical techniques (e.g. VSP, CSEM, fibre optic methods) and wellbore measurements of in situ geological and geophysical properties

- In situ fluid monitoring

- Tracer technologies, including optimisation of high-temperature tracers

- Cross-interpretation of well logging

• Innovative sensor technology, including performance at high temperatures and in harsh conditions

• Advanced data acquisition and processing, computational and processing capabilities, and integrated interpretation of surface survey data

• Joint inversion and modelling, and combining exploration and field monitoring objectives

• Developing technology to take advantage of existing data (e.g. smart reprocessing)

TOPIC 3: EXPLORATION WORKFLOWS - CONCEPTUAL MODELS, RESERVOIR CHARACTERISATION, PERFORMANCE AND DECISION MODELS

Objective

Depending on the heat source and the geological controls on heat transport and thermal energy storage capacity, geothermal resources can be classified into different types, each requiring their own optimal exploration workflow. In order to reduce costs and improve the robustness of exploration, we need open, dynamic and transparent workflows which can be customised and optimised to match these specific resource types, as well as improved multi-scale and multi-disciplinary approaches allowing for inference using conceptual models and reservoir characterisation, which should in turn be underpinned by fundamental understanding and confirmation of processes and properties.
Workflows are aimed at enhancing the knowledge and the interpretation of various geothermal systems. Consequently, the goal is to reduce capital expenses (CAPEX) while still reducing risk, and including uncertainty analysis based upon performance models as well as decision and risk methodologies in order to enhance the chance of success.
For areas where information is scarce, the aim is to develop and test novel methodological approaches in order to unlock hidden geothermal potential. These can be improved by adopting portfolio and option theory approaches developed for the hydrocarbon industry, dedicated exploration techniques, and synergy when exploring geo-resources (double plays).

Current status

Many exploration concepts and techniques, thoroughly described by numerous papers and books, have been combined and integrated into the geothermal exploration workflow at several selected sites in magmatic and basement/sedimentary environments as part of the FP7 IMAGE project. An integrated approach focused towards multi-disciplinary complementarity, including geological, geophysical and geochemical techniques as well as numerical models, was employed to predict the geothermal target (productive resources) and to design the well. This is the approach currently being utilised in a number of EU projects (GEMEX, DESCRAMBLE, DEEPEGS, DESTRESS, MEET, CHPM2030). The exploration workflow has been a main focus of the IMAGE project[3], which developed one for volcanic areas based on the experience gained in Iceland and calibrations in the Azores. The project highlighted the need for a multi-scale coupled model approach from continental to concessional scale, and the different roles played by individual methodologies. Numerous geological processes and conceptual play models are slowly progressing thanks to different projects and the data collection and applications involved.

Potential for technological development

Technological development options include:

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

- Developing predictive models, processing existing data and workflows for reservoir characterisation for different reservoir types, focusing on multi-disciplinary integration and interpretation.

- Developing public and transparent performance models as well as decision and risk management (DRM) approaches for optimal decision-making as part of the exploration workflow, providing tools and a methodological framework for techno-economic performance assessment.

- Demonstrating portfolio approaches, applying a value-of-information approach.

- Using adaptive technical and organisational approaches to repurpose failed wells for other uses (double play).

[3] IMAGE Project Final report (2017) http://www.image-fp7.eu/reference-documents/deliverables/IMAGE-D2.05-2017.11.02-IMAGE-final-book-public.pdf

TOPIC 4: EXPLORATION CATALOGUES – RESERVOIR ANALOGUES, ROCK PROPERTIES AND MODEL CONSTRAINTS

Objective

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

Current status

The characterisation and utilisation of subsurface reservoirs generally relies upon applying geological and geophysical investigation/exploration methods and/or numerical models – both requiring, in turn, knowledge of physical rock properties at depth. In order to avoid time-consuming literature research, problems arising from unwanted generalisations, and missing complementary information needed for further interpretation of the measured values, a PetroPhysical Property Database has been developed within the scope of the IMAGE project[4].This database contains data selected to represent the properties of the rock matrix, with characteristic scales of rock samples ranging from a few centimetres to decimetres. It does not contain rock property data from field measurements which integrate larger rock volumes, and may include open or partly open discontinuities, several rock types and properties.
IMAGE and later GEMex projects explored the use of Field Analogue sites, which serve as input for conceptual models and provide property information, helping considerably to constrain explorative concepts which are then checked during site investigation and development.

Potential for technological development

Technological development options include:

- Building and extending relevant rock property databases, in synergy with legacy data from hydrocarbon exploration and production
- Developing a reference set of lighthouse reservoir models and analogues for different geothermal reservoir types
- Developing new upscaling approaches, ranging from rock sample properties to borehole geophysical logging and integrative exploration geophysics
- Using the empirical correlations of different properties at different scales for geostatistical reservoir configuration/characterisation

[4]IMAGE Project Final report (2017) http://www.image-fp7.eu/reference-documents/deliverables/IMAGE-D2.05-2017.11.02-IMAGE-final-book-public.pdf

• Building multiscale reference maps and models to provide constraints for regional and site models, integrating geophysical, lab and structural models

• Building a relevant database on fluid-rock interaction, providing constraints on the variation of rock properties in the presence of hydrocarbon/geothermal fluids

TOPIC 5: ASSESSING RESOURCE POTENTIAL

Objective

Approaches aiming for a reliable estimate of geothermal resource potential before exploratory drilling and flow testing still require a unified definition and harmonisation across Europe. These approaches are needed for the site development and bankability of projects, but also for regional assessment of potential for the purpose of societal development policies and industrial play-based development. In order to achieve this goal a reliable methodology and tools to perform resource assessment have to be developed, in addition to communication and reporting protocols.

Current status

Geothermal reporting codes have been developed in Canada and Australia for their specific stock exchange markets. Such codes lack the necessary element for the consistent comparison of geothermal resources with respect to other energy sectors.
An internationally applicable scheme for the classification, reporting and management of energy and mineral resources was developed under the auspices of the United Nations Economic Commission (UNFC) for Europe, initially for the petroleum and mining sectors before being expanded to include renewable energy sectors, including geothermal. Although UNFC takes into account economic, environmental and social aspects/risk management, this classification is essentially related to market aspects.
There is still a need for a comprehensive and common assessment and comparison framework serving as a foundation for a comprehensive overview of current and future energy sustainability scenarios at project, company, national, regional or global level, to be used by investors, regulators, governments and consumers.

Potential for technological development

Technological development options include:

• Defining Best Practices for quantification of geothermal reserves and resources, including the estimation of recovery factors and other critical performance parameters (economic, environmental and social), using demonstration sites and calibration with developed resources

• Public and transparent performance analysis tools for resource potential and site assessment

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

TOPIC 6: BEYOND CONVENTIONAL RESOURCES

Objective

Unconventional geothermal resources, such as super-hot geothermal systems (SHGS), Enhanced Geothermal Systems (EGS), offshore resources, and reused oil and gas wells, can significantly contribute to geothermal energy growth in the future.
In order to develop SHGS (> 400°C), the major exploration objective is acquiring the ability to detect suitable reservoirs in terms of temperature, fluid bearing and permeable zones, with acceptable fluid chemistry for production.
EGS are characterised by enhanced flow rates thanks to innovative borehole design and reservoir stimulation (e.g. fracking, jetting, chemical treatment, thermal cracking). EGS technologies are key to unlocking less permeable geothermal reservoirs and improving poorly performing wells. EGS is considered an important option for the development of intermediate temperature resources (approx. 125-250°C) at large depths (4-8 km) for direct heat or power production outside of magmatic areas. Major exploration challenges relate to predicting reservoir structures and properties.
Other unconventional resources such as off-shore magmatic resources in addition to geopressurised and coproduced resources (in the hydrocarbon field this might be producing hot water, or repurposing mature and closed/abandoned hydrocarbon wells) have been investigated in only a few areas of Europe: their abundance and techno-economic relevance calls for further investigation. The reuse of oil and gas wells reduces uncertainty regarding profitability and allows sustainable solutions for large-scale development to be designed using conventional assets. Furthermore, the conversion of hydrocarbon fields into geothermal ones may be an opportunity to create a positive social response in areas where oil and gas wells are located.

Current status

The challenges with regard to exploration resources can be most effectively addressed via global cooperation, in order to optimally benefit from shared knowledge and access to costly natural laboratories. R&D for unconventional resources has been studied in FP7 project IMAGE and is currently underway as part of H2020 projects GEMEX, DESCRAMBLE, DEEPEGS, DESTRESS, CHPM2030. These projects are providing insights into coupled geological processes as well as performance under varying physical conditions and various rock and fluid geochemical compositions in the investigated areas.

Potential for technological development

Technological development options include:

- Exploration methods for the roots of SHGS geothermal systems, as well as in-depth understanding and predictive models for properties and processes beyond conventional temperatures

- Developing theoretical and experimental methods to estimate the physical and mechanical properties of rocks near brittle/ductile conditions

• Analysing deep super-hot fluids and depleted hydrocarbon reservoirs for low temperature resources

• Exploration methods for the roots of EGS geothermal systems, as well as in-depth understanding and predictive models for properties and processes beyond conventional depths

• Developing and testing exploration methods to detect proper reservoir conditions

• Researching novel resources, including magmatic offshore, geopressurised and coproduced resources, in order to define their abundance and techno-economic feasibility

B. RESOURCE ACCESS AND DEVELOPMENT

Introduction

Given that up to two thirds of the costs of geothermal projects are related to the drilling and maintenance of the well field, a major objective of the SRIA is to provide technologies that can substantially reduce these costs. When considering the Strategic Targets of the SET Plan-Declaration of Intent on Deep Geothermal Energy (Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and 50% in 2050), cost comparison is performed using the value set for 2015[6]: a global rig rate of USD 25-27 K/day.

Reduced drilling costs can be achieved through new or high-performance drilling techniques and wells. Improved geothermal well maintenance implies the use of alternative materials, casings and production equipment which is better protected against corrosion and scaling, as well as optimised management of the geothermal resource (e.g. total reinjection, pressure maintenance, adapted production schemes). Such R&I goals, which must also satisfy environmental requirements, serve as reference for the majority of European geothermal reservoirs, which often occur in densely populated areas and are characterised by low-to-medium temperature conditions.

Another basic challenge is drilling deeper in order to reach high-temperature resources. While superhot resources (T>400 °C) are estimated to multiply production up to tenfold per well, drilling at deep depths involves challenging physical (thermal, pressure, stress, rheological) and chemically aggressive conditions. The technical limitations of currently available sensors and tools come as a result of the materials used to complete the wells and the equipment used during drilling and operation. A broad research spectrum, covering all technology readiness levels, is required in order to improve existing technologies or to develop new ones over the medium to long term.

Proposed topics start with different approaches to the drilling system, which can lead to potential improvements in many parts of the processes by considering the drilling process in a holistic fashion. In this respect, the development of a European knowledge base is envisioned so that experiences with geothermal drilling might be shared from an operative perspective. Currently, many issues encountered during drilling operations which are then solved in practice are scarcely reported, if at all. Sharing knowledge and experience (as further discussed in Chapter E) and mutual learning via joint drilling protocols and guidelines will speed up technological development.

The topics discussed afterwards may be part of such customised drilling systems, or they can also be standalone. Less common or radically new technologies for breaking rocks such as thermal drilling, hammer drilling, electro pulse drilling or laser drilling, are options to be utilised in the long or medium term. These require additional research in order to be applicable for drilling deep geothermal wells. Reliable drilling fluids are extremely important for safety during drilling operations. High-temperature application poses challenges of its own. High temperatures and corrosion are also bottlenecks for bottom hole assemblies, especially for downhole motors and measurement while drilling (MDW) devices.

[6]Data from EGEC Geothermal Market Report, 2015

Reliable well construction and geothermal casing integrity for special applications at both low and high temperature are prerequisites for environmentally safe geothermal exploitation. Research approaches are presented within several topics. Identifying and surveying these systems requires electronics which are reliable above 175°C and can be used to take measurements while drilling or as part of monitoring approaches for future geothermal applications.

When considering the utilisation of especially low temperature reservoirs for combined heat and power generation, the main bottleneck is presented by the current status of downhole pump technology, which cannot yet be regarded as technically reliable enough to facilitate high availability for all geothermal regions and conditions, as the applied techniques themselves suffer from technical limitations. Before attempting simultaneous upscaling for higher temperatures and flowrates, research should first focus on removing existing recurrent and fundamental technical failures. The objective should be to develop purely "geothermal" solutions (e.g. for the seal of a pump system) where improvements from oil applications are definitely not sufficient or appropriate. It is upon this basis that upscaled measures and procedures using higher temperatures and flow rates should be provided. Finally, green products should be used during the resource access and development phase in order to introduce geothermal into the circular economy.

Targets

- Achieve cost reduction in resource access through the use of unconventional resources, EGS, and/or hybrid solutions coupling geothermal with other renewable energy sources by developing improved or new ways of drilling deep geothermal wells (faster drilling techniques and reduced drilling lost time) and data analysis

- Improve and standardise drilling technology and well completion in order to ensure well integrity during drilling and exploitation

- Achieve cost reduction in O&M by
    - Improving overall plant efficiency, including wells, pumps, pipelines and plant equipment
    - Reducing the downtime of geothermal plants due to scaling or corrosion, equipment replacement or cleaning
    - Increasing the lifetime of components and equipment

- Improve and standardise installation and assembly methods

- Improve environmental performance and mitigate unsolicited side effects (induced seismicity, emissions into the environment)

- Improve energy yield through improved hydraulic connection to the reservoir, increase reservoir performance and enhance O&M procedures

- Increase or extend the lifetime of plants and develop streamlined end-of-life strategies

TOPIC 1: ADVANCEMENT TOWARDS ROBOT DRILLING TECHNOLOGIES

Objective

Develop and provide the means and methods to considerably reduce lost time and resolve well integrity problems by controlling and/or automating the drilling process. Lost time due to wellbore stability or lost-in-hole accidents typically occur when drilling geothermal wells in unknown geological settings. Methods should be based on knowledge gained from past geothermal drilling operations as well as from the oil and gas industry, but should also be shaped by the special requirements of geothermal drilling in medium-low permeability, hot and hard rock conditions. The effectiveness of these methods should be evaluated in the design phase and the drilling programme adapted accordingly.

The technologies to be developed need to satisfy the stringent economic constraints that apply to geothermal projects. In particular, geothermal drilling automation technologies are expected to reduce costs, increase wellbore integrity and improve Health, Safety, and the Environment (HSE) at the well site. Casing drilling may provide advantages in terms of saving time and technical problems. Open questions persist regarding integrity and fatigue life under challenging conditions in geothermal applications, e.g. reconstructing the complex loads acting on the casing string while drilling and during the productive life of a geothermal well.

In addition, new technologies which enable directional drilling of deviated wells in formations with a temperature of 150°C to 300°C require special development of high-performance drilling systems.

Current status

Over the past decade, the hydrocarbon and mining industry has made tremendous progress in developing new downhole sensors, downhole-to-surface communication channels and algorithms to analyse and interpret raw data from drilling devices and the borehole. There are also early approaches to using downhole data for surface control of the drill rig, even in a partially automated way. However, most of these technologies cannot be used economically in the geothermal setup, and the type of sensors used does not match the differing needs of geothermal projects.

For casing drilling purposes, there have so far been a number of standard laboratory facilities established across industry to carry out analysis of the response from tubulars under complex loads. These facilities, despite being accepted, have not been able to comprehensively reconstruct the working conditions for casing string global loads.

State-of-the-art directional drilling using downhole motors with standard elastomer-based stators and measurement-while-drilling (MWD) systems is limited to temperatures of 150°C or 175°C.

Potential for technological development

Methods and means coming from the oil and gas drilling industry have to be carefully screened, selected and adapted to the specific needs of drilling for geothermal resources, with a particular focus on European locations. These adapted methods and means should then be tested in the field. Areas of technological development will include downhole sensors, bi-directional communication channels, data analytics, learning databases, automation algorithms and surface control processing hardware and software. Rig

mechanisation, such as pipe handling machines, will not be developed under this item. Possible technological developments include new hardware and software devices that reflect the specific needs of geothermal drilling, and automation of the geothermal drilling process through the integration of downhole measurements and surface control. The benefits of these new technologies should be demonstrated through laboratory simulation and testing in pilot projects in the field (in conjunction with geothermal operators).
Given new and comprehensive full-scale laboratory testing facilities for innovative drilling options (e.g. alternative casing materials, casing drilling), the behaviour of casing string's material and connections can be more accurately estimated and therefore provide operators much greater clarity when selecting connections and materials.
Such facilities may also help to develop and test a commercial, very high-temperature (>300°C) directional drilling system based on a 300°C+ downhole motor and MWD System. This would improve the cost efficiency of drilling systems for geothermal applications.
Low cost (non-intrusive) technologies to accelerate underground data collection in high risk areas, e.g. optimised slim-hole wells, would be also beneficial for reducing exploration costs.

TOPIC 2: RAPID PENETRATION RATE TECHNOLOGIES

Objective

Develop proven or new rock destruction mechanisms into highly efficient and versatile rock destruction processes for geothermal applications. This goal envisions maximising the effectiveness of the energy transfer used to destroy rock, thereby improving the overall energy efficiency of the drilling process and incorporating downhole measuring techniques with new drilling methods. This should demonstrate effective and efficient methods of rock destruction when drilling long sections/mono-bore wells, resulting in realistic solutions which raise the attractiveness of drilling for geothermal wells in alternating soft medium and hard rock formations.

Current status

Rotary drilling is currently the dominant drilling method in the geothermal sector. In recent decades however, several alternative methods to break rocks haven been developed and tested. These include breaking (hard) rock via hammer drilling, thermal alteration, high-pressure fluid injection, spallation or electric discharge into the rock. Some of these methods are already being used in other sectors. Percussion drilling or hammer drilling is commonly used in the mining sector. High powered, mud driven hammer technology for deep wells is under development and being commercialised. Laser techniques have been used to remove scaling within geothermal wells. Jet drilling is routinely applied to drill radials to increase production from oil and gas wells and is being applied to drill through soft sediments. Other techniques such as spallation, flame-jet and electric discharge drilling have only been tested at lab scale. Experimental and testing data indicates that under certain geological conditions these drilling methods can result in higher rates of penetration (ROP), less wear and – in some cases – lower energy use than traditional rotary drilling. In addition, they may be effective for operations aiming to increase or restore the productivity of geothermal wells: examples

include the drilling of radials by jetting in relatively soft or porous rocks and the use of laser drilling to remove scaling.
Innovation can also derive from a combination of different drilling methods. Preliminary lab and field results show that a combination of a laser and a mechanical drill bit can lower the required weight on bit (WOB) and reduce the torque on the drill string. This results in less wear on the equipment and can lead to fewer round trips to replace worn drilling bits.

Potential for technological development

Rock breaking and rock removal for conventional mechanical drilling methods should be greatly improved in order to increase drilling speeds (currently up to 3 m/h in hard rock), and consequently reduce the cost of drilling[7]. Upgrades should be made to the above-mentioned new drilling mechanisms and technologies in order to move on from current testing (either at lab scale or in the field under full-size drilling conditions) and become applicable to drilling deep geothermal wells. This includes R&D to better understand and control the rock breaking/removal mechanism, the design of functional drilling bits and related issues such as power, light or fuel transport towards the bit.
Furthermore, development is required with respect to the bottom hole assembly (BHA) necessary for 'full-size drilling conditions'. This development should lead to effective solutions for dealing with drag, removing cuttings, and allowing directional drilling and measurement while drilling (MWD).
The most promising aspect is probably the integration, fusion and optimisation of separately existing technologies with proven high-performance techniques in drilling, thereby reducing research and development risks and increasing project attractiveness and enhancing the chance for the technology to go to market.

R&D should aim to:

- Develop drilling methods for hard rock which avoid bit wear and have a high rate of penetration (ROP) > 5 m/h
- Research and optimise rock destruction principles
- Mitigate dangerous drill string vibrations using bottom-hole assembly (BHA) damping systems based on mechanical characterisation (Neotork, AST-Tomax, HTX-Fracks-International etc.); downhole memory recorders (NOV, Varel) could be used for the purpose
- Develop hybrid drilling systems in order to drill with a higher ROP, lower weight on bit (WOB) and less torque
- Design and test adequate BHAs
- Develop and test radial drilling methods and borehole designs for crystalline and hard rock conditions
- Demonstrate the benefits of technology under field conditions

TOPIC 3: GREEN DRILLING FLUIDS

Objective

Novel technologies and eco-friendly materials for the formulation of suitable drilling fluids which are stable under the conditions faced in (ultra-)hot geothermal reservoirs or that can be used in combination with new drilling methods (see topic B.2).
Solutions should be able to provide a good compromise between cooling power, temperature drop, rheology and operation time (cost-effective), and should have limited environmental impact, if any. These drilling fluids should be capable of protecting against corrosion from mineralised (hot) water or acid gases.

Current status

A series of potential additives for enhanced thermal and rheological properties exist, such as:

- Traditional additives for water-based drilling fluid potentiated with additives like Bentonite, Xanthan Gum, Starch, Synthetic polymers, copolymer and tetra-polymers

- Non-conventional drilling fluids: carbon dioxide (gas) as circulation fluid, ionic liquid, vegetable oil (chemically-modified crude palm oil), active cooling methods based on phase change from solid to liquid as well as from liquid to gas

- Nanoparticles: Nano zinc oxide, carbon nanotubes, silica nanoparticles, aluminium oxide nanoparticles, graphene, and hollow glass spheres

- Green and eco-friendly products or additives (mainly for the purpose of controlling filtration): pistachio shells, sugar cane ash, tamarind gum, ground coca bean shells, rice fractions, cotton seed hull, coconut coir, (natural) fibres, ground peach seeds, ground nut shells and nut flour

Potential for technological development

Strengthen collaboration with producers of additives and R&D centres focused on nanomaterials, polymers, biodegradable polymers, heat transfer studies, and formulation of outstanding drilling fluids based on simulation data, lab experimentation and field trials, as well as relevant environment testing. The aim is to:

- Design new drilling fluids that are stable under high-temperature, chemically aggressive conditions

- Develop drilling fluids with improved rheological properties in order to drill faster and more cheaply into hard rocks and hard environments

- Develop drilling fluids for the efficient removal of cuttings from deep and/or highly deviated wells

- Develop drilling fluids that protect drilling equipment and casings against corrosion from mineralised (hot) water or acid gases

- Develop effective methods to control mud losses in geothermal reservoirs

- Attention should be paid to the rheological properties of the new drilling fluids, their environmental characteristics such as biodegradability and recyclability, and their potential to increase wellbore stability and provide corrosion protection.

TOPIC 4: RELIABLE MATERIALS FOR CASING AND CEMENTING

Objective

The three main objectives are:

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

- Investigating and demonstrating high-performance, cost-effective
    - **I.** corrosion-resistant materials, including cladded materials
    - **II.** reduction of casing stress and strain to below yield stress
    - **III.** flexible couplings allowing axial casing movements and casing-cement layers which prevent the casing from sticking when warming up.

- Developing standards to ensure the integrity of geothermal wells.

Despite a handful of great advantages presented by casing drilling in terms of cutting down on time and technical problems, there are still open questions regarding the integrity and fatigue life of wells drilled under challenging geothermal conditions (i.e. ultra-high temperatures and pressure, aggressive fluid composition)[8]. Reconstructing the complex loads acting on the casing string while drilling and during the productive life of a geothermal well at laboratory scale is a very powerful tool for responding to these questions and is therefore the objective of this research. Lab observations should result in new casing materials and concepts (e.g. corrosion resistant materials including cladded materials, flexible couplings that allow axial casing movements) and new cement formations that optimise heat transfer, resolve issues occurring across the lifetime of the well, reduce stress and strain below yield stress, modify the casing-cement layer to prevent the casing from sticking during warm-up, allow for effective hardening of cement in contact with hot, aggressive fluids, and improve the resistance of casing and cement

Current status

The first in situ results show that high austenitic stainless steel casing types and nickel alloys have promising resistance against corrosion by the hot, mineralised fluids encountered in Icelandic geothermal fields. Aging and possible phase changes due to high temperatures have to be verified and standardised for high-temperature

[8] J. H. TerHeege, J. Wollenweber, B. Orlic (2017) Discrete Element Modelling of Wellbore Integrity in High Temperature Geothermal Reservoirs. American Rock Mechanics Association Symposium, June 25-27th 2017, San Francisco, California (ARMA 17-176).
I.O. Thorbjornsson, Gunnar Skúlason Kaldal, Bjarni Steinar Gunnarsson, Árni Ragnarsson (2017) A New Approach to Mitigate Casing failures in High-Temperature Geothermal Wells. GRC Transactions, vol. 41: 585-591.

geothermal use. Moreover, testing is needed to see how these materials behave under other reservoir conditions (chemical and temperature)[9].

The application of a protective coating is an alternative when using high-grade steel types and alloys. This is typically done through deposition or cladding; if cladding is used to employ high-cost materials economically, development is needed to lower the material cost to 25-35% of using these materials at full thickness; the current material cost is around 70%.

The success rate of high-temperature wells (>300°C) with a "locked" casing is as low as 50% due to structural failures resulting from plastic deformation and collapse of the casings. Work on a Flexible Coupling concept, allowing for axial movement of the casing, offers hope for a situation where casings are at a controlled, below-yield level of stress.

So far there have been several standard laboratory facilities established across industry to analyse the response of tubulars under complex loads. These facilities, despite being accepted, have not been able to comprehensively reconstruct the working conditions for casing string global loads, as they lack one or more loading conditions. This results in a less accurate understanding of the material behaviour in the real and harsh conditions encountered as a part of geothermal application.

Novel cement material has been tested in order to improve overall heat transfer and study the influence of remedial cementing, as well as to increase the lifetime of cement, especially in high-temperature conditions.

Potential for technological development

When using conventional design and completion techniques, high costs are linked to well failures, often requiring permanent plugging or reduced well flow as a result of mechanical instability or plastic deformation. Corrosion of industry standard materials for casings due to sour fluids in deep drilling needs to be solved in a way that is both economical and practical.

Conventional test facilities have proven limited when recreating the loading conditions encountered by tubulars in (ultra-hot) geothermal wells. New, comprehensive lab facilities allowing for full-scale testing of casing string material and connections are needed in order to more accurately estimate component behaviour. This will provide well engineers and operators with better guidance when selecting connections and materials depending on the (expected) reservoir and production conditions, increasing the environmental safety and cost-efficiency of drilling operations.

Potential innovations and technological developments include:

- New, economical solutions for corrosion resistant casings
- Developing cladding with the aim of lowering costs
- Verifying and demonstrating novel coupling techniques in order to lower the rate of casing failures due to plasticity or mechanical instability

[9] Á. Ragnarsson, P. Durst, E. Randeberg, T. Reinsch, I. Thorbjornsson, J. Wollenweber, W. De Jong, G. Kampfer, Ó. Sigurdsson And F. Vercauteren (2018) GeoWell - Innovative materials and designed for long-life high-temperature geothermal wells, Oil Gas European Magasine 44(1):14-16 (doi: 10.19225/180301)

- Developing novel cement formulations in order to improve heat transfer and resolve other issues, lower stress and strain on the casing during warm-up and guarantee efficient hardening and stability under harsh conditions

- Carrying out research and detailed analysis of the circumstances experienced by the casing string during geothermal applications

- Studying and analysing material and connection behaviour effectively, facilitating proper material selection i.e. efficient estimation of economical and operational aspects

- Developing test facilities to reconstruct the real conditions of casing drilling for geothermal applications

- Developing design and maintenance standards for geothermal wells to ensure wellbore integrity

TOPIC 5: MONITORING AND LOGGING WHILE DRILLING (INCLUDING 'LOOKING AHEAD' OF THE BIT)

Objective

Enable the acquisition and improvement of information acquired while drilling (e.g. in order to evaluate the formation, anticipate overpressure formations, position the drill bit, predict risk, look ahead and around, and provide support for drilling in critical conditions i.e. supercritical and melting zones and brittle-ductile transition areas) in geothermal environments by using innovative methods such as improved downhole recording and communication.

In order to monitor, analyse, control and optimise operational processes related to drilling and well performance, it is necessary to create new technological systems that allow changes in operating conditions to be anticipated within a relevant timeframe. Both traditional technologies for the monitoring of drilling and testing operations as well as production need to be adapted to the hostile downhole conditions encountered in high-temperature geothermal wells.

In addition, the environmental aspects of geothermal resource utilisation are playing an increasingly significant role, one which has to be consciously fulfilled. If relevant data can be made available and combined with a deep understanding of the process, rig and field operators will then be able to adjust drilling procedures, production and injection schemes, and production strategies in order to optimise the performance of geothermal wells and fields. Proper planning and improved real time decision-making will allow geothermal resources to be managed more effectively and the cost of operational and maintenance activities to be minimised.

Parameters to be monitored with innovative technologies include drilling parameters (e.g. the position of the bit, vibrational load, weight on bit (WOB), torque, mud weight and flow), reservoir and production conditions (e.g. pressure, temperature, pH, electric conductivity, dissolved solids) and well integrity (e.g. cement and casing mechanical integrity monitoring, zonal isolation).

In addition, tools should be developed to 'look ahead' of the bit. These tools will allow rig operators to detect overpressure early, evaluate the formation and predict bottom hole temperatures. Moreover, the possibility of providing (2D and 3D) imaging of the formations around and ahead of the bit will provide precious information about the characteristics of the geothermal reservoir, possibly including changes in deep rheological conditions.

Current status

Recently, single well imaging techniques (SWI) including seismic sources and receivers close to the bottom hole assembly (BHA) have been tested. Other innovative imaging techniques include seismic while drilling (SWD), cross-well SWD and vertical seismic profile while drilling (VSP-WD). These systems use either standard acoustic logging while drilling (LWD) tools or newly developed tools to image the borehole surroundings with signal frequencies in the kHs range. SWD prediction (looking ahead of the bit) and check shot can increase the investigation range up to several hundreds of meters, or more. [10,11]

These new imaging techniques even make it possible to take advantage of the recorded seismic wave field in its entirety in order to image surrounding structures up to tens of feet. Advantages of this approach include depth-independent resolution and low extra costs for data acquisition. High spatial wave field recording is possible due to quasi-continuous recording without coupling to the borehole. A limitation can be a low signal-to noise ratio, in particular for events recorded later, and therefore a limited exploration range.

Potential for technological development

Technological developments are needed to guarantee effective measurement and logging while drilling in high-temperature geothermal wells and challenging surface and geological settings (e.g. densely populated areas, foothills, mountain regions, areas where shallow geology disturbs wave propagation, deep crystalline rock, melting zones). Examples of potential technological developments include:

- Tools operating under high-temperature and/or high-pressure conditions
- Tools operating in heavily deviated (sub)horizontal wells
- Tools for data measurements between the surface and positions in the well during drilling, e.g. the drill bit SWD System
- Analysis of reservoir heterogeneities, borehole waves and reverberations, also linked to the mechanical properties of the drilling system
- Technologies to provide cross-well data
- Better image production, performing rock characterisation close to the target with high resolution data

[10] Poletto, Flavio; Corubolo, Piero; Schleifer, Andrea; Farina, Biancamaria; Pollard, Joseph S.; Grosdanich, Brad (2011) Seismic While Drilling for Geophysical Exploration in a Geothermal Well. Geothermal Resources Council Transactions35: 1737-1741

[11] Rabbel, W., Jusri, T., Khon, D., Motra, H.B., Niederau, J., Schreiter, L., Thorwart, M., Wuttke, F., and the DESCRAMBLE Working group (2017) Seismic Velocity Uncertainties and their Effect on Geothermal Predictions: A Case Study. Energy Procedia 125: 283-290 (doi:10.1016/j.egypro.2017.08.178).

• Methods to adjust the well trajectory to a more precise target during drilling, thanks to 'real-time' data processing and interpretation

• Real-time downhole-surface transmission, e.g. mud pulse, EM, acoustic drill pipe

• Surface-synchronised down-hole memory recorders to provide While Drilling (WD) results which can afterwards be synchronised with surface system data following tool retrieval

• Minimisation of drilling string vibrations (for an optimised and reliable signal to noise ratio) by using cutting-edge shock absorber technology above the Bottom Hole Assembly (BHA)

• Low cost (non-intrusive) technologies to accelerate underground data collection in high-risk conditions, e.g. in slim-hole wells

TOPIC 6: HIGH-TEMPERATURE ELECTRONICS FOR GEOTHERMAL WELLS

Objective

Develop electronics and sensors to be used in high-temperature geothermal wells during drilling operations in order to ensure reliable measurement while drilling (MWD) and to enable logging while drilling (LWD). These are also to be used during well construction and testing, and to perform (continuous) integrity checks of the wellbore and wellbore equipment.
The drilling of high-temperature and high-pressure geothermal wells requires sensors and electronics with a high temperature and pressure rating. Improved cooling solutions based upon the circulation of drill-mud can be developed for tools that are used during drilling operation.

Current status

Currently tools from the oil and gas industry are being adopted for use when drilling geothermal wells. Many sensors measuring drilling parameters such as Bottom Hole Assembly (BHA) shock and vibration are limited to 175°C. There are few tools which can monitor and/or optimise the drill string in real time at higher temperatures. In 2013 Honeywell reported demonstration of a steering tool capable of operation at 300°C.
Logging tools and sensors for slickline operations are available up to 450°C (DESCRAMBLE-project), but the available tools for measurement and logging while drilling are very few and limited in use. Moreover, communication over wireline (E-line) is not available above 300-350°C.[12,13]

[12]Ruggero Bertani, Henrik Büsing, Stefan Buske, Andrea Dini, Magnus Hjelstuen, Massimo Luchini, Adele Mansella, Roar Nybo, Wolfgang Rabbel, Luca Serniotti and the DESCRAMBLE Science and Technology Team (2018) The First Results of the DESCRAMBLE Project. Proceedings, 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, 2018 SGP-TR-213
[13]Jon Vedum, Morten H. Røed, Sigbjørn Kolberg, Magnus Hjelstuen, Anders E. Liverud, Øyvind N. Stamnes (2017) Development of a Novel Logging Tool for 450°C Geothermal Wells. International Microelectronics Assembly and Packaging Society (https://doi.org/10.4071/2380-4491.2017.HiTEN.11)

Other issues that need to be tackled in order to improve the drilling, testing and operation of high-temperature geothermal wells include:

- Limited knowledge of predictive models of BHA performance at high temperature
- Few real time downhole monitoring tools for during injection and production
- A limited number of tools available for well logging and evaluation in high-temperature wells (>150°C)
- Little knowledge of intelligent completion hardware, software tools, and devices e.g. inflow devices, production logging, monitoring
- Downhole real-time monitoring along the production string and in the reservoir interval, as well as in low temperature wells.

Potential for technological development

Envisioned technological developments include:

- High-temperature electronic components which can withstand temperatures above 175°C and up to 300°C
- E-lines which can withstand temperatures above 300-350°C
- Improved heat shields (Dewars) and improved cooling techniques for electronics and sensors, allowing the use of standard electronics
- Integration of sensing technologies (e.g. fibre optics) for high-temperature conditions into the well design.

TOPIC 7: EFFECTIVE AND SAFE TECHNOLOGIES FOR ENHANCING ENERGY EXTRACTION

Objective

Enhance the productivity of low permeability rock in order to increase energy extraction. Technologies utilising stimulation treatments to develop suitable heat exchangers in order to extract economical amounts of heat, usually referred to as Enhanced Geothermal Systems (EGS), still face numerous hurdles.
The hydraulic stimulation used to enhance permeability still requires an advanced injection strategy in order to control fracture propagation and simultaneously reduce the risks of unwanted seismic events below a given threshold reflecting the vulnerability and exposure of people, buildings and infrastructure.
Alternatively, new heat extraction solutions could be developed that do not require the enhancement or creation of a fracture network, but rather rely entirely upon fluids circulating within boreholes. These closed-loop solutions primarily aim to extract heat through heat conduction at the borehole casing.

Current status

Enhanced geothermal systems (EGS) are engineered reservoirs developed to extract economical amounts of heat from geothermal resources with low permeability and/or porosity. These systems can be developed in two ways: either by enhancing or creating the desired reservoir conditions, or by creating an underground heat exchanger using drilling techniques only.

In general, hydraulic stimulation can be described as the injection of fluids at high flow rates into reservoirs in order to develop new fractures or reactivate existing ones, enhancing the permeability of the system and improving productivity. In order to enhance the productivity of reservoirs, a site-specific concept is necessary to actively make reservoir conditions profitable by using specially adjusted stimulation treatments, such as multi-fracture concepts, site specific well path design and flow rate controlled (cyclic) concepts, or thermal-chemical treatments. The overall goal is to develop a sufficiently large heat exchanger at depth to extract the necessary amount of heat. In addition to a purely hydraulic approach, stimulation can be combined with a chemical treatment and/or thermal fracturing (i.e. cold water injection). This is achieved by adding acids to extend hydraulic pathways by dissolving minerals or via thermally induced fracture development.

Another option is Radial water Jet Drilling (RJD) technology to increase inflow into insufficiently productive 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 unconnected highly permeable zones into the main well. A combination of chemical treatment and radial jet drilling is also conceivable.

Hydraulic stimulations in EGS systems currently in development are carried out selectively, uniquely and in a controlled fashion in order to achieve sufficient flow rates for the economical utilisation of the earth's heat for direct heating and the provision of base load electricity. One focus of geothermal technology development is the sustainability of fracture opening. The other focus is the optimisation of stimulation treatments with respect to unwanted effects like induced seismicity and hence reducing the probability of perceived events. Designing a special well path concept, including sub-horizontal sections in the reservoir and special alignment according to the stress field, offers the possibility for multiple fracture treatments in a well to develop the geothermal field.

The DESTRESS Project in Europe and FORGE Project in the USA are working on these aspects.

In seeking to avoid hydraulic stimulation, options to extract heat from deep, hot rock through conductive heat flow and/or natural convection have been investigated. This has resulted in a number of conceptual, 'fully drilled' heat extraction systems. These concepts are based on numerical models. Field data evaluating their viability is scarce or otherwise unavailable.

Potential for technological development

The current technology for hydraulic stimulation in EGS requires further development. Designing a special well path concept, including sub-horizontal sections in the reservoir and special alignment according to the stress field, offers the possibility for multiple fracture treatments in a well to develop the geothermal field. Combined stimulation technologies should also be further investigated and developed. For example, radials

increase the pay-zone and overcome the near-wellbore skin, whereas chemical treatment increases hydraulic performance in the vicinity of the wellbore and the radials: their optimal combination would improve performance while reducing seismic risks.
The effectiveness of the above-mentioned and similar stimulation techniques should be proven and improved through field testing. Moreover, there is a need to investigate the sustainability and impact of these stimulation techniques. This could convince project developers and operators of the added value of these stimulation techniques and could help to build confidence at the level of all stakeholders.
In addition, lab and field tests are needed to evaluate the viability of 'fully drilled' heat extraction concepts. The results of these tests should be used to broaden knowledge of the thermal and mechanical characteristics of deep, hot rock, and to calibrate and refine the numerical models assessing the thermal and mechanical behaviour of deep heat extraction systems.

TOPIC 8: TOTAL REINJECTION AND GREENER POWER PLANTS

Objective

Development of viable, safe, and cost-efficient technologies to improve the environmental performance of high-temperature geothermal power systems by complete reinjection of fluids into the reservoir total and complete control of non-condensable gases (if any). The release of steam and potentially hazardous chemical compounds from high-temperature geothermal resources and into the atmosphere and ecosystems can be avoided through:

- The development of coupled well-reservoir multiphase flow models, taking into account the interactions between the chemical and physical properties of geothermal fluids and the geo-mechanical behaviour of reservoir rocks.

- The development of technology for the capture, sustainable use, abatement or reinjection of Non Condensable Gases (NCGs), including the selection of the most advanced materials capable of operating in harsh environments.

- Demonstration of the competitiveness of newly developed cost-efficient technologies in field test sites, including monitoring of plant performance and comprehensive economic analysis.

Current status

Total reinjection is not yet a common practice in high-temperature geothermal power generation systems, mostly due to the high concentration of CO2 and other NCGs in the geothermal fluid. A pilot experiment in Iceland captured the waste gases, dissolved them in the exhaust geothermal water stream, and re-injected the aqueous solution. The re-injected acidic gas-charged fluid provokes the dissolution of subsurface basaltic rocks, which increases reservoir permeability and promotes the fixation of the dissolved gases by mineralisation. This technique is not immediately applicable in the case of sedimentary or crystalline reservoir rocks or for high rates of CO2.
The reinjection of CO2 and other NCGs is quite common practice in petroleum industry

in the context of Enhanced Oil Recovery. Gas and steam injection has been used for 30 years to increase production by reducing oil viscosity and supporting reservoir pressure. Procedures based on the pH, thermodynamic conditions, composition and physical properties of the fluids are usually applied as indirect methods for corrosion rate control and scaling issues, which could affect the surface equipment and reinjection wells. The chemistry of the fluids and interactions with rocks have a crucial importance in reinjection projects, minimising operational risks and improving geothermal sustainability.
This topic is currently under scrutiny as part of the H2020 GECO Project.

Potential for technological development

- Laboratory tests and modelling of reinjection systems for NCGs.
- Global computational tools like coupled well-reservoir simulators, with the aim of optimising and calibrating the injection in both surface and subsurface domains.
- Proper well completion with site-specific design.
- Development of innovative systems to avoid/reduce the discharge of geothermal fluid into atmosphere during power plant outages.
- Radioactive material processing.
- Metallurgic studies and development of new materials for equipment in sour high pressure – high-temperature environments.

TOPIC 9: REDUCING CORROSION AND SCALING AND OPTIMISING EQUIPMENT AND COMPONENT LIFETIME

Objective

In the geothermal industry, several solutions are used to deal with corrosion, erosion and scaling. Often, the selection of these measures to mitigate scaling and corrosion is based on experience. The development of adapted monitoring tools and research into their effectiveness and the environmental effects of measures used to control scaling and corrosion can lead to:

- Safer operation, avoiding unexpected plant accidents linked to equipment failure due to corrosion or scaling
- Maximised plant reliability, avoiding unplanned downtime due to unexpected corrosion or scaling issues
- Asset protection, minimising corrosion in order to maximise the lifetime of all plant equipment (wells and surface equipment), which makes up a significant percentage of plant investment

- Maximised energy recovery by maximising heat transfer through exchangers and minimising energy losses due to measures such as bubble pressure control

- More environmentally friendly operation, using less chemicals to control scale and corrosion and using greener chemical products

Current status

Corrosion protection in geothermal plants is a well-established technology. The use of filming corrosion inhibitors is widespread, leveraging experience developed over decades of corrosion control in the oil and gas industry. Films and coatings, however, suffer from physical erosion.[14]

Scale control in geothermal plants is another well-established technology. As it stands, there is virtually no geothermal plant suffering from a scale problem that can't be solved. Chemical treatment companies have leveraged boilers, cooling towers, seawater evaporators and oilfield scale-control technology in order to solve scale issues in geothermal plants.

Scale monitoring is a reality. Plants have several means of tracking plant operating parameters, allowing them to track scale accumulation in surface equipment or wells.

Scale predictive models are also well-established. Unlike corrosion modelling, scale modelling in geothermal has been a research field for years, with several examples of modelling software like WATCH or Nalco's Geomiser. These tools are already commonly used to predict the risk of scaling in new projects or existing plants.

Scaling and Corrosion prevention is usually done when planning the system, using well-designed plant schemes which allow for the control of bubble pressure (e.g. CO2) throughout the plant in addition to wellhead and reinjection pressure and temperature control, using specific materials designed for the operating conditions, and chemical injection lines designed for the expected scaling.

Erosion is now typically solved by upgrading metallurgy, which is an expensive solution. Here there is an overlap with material studies due to physical erosion, sulphydisation, hydrogen cracking, dusting and many other mechanisms involving effects driven by chemistry and physics.

Most monitoring is done by analysing the operating fluids in key points of the plant (well bottom, wellhead, heat exchanger, reinjection). It usually investigates any scale found on pipelines, pumps etc. during cleaning and maintenance works.

The fluid flow path is investigated using various tracers, while logging methods (electrical methods, caliper, sonic etc.) are used to control the system integrity. Tracers (e.g. Perfluorocarbons (PFCs), naphthalene sulfonic acids (NDS), SF6, alcohols (methanol), halides (KI) and inert gases (Kr, Xe)) are used to evaluate the flow path and to determine reservoir rock volume and the water-rock heat transfer surface in geothermal reservoirs. The available tracers are not stable at high temperatures and may interact with components within the geothermal fluid, however.

[14] Allegrini, G., and Benvenuti, G. (1970) Corrosion characteristicsand geothermal power plant protection (collateral processes of abrasion, erosion and scaling). Geothermics 2, 865-88

Environmental impact:

- Currently mining authorities give approval for the addition of chemicals into the geothermal fluid in order to avoid scale or corrosion

- Typically, approval or assessment is based on Biodegradability using OECD tests or is based on CEFAS product classification. None of these criteria represent a thorough understanding of the impact of chemical usage in geothermal reservoirs

Potential for technological development

- Currently, corrosion and scaling is typically defined on a case-by-case basis that depends upon the experience of the experts involved in the project. The developments of guidelines to assess, monitor and control scaling and corrosion could reduce the use of chemicals and minimise environmental impact. These would include reliable models for corrosion forecasting. Lessons can be learned here from O&G. Predictive corrosion control is needed early on during project development.

- The ultimate fate of chemicals used for scale and corrosion prevention in geothermal reservoirs and the surrounding environment needs to investigated, e.g. through simulation and/or modelling in addition to lab and field experiments.

- Greener corrosion inhibitors can reduce environmental impact. Today, all filming corrosion inhibitors are surfactants and pose a risk to the environment. Alternatively, new coatings and corrosion-resistant materials could be developed that would no longer call for the use of chemical treatment programmes. Moreover, functional coatings for material surfaces could help to reduce or even avoid the formation of scale.

- Continuous, non-destructive, non-intrusive quantitative and qualitative methods, e.g. based on nuclear techniques (gamma transmission, neutron activation), should be developed for on-line measurement of scale formation.

- Wireline scale cleaning could be developed as an alternative or complementary solution to continuous scale inhibitor use.

- Develop stable tracers (both passive and active) to monitor preferential flow paths and determine reservoir rock volume and water-rock heat transfer surface for high T and supercritical reservoirs.

TOPIC 10: EFFICIENT RESOURCE DEVELOPMENT

Objective

R&D initiatives within this topic are aimed at enhancing the capacity to control and predict the management efficiency of a geothermal power plant. From an industrial perspective, this objective implies a reduction of costs during both design and implementation phases. Such a goal may be achieved by developing innovative full-cycle prediction models to address one or more of the following issues: (a) coupling the estimate of reservoir potential with near-well phenomena and well-flow stability, (b) assuring flow stability in the distribution network in terms of pressures and temperatures, (c) controlling and predicting scaling or corrosion phenomena in pipelines, (d) estimating various scenarios during the network design in order to achieve optimal network configuration, and (e) controlling and reducing plant emissions and minimising chemical consumption through optimised process control and management, reducing environmental impact.

Current status

Over the past two decades, enormous efforts have been made to understand the mechanisms of energy transport in geothermal piping networks. Several studies have been performed to evaluate, identify and solve issues related to the simulation of heat and mass flow in network and process plants, with emphasis on the following aspects:

- Characterisation of the flow of fluid affected by uncertainties in the basic data of a geothermal well
- Thermodynamic models coupled to the flow of steam
- Models for the flow of mass and heat in geothermal wells

Several computational models of geothermal piping networks have been covered in the technical literature, as well as models related to reservoirs and process plants, including advanced fluid cycles.[15] Conversely, the current state-of-the-art is quite poor when it comes to integrated models covering all aspects of a geothermal installation in terms of physical capabilities, production issues, management operations and production optimisation. Excluding the codes used for nuclear power plants licensing (which are very complex, not available for the market, and heavily restricted in terms of licensing and user qualification), the other tools are limited in terms of physical description and capabilities. They are based on broad simplifications of the real behaviour of components, greatly impacting the accuracy of system design. Most of the models available for geothermal networks are confined to the study of stationary flow, neglecting the ways in

[15] García-Valladares, O.; Sánchez-Upton, P. & Santoyo, E. Numerical modelling of flow processes inside geothermal wells: An approach for predicting production characteristics with uncertainties Energy Conversion and Management, 2006, 47, 1621 – 1643 (doi:10.1016/j.enconman.2005.08.006)
Qing-tang Liu, Zeng-gang ZHANG, Ji-hong PAN, Jing-qiang GUO. (2009) A coupled thermo-hydraulic model for steam flow in pipe networks. Journal of Hydrodynamics, Ser. B Volume 21, Issue 6, 861-866 (https://doi.org/10.1016/S1001-6058(08)60224-3)
B. Hasan and S. Kabir (2010) Modelling Two-Phase Fluid and Heat Flows in Geothermal Wells. Journal of Petroleum Science and Engineering 71(1-2):77-86 (doi:10.1016/j.petrol.2010.01.008)
Eduardo Sanches, Carlos F Torres, Pablo Guillen, German Larrasabal (2013) Modelling and simulation of the production process of electrical energy in a geothermal power plant. Mathematical and Computer Modelling 57(9-10):2140-2148 (doil: 10.1016/j.mcm.2011.03.021)
Mahendra P. Verma, (2013). Steam transport simulation in a geothermal pipeline network constrained by internally consistent thermodynamic properties of water. Revista Mexicana de Ciencias Geológicas, v. 30, núm. 1, 2013, p. 210-221
Huang Yicun and D.H. Freeston (1992) Non-linear Modelling of a Geothermal Pipe Network System - A computer approach to network analysis Proc. 14th New Zealand, Geothermal Workshop
Jason Peluchette and Brian J. Anderson (2013) Optimisation of integrated reservoir, wellbore, and power plant models for enhanced geothermal systems. Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, 2013 SGP-TR-198
James Nogara, Sadiq J. Zarrouk (2018) Corrosion in geothermal environment: Part 1: Fluids and their impact. Renewable and Sustainable Energy Reviews, Volume 82, Part 1, February 2018, Pages 1333-1346 (https://doi.org/10.1016/j.rser.2017.06.098)

which fluid composition, transient operation and interaction with the electrical grid and process plant all impact production. In addition, despite the large amount of available literature regarding the impact of scaling in geothermal pipes and components, and corrosion issues due to aggressive gases, few research initiatives have been carried out to couple the above phenomena with geothermal fluid mechanics development.[16] So far there have been no significant activities or available tools which are well-developed in terms of coupling design, management, and the long-term operation of geothermal plants, which are the strategic points for making geothermal energy more economically profitable, more environmentally friendly and more standardised, leading to easier replication worldwide.

Potential for technological development

The stark differences in terms of temperature, pressure, and chemical composition of the geothermal reservoir when considering the surface equipment (especially when dealing with deep geothermal plants), interactions in terms of physical behaviour and the operational requirements of geothermal installations, the impact of working conditions on component materials, and finally requirements to reduce the environmental impact of these plants, require a predictive capability to address: (i) the multiphase flow behaviour of wells, pipes and other components; (ii) challenges posed by geothermal fluids in terms of component performance; (iii) the impact of new materials, equipment or operative methodologies in future geothermal plants. This aspect is essential for the design and operation of a complex system that integrates these different elements with dynamic behaviour. The integration of several scientific areas which are typically isolated from each other (reservoir, well engineering, fluid dynamic and pipeline transportation, fluid chemistry, power plants and production cycles, safety analyses) will allow identification of interactions, feedback and the impacts of each area upon others. These new insights may help to define new working methodologies and develop new knowledge in order to manage phenomena occurring in the crossing areas and interfaces between geothermal environments. Finally, thanks to a predictive approach regarding the behaviour of a complex system such as a geothermal plant, this will allow the specific efforts of different disciplines to be integrated into a common frame of reference, taking into account interactions and feedback from different production aspects. This approach will boost the design of optimised solutions, especially in the following areas:

- Reservoir management strategies and prediction of production potential
- Aggressive fluid management, equipment protection and emission reduction
- Production system design optimisation and environmental impact minimisation
- Design of unconventional and hybrid systems, and prediction of performance
- Integrated electrical grid power plant design and management
- Cost–benefit forecasting analyses based on a deterministic scenario approach

[16] James Nogara, Sadiq J. Zarrouk (2018) Corrosion in geothermal environment Part 2: Metals and alloys. Renewable and Sustainable Energy Reviews, Volume 82, Part 1, February 2018, Pages 1347-1363 (https://doi.org/10.1016/j.rser.2017.06.091)

TOPIC 11: ENHANCED PRODUCTION PUMPS

Objective

During operation, energy demands for pumping as well as the maintenance and replacement of production and injection pumps can be a burden on overall plant efficiency and profitability. As a result, the overall objective is to improve pump efficiency and longevity, secure production reliability, and develop tools for avoiding two-phase flow in areas such as wells in order to enhance exploitation economics.

The main goals are to:

- Analyse the existing production pump operations of existing geothermal plants in terms of premature failures

- Develop appropriate condition monitoring tools to predict operation failures and optimise Electrical Submersible Pump (ESP) and Line Shaft Pump (LSP) constructions

- Develop new technical solutions and components for ESP and LSP for existing operations up to 140°C, up to 150 l/s and installation depths up to about 900 m in order to reach normal longevity for standard applications

- Improve submersible pump operational efficiencies and longevities, securing sustainable single-phase liquid (i.e. gas/steam free) production at optimum power ratings within the 120-200°C binary cycle geo-power temperature range

- Bridge the higher temperature 200-300°C technology gap expected from oil and gas ESP steam flood practice and LSP in-house manufacturers' experience in addressing sensitive fluid environments.

Current status

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

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

At present, high-temperature serviced ESPs operate at approx. 250°C in steam flooded

horizontal wells aimed at recovering heavy crude via the so called SAGDS (Steam Assisted Gravity Drainage) process. However, it should be borne in mind that (i) power ratings limited to approx. 250 HP, and (ii) the induced motor winding temperature is 300°C. Elsewhere such operating conditions would require considerable efforts to design high-temperature resistant enclosed line shaft/bearing assemblies and stable shaft lubricating mixtures.
Beyond the search for higher temperatures (> 200°C), the booming development of medium temperature (80°C-180°C) resources in combination with large scale district heating and combined heat and power (CHP) production urges the pump industry to solve current technical problems in order to build pumps with a high power rating (1600 HP or more) to cope with a high lift (up to 1000 m) and high flow rates (80 l/s or more). Limitations resulting from the shaft drive have to be solved and a technical solution is needed to avoid permanent lubrication losses.
If the lifetime and power rating were improved, two things would be required in order to achieve production in thermochemically hostile fluid environments; firstly, robust downhole chemical injection lines, and secondly, permission from the relevant authorities to inject environmentally compatible inhibitor agents. Submersible pumping systems being set below the flashing front (i.e. in single phase liquid state, multiphase flow production) would address the issue of two-phase geothermal reservoirs and deserve specific technological research accordingly.

ESP technology

In order to attain optimal conditions, decisive improvements have to be made to the ESP systems that are already operating at deep installation depths and in deep reservoirs with high mineralisation or salinity.

Seal

Within the ESP system, the seal unit plays a crucial role, as it combines the following essential functions:

- Sealing the thermal water from the lubricant
- Transmitting the torque of the motor
- Bearing for axial load from the pump head
- Compensating for the thermal expansion of lubricant
- Allowing outgassing of fission products from oil
- Filtering contaminating sediments from the lubricant

Given that it is still responsible for a lot of pump failures, these functionality criteria have to be implemented into new geothermal pump seal technology. Improvements to existing concepts have proven insufficient, and in light of expectations that future operating conditions are set to become even more challenging, a completely new approach to developing seal units, one that is tailored to geothermal purposes, is required.

Motors

The temperature of the motor can already reach its limit when operating at maximum load with water temperatures between 135°C and 140°C, especially when operating conditions (e.g. scaling) are becoming harsh. Amongst others, there is an urgent need to fulfil the following requirements:

- High-temperature motor operation for deep installations
- Easy maintenance, repairability and handling
- Standardisation of the motor base (for manufacturer-independent utilisation)
- Durable sensor systems for condition monitoring and transmission of operation data
- Reduction of partial discharge and control thereof
- Detection of oil properties

Hydraulic stages

In most cases, the combination of the above mentioned parameters and values do not imply full utilisation of a high-productivity well, although (hydraulic and electric) designs should meet the requirements. Besides other effects resulting from turbulence, gasification and scaling can have a negative impact on production rate. The improvement of bearings cannot be considered sufficient. The hydraulic system has to be re-designed for geothermal applications.

LSP technology

The leading position of LSP on the market is finally being challenged by late-arriving ESP manufacturers, creating competition which is beneficial to the geothermal community. Future R&D developments should be directed towards the dominant high-temperature geo-power sector and related pressurised liquid reservoir settings exhibiting fluid temperatures close to, if not exceeding, 300°C.

Potential for technological development

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

C. HEAT AND ELECTRICITY GENERATION AND SYSTEM INTEGRATION

Introduction

This chapter focuses on energy conversion processes, the surface systems of geothermal plants and the integration of geothermal heating, cooling and electricity supply into the energy system. The challenge here is to maximise generation while keeping costs as low as possible.

Novel technologies should focus on enabling total exploitation of geothermal energy while reinjecting the fluid and balancing the mass underground, thus reducing reservoir geofluid depletion.

A critical priority is also to go beyond conventional generation by exploiting the vast and deep superhot geothermal resources, which are estimated to be 10 times greater than hydrothermal resources and on the same order of magnitude as EGS resources. One potential means of cost reduction for geothermal resources is also the co-production of metal and non-metallic material contained in the geothermal fluids in addition to thermal and electrical energy.

Deep geothermal adds flexibility to the energy landscape of the future. This landscape will be characterised by interconnected local energy grids which are fed by a variety of energy sources and which connect the three energy sectors, i.e. electricity, heating and cooling, and transport. These local grids will be driven by new market models in which the separation between energy producers and consumers will be less sharply defined than it is today.

Geothermal fits into this landscape of interconnected grids with the supply of small and large scale combined heat and power plants, which can fluctuate according to the needs of the heating or power grid to suit determined priorities. It also has a role to play given its potential for developing Underground Thermal Energy Storage (UTES) and for the individual geothermal systems of shallow geothermal. In addition, geothermal can provide the heat, power and carbon required to produce synthetic fuels or base chemicals.

Considering the significant potential of geothermal power production for stabilising the electricity grid, an adaptation from the traditionally base load profile of geothermal electricity production towards flexible production schemes may help to meet the needs of a changing and flexible electricity system and the specific requirements of energy supply to European islands. The priority goals to allowing this potential to be unlocked are the following:

- Demonstrating the technical and economic feasibility of responding to the grid operator's requests, at any time, to increase or decrease output and ramp up and down. Demon-strating automatic generation control (load following/ride-through capabilities for grid specifications) and ancillary services of geothermal power plants. The potential flexibility of geothermal power production should be associated with the concomitant supply of geothermal heat to district heating, agricultural or industrial applications.

- Addressing flexible heat/cold and electricity supply from binary cycles and EGS power plants, including upscaling plant capacity and coupling with other renewable energy sources.

- Addressing the specific problems of geothermal power production in isolated energy networks (islands), such as grid infrastructure and demand-side management.

- Integrating thermoelectric energy storage with district heating networks and dedicated equipment (e.g. heat pumps, ORC turbo-expanders, and heat exchanger networks, with hot and cold reservoirs able to cover variable demand of heat, cold and electricity).

In order to enable the achievement of this potential, it is also necessary to develop adequate transmission and distribution infrastructure and to interconnect this with other flexibility options (e.g. demand-side management and storage), and to test dispatchability. Furthermore, flexible generation should be able to provide additional services to the grid such as peak power, playing a role in electricity balancing/the reserve market.

Targets

- Increase efficiency and reduce losses and internal consumption as part of energy conversion processes

- Improve the reliability and durability (resistance to corrosion, abrasion) of surface system equipment

- Reduce the overall cost of heat and power generation

- Adapt plants to be base load and dispatchable in order to facilitate larger shares of renewables in the energy system and improve integration of geothermal energy through an enhanced interaction with energy storage, demand response and smart interconnection with other technologies.

TOPIC 1: ADVANCED BINARY PLANTS

Objective

The objective is to develop advanced low to medium temperature binary plants. On the one hand, the goal here is to minimise second-law efficiency losses. On the other hand, from a techno-economic perspective, the cost-efficiency pursued depends upon the economics of each project. Consequently, the primary aim is to develop techno-economically tailored solutions which reduce overall plant costs or maximise plant efficiency. Moreover, since the thermal source is continuously available, reliability, availability and grid-balancing flexibility are key factors reflected in the implementation of redundancies for critical items and the use of high quality components.

Current status

According to the second-law analysis (the most powerful tool for understanding the rationale of a power cycle and the potential efficiency gains that can be achieved in relation to a well-defined ambient environment and a resource at a given temperature), currently installed binary plants are close to the maximum efficiency, reaching almost 75% when exploiting fluids at different pressure levels with cascaded heat transfer processes. Pushing plant efficiency to its highest level however is not recommended, as it would lead to cost increases jeopardising project feasibility.

At the present time, most of the installed geothermal binary power plants utilise hydrocarbons as working fluid, and because of European and Local regulations on the amount of flammable fluid employed, technology providers must provide technical solutions that face significant constraints in terms of engineering the size and features of technical components which include auxiliary systems when addressing challenges such as firefighting and operational issues. In fact, there are only few geothermal power plants installed which use organic non-flammable working fluids, i.e. refrigerants. The number of installed geothermal plants utilising such working fluids could only increase as a result of technical and commercial development of new and more readily available refrigerants.

The current state of the art includes supercritical cycles, with some examples using CO2, even if none of the available working fluids respond to the required boundary conditions, i.e. the geothermal resource does not allow the critical temperature of the working fluid to be reached. In fact, thermal efficiencies are very low because of the small temperature difference between hot and cold sources. As it stands all of the projects employing CO2 as working fluid are in an R&D phase and are receiving funding through specific research programmes. In addition, R&D examining the use of hybrid renewable systems that could significantly improve thermal efficiencies is underway.

Potential for technological development

Energy cost reduction for binary systems will be achieved by:

- Reducing the plant footprint and the overall plant costs, thanks to the development of new geometries and arrangements together with the employment of more cost-effective and specific materials for each plant component

- Increasing average turbine efficiency throughout continuous development in the Computational Fluid Dynamics (CFD) technology

• Increasing net cycle efficiency with the use of new fluid mixtures both in subcritical and supercritical configurations

• Reducing thermal waste without increasing either the number of rotating components or plant complexity by designing new multilevel configurations which also enable a reduction of the irreversibilities between the thermal cycle, the resource, the environment and the end use

• Reducing Balance of Plant (BOP) costs

• Upscaling the capacity of power and heat plants

Technological development aiming to improve plant performance should focus on the working fluid, which is one of the most impactful variables in the thermodynamic balance.

Features to be considered for these improved fluids are:

• Saturation conditions

• Thermal stability

• Flammability

• Explosivity

• Low Ozone Depleting Potential (ODP)

• Low Greenhouse Warming Potential (GWP)

• Cost reduction

Given a wide range of working fluids to choose from, the versatility of the Organic Rankine Cycle (ORC) could be enhanced, and boundary conditions that were previously incompatible with techno-economic feasibility could become exploitable.
Disruptive solutions such as gas-lift or other non-conventional systems could play a game-changing role in increasing the amount of primary energy available for power production processes.
Another technological challenge is improving specific components of the binary cycle: designing an improved heat exchanger, selecting material, surface structure and coating to enhance heat transfer and minimise scaling, increasing cooling system efficiency by improving the air-cooler/condenser, and matching in order to cycle the efficiency of components (also developed in other topics below); hybrid cooling of binary cycles working with low temperature geothermal sources, and integration with heat or cold supply via novel cascading concepts. Lastly, a standard technology which is suitable for limiting the release of Non-Condensable Gases (NCG) could reduce the overall carbon footprint of geothermal binary plants.

TOPIC 2: INNOVATIVE DESIGN AND INTEGRATION OF BINARY CYCLE TECHNOLOGY INTO NEW AND EXISTING FLASH PLANTS

Objective

The goal is to improve geothermal heat to power conversion efficiency via the integration of binary plants as bottoming units to geothermal flash plants. An initial step is to demonstrate a reliable combined flash-binary plant featuring improved conversion efficiency, with reduced costs and a flexible power output which can be remotely controlled by the grid operator. The long-term aim is to have all geothermal flash plants equipped with bottoming binary units.

Current status

Binary plants have been traditionally integrated into flash plants as bottoming units, either at the steam loop after the turbine exhaust or at the separated brine line. These kinds of flash-binary configurations allow higher heat to power conversion efficiency than single or double flash plants, and allow better handling and control of non-condensable gasses. In addition, such plants can be modified to continuously and rapidly adjust their power output to respond to changes in grid requirements.
Despite these benefits, there are currently only a few binary plants which have been integrated as bottoming units into flash plants. The main reasons are the much higher costs of binary plants (ranging typically from 1500 to 3000 €/kWe in capital cost with an average of 1.70 c€/kWh€ when operational) compared to second flash unit plants (from 600 to 1100 €/kWe in capital cost with an average of 1.28 c€/kWh(e) while operational), the lower capacity of the binary plants in comparison to flash plants, and the additional scaling that occurs at the resulting lower brine reinjection temperatures.

Potential for technological development

Technological improvements should aim at removing market penetration barriers for the integration of binary systems into flash plants. Key challenges include the effective reduction of costs, increasing binary plant capacity, developing control methods for grid integration according to instant load requirements, and remote control by the grid operator, as well as establishing standard scaling inhibition methods for the integration of binary plants into flash plants.
At component level these methods may include reengineering materials, turbine and lubrication systems, cooling systems, integrated power plant automation, fluid handling and scale inhibition systems.
Large scale market penetration can be facilitated by studying, evaluating and optimising alternative concepts and developing the business case.
Advanced integration of conventional (steam) geothermal power plants with binary power plants in order to optimise geothermal brine usage.

TOPIC 3: HIGH-TEMPERATURE BINARY POWER PLANTS

Objective

The objective of this topic is to extend the application of binary plant technology to the exploitation of high-temperature geothermal resources in such a way that, in comparison to the conventional, widely adopted technology of flash steam, a more environmentally friendly and cost-effective exploitation of these kinds of resources can be achieved.

Binary plants are more environmentally acceptable than any other kind of geothermal power plant because the geothermal fluid can be segregated throughout the whole process, from the production well to the reinjection well. In this way, the release of gases or other potentially unfavourable substances into the environment can be largely prevented, thus limiting and in many cases eliminating pollution problems. Moreover, if no condensate or liquid fraction of the geothermal fluid is used for heat rejection to the ambient, full reinjection of the geothermal fluid is feasible, and no depletion of the geothermal reservoir occurs.

Alongside positive environmental performance, increasing energy conversion efficiency and improving the cost-effectiveness of binary plants remain fundamental objectives. Moreover, new material solutions are needed in order to cope with scaling and corrosion issues, such as the development of high resistance materials, functional coatings, or filming corrosion inhibitors which would then be required for all surfaces coming into contact with the geothermal fluid.

Current status

Binary technology for high-temperature applications such as biomass and waste heat recovery is currently in use and considered "state of the art", with more than 400 plants in 40 different countries. For geothermal applications, however, Organic Rankine Cycle (ORC) technology has traditionally shown to be applicable for electricity generation with low-temperature resources (close to 90-100 °C), and to involve a definite thermodynamic advantage (in terms of achievable power production) compared to conventional flashed steam cycles for resources at moderate temperatures (up to 150 °C).

Production of electricity from high-temperature geothermal resources (higher than 180°C) shows a range of efficiency between 14.5% and 19.5%, depending on the area of production, the thermodynamic properties of the steam, the average age of the plants, their manufacturer, and so on. Taking a weighed average of the data, 16% is a reasonable estimate. In the range 150-170°C, binary technology is used often but not exclusively, with a gross efficiency reference value of 11%.

At higher temperatures, (i.e. temperatures T > 180 °C or enthalpy 1500 kJ/kg), the resource is typically steam dominated, and the decision to select binary technology, which has occurred only very rarely (e.g. Las Pailas plant, Costa Rica), implies the use of a so-called high-temperature/high-enthalpy binary plant with a somewhat different plant scheme and the following features:

- It is capable of exploiting both separated hot brine and steam (two phase flow)
- It allows for zero-emission operation if no geothermal fluid is used for the heat rejection process, and full reinjection of geothermal fluid and gases is possible
- It does not deplete the geothermal steam, unlike traditional single flash plants

• It can provide energy to the grid sooner, thanks to the faster implementation time

• It can be relocated as it does not have a complicated steam gathering system and can be assembled in a modular fashion

• It has a low requirement for land (wellhead generation)

• Is a stable base-load energy generation system

• It can be operated in remote areas and with isolated grids

• It is scalable to utility size (thanks to modular technology)

Potential for technological development

Increased energy efficiency and cost-effectiveness must be pursued while at the same time assessing potential risks and solving problems which could occur due to the unusually high temperature and chemistry of the geothermal fluid.

By exploiting high-enthalpy, steam-dominated resources, a benefit of binary technology is that, while traditional flash steam power plants exploit only the steam fraction of the geothermal flows, binary can use also the liquid fraction in order to increase the specific utilisation of the resource. Power plant layouts and material selection for the components need to be carefully considered, however, in order to exploit the whole resource potential.

Thermodynamic cycle optimisation typically involves minimising second-law losses, i.e. ensuring a good match between the steam and brine flow on the one side and the ORC working fluid on the other side. In the field of conventional binary applications, the geothermal fluid is generally a completely liquid source, but at high temperature it is likely to be a two phase mixture, with non-condensable gases in the gaseous flow, requiring a much more sophisticated optimisation and an appropriate power plant layout. The investigation of the geothermal fluid chemistry and its properties is crucial for the successful design of the power plant. If NCGs are present, they must be considered as part of the heat exchangers' design process. A number of series and parallel preheating heat exchangers are a suitable method of extracting heat from the steam, which is then condensed and cooled down to reinjection temperature, i.e. the lowest allowable temperature compatible with possible scaling problems. In ORC plants, the reinjection brine temperature can also be maintained above the saturation level before scaling can occur, by means of a recuperative cycle requiring a properly designed internal heat exchanger (recuperator). Another important issue is the cycle working fluid: knowing that eligible cycle working fluids are selected according to the geothermal source temperature, innovative working fluids may be required to fulfil high-temperature applications; investigation is needed to define the fluid characteristics (above all thermal stability and thermodynamic properties).

A binary plant can be efficiently operated, maintaining the geothermal fluid at high pressure in order to avoid scaling in the production well. However, performance can be more efficient in comparison to a flash plant only if a significant portion of heat is extracted from the separated brine. Depending on the brine chemistry, however, this does pose a risk of silica (or other species, e.g. stibnite) precipitation occurring, as the saturation condition of the brine may be encountered at low temperatures. Finally,

another challenge is the possible corrosion that may occur in the pipelines or the heat exchanger tubes of the power plant: high resistance materials, adequate coatings or filming corrosion inhibitors are therefore mandatory for the components in contact with the geothermal fluid, in order to ensure long-lasting operation and high availability of the components.
In light of the above, efficient exploitation of the high-temperature binary plant is possible only with a carefully and thoroughly designed plant, in-depth investigation of the geothermal fluid chemistry, the adoption of suitable high resistance materials to prevent corrosion, and the implementation of a scaling mitigation procedure (e.g. by means of scaling inhibitor dosing or pH control, or designing the system to remain above the saturation point).

TOPIC 4: POWER CYCLES AND MITIGATION FOR SUPER HIGH-TEMPERATURE RESOURCES, HIGH-ENTHALPY STEAM DIRECT EXPANSION

Objective

The goal is to develop the necessary technology for surface and power plant installations that will allow the exploitation of superhot geothermal systems (magma, partially molten rock and/or supercritical geothermal resources).

Current status

Superhot geothermal resources are magma and/or supercritical geothermal systems that have much higher enthalpy and pressures than the geothermal systems currently being utilised to generate electricity today. They are encountered amongst young volcanic rocks along plate boundaries and at hot spots, near still-hot and/or partially molten igneous intrusions, and at the roots of well-established high-enthalpy geothermal fields.
A superhot geothermal well needs no downhole pumps due to high-enthalpy steam direct expansion and condensation, which has much higher heat to electricity conversion efficiency due to its favourable thermodynamic conditions. It results in less geothermal energy production costs due to economies of scale at well level, as it delivers 10 times more energy than a typical high-enthalpy geothermal well.
At present, superhot geothermal resources have been tapped in a few places in Europe and worldwide, but no exploitation is taking place due to the highly corrosive and abrasive nature of the produced fluids attributed to entrained acid gases (HCl, HF, and H2S) coupled with silica scaling and erosion. The most advanced project is the IDDP-1 in Krafla, Iceland, where wet scrubbing for steam purification (so that it can be utilised for power generation) has been tested on the surface by several experiments using groundwater or steam condensate with or without alkalis and alkaline brine, the longest of which lasted for 14 days. The improvement of this basic idea by the IDDP is to produce water at supercritical conditions and bring it to the surface as 400-600°C superheated steam at subcritical pressures (<220 bar). The IDDP-1 well had to be abandoned following the failure of key surface equipment (master valves) due the severe pressure, temperature and fluid conditions prevailing at the surface (temperature ~ 470 °C and pressure ~180 bar flowing). Further research is ongoing, with the new IDDP-2 project in Iceland and in Larderello, Italy, where temperatures and pressures above the supercritical condition have been accessed.

Potential for technological development

Key challenges for further technological development are:

- Demonstrating reliable fluid treatment and steam purification methods, so that the purified steam can be delivered to the turbines in order to generate electricity

- Demonstrating reliable surface equipment suitable for commercial exploitation

- Demonstrating reliable electricity generation from a superhot geothermal well

- Demonstrating the wet scrubbing steam purification method during power generation

- Further field experiments and demonstration should also include:
    - Optimisation of the wet scrubbing method in terms of scrubbing water chemistry, heat recovery and step power generation in order to improve overall heat or power conversion efficiency

    - Downhole wet scrubbing in order to alleviate the severe fluid conditions prevailing at the surface and increase the reliability of surface equipment

    - Dry scrubbing, as this is the fluid/steam purification method resulting in the highest power plant energy efficiency

    - Testing or development of new materials and corrosion-resistant surface equipment for extreme high temperature and pressure operation

TOPIC 5: FLEXIBLE PRODUCTION OF HEAT AND POWER

Objective

Given the growing share of intermittent renewable power production, particularly in terms of priority access to the grid, other types of plants will increasingly have to provide fluctuating back-up power to meet unpredictable demand and supply peaks. Geothermal plants can play an important role in providing back-up power by adjusting power production within various response time-frames in order to assist in stabilising the grid. In contrast to intermittent RES, deep geothermal energy can be used continuously throughout the year as it generates an output which is almost independent of the weather conditions. In order to react to a grid's requirements, however, the geothermal plant needs to be transformed into a flexible plant.

The design of most existing binary geothermal power plants has been optimised for electricity production exclusively. Depending on the market prices for electricity and heat, it is possible to improve the economics of low-temperature geothermal power plants by using part of the heat directly. Nevertheless, it is expected that a somewhat reduced heat-to-electricity conversion, together with the "recovery" of the higher-temperature "waste" heat in a combined Heat and Power (CHP) configuration will result in better economics and higher exergetic efficiency. However, in most cases, heat demand fluctuates strongly throughout the year, meaning that a flexible CHP plant that can fulfil varying heat-demand is called for.

Current status

As it stands the majority of the Organic Rankine Cycle (ORC) systems are largely not very flexible since they are only efficient in one or a few operating points – the maximum power point. As a consequence, they can only convert heat into electricity at a fixed quantity and with a fixed conversion rate. The second disadvantage is due to the tight coupling of power with heat production. The ORC turbine is treated as a sub-system of the heat and power plant and it is integrated into its control system without connection to the overall energy grid. It can therefore only be operated according to heat provision, and not according to the heat and electricity demand within the overall energy grid.
Some manufacturers are starting to begin research and development to increase the flexible operation of the ORC based on novel or adapted turbines and expanders, or instead taking a more modular approach (smaller, cascaded, and controlled units).

Potential for technological development

Increase the flexibility of electricity production from geothermal wells by:

- Adapting the expanders/turbines and other components to increase flexibility, moving towards electricity production coping with the needs of the electrical and thermal network in a cost-effective way

- Improving the modular design of power plants to better adapt to electricity needs and heat demand without reducing overall electrical efficiency and annual production

- Optimising the connection configuration between the geothermal source, the binary plant and the district heating network (e.g. parallel connection, serial connection, combinations, etc.) in order to increase electricity production, taking into account the heat profile and temperature regimes of the district heating network

- Generating different voltages for smart grids with specific applications, such as for an island or island mode, is key for flexible geothermal power production

TOPIC 6: HIGH-TEMPERATURE THERMAL ENERGY STORAGE (HT-TES)

Objective

Thermal energy storage can play an important role in levelling out the mismatch between (electricity and heat) production and demand. Until now, most power plants do not include storage. Both low and high temperature systems can play a role in thermal energy storage.

The goal of this topic is to highlight the technical challenges and potential of HT-TES, and provide site-specific solutions for its implementation in different application scenarios. This will be achieved by developing technologies and workflows to reduce costs and improve heat-storage and production performance, combining surface structures (i.e. waste heat source, heat exchangers, distribution network systems including different energy storage technologies and advanced demand-side management) and subsurface characterisation and management (i.e. reservoir modelling, tracer tests, drilling and well integrity preservation) into a unique source-to-sink system.

Current status

The deployment of renewable energy sources for both power and heat production is accelerating in Europe. This trend is expected to continue. However, variations in both energy availability and demand and their integration into the existing energy infrastructure pose challenges in terms of operational variability and balancing. Peak shaving and heat storage can help to balance demand and supply in order to make better use of infrastructure and assets (e.g. increase full-load hours for geothermal heat sources). Thermal energy storage can be a flexible solution to be implemented and integrated into existing heating networks in the form of Underground Thermal Energy Storage (UTES), tank and pit storage using different storage media, and storage in the building mass or the District Heating infrastructure itself. Different types of electric storage and power/heat-to-gas/fuel conversion would further increase the system's flexibility.

The different types of TES can contribute to developing innovative projects for Combined Heat and Power (CHP), coupling geothermal to fossil fuel power stations and renewable energy sources such as PV or waste-to-power plants. Moreover, TES can contribute to reducing greenhouse gas (GHG) emissions into the environment, both by partially replacing fossil fuels and by developing solutions for coupling CO2 capture and heat storage.

UTES applications cover a wide variety of opportunities: ATES (Aquifer Thermal Energy Storage), BTES (Borehole Thermal Energy Storage), PTES (Pit Thermal Energy Storage), TTES (Tank Thermal Energy Storage), and MTES (Mine Thermal Energy Storage) systems. These systems rely mainly on rather low temperatures and shallow depths for local uses. High-Temperature UTES (HT-UTES) covers the 25-90°C temperature range, and the targets of interest can reach up to 2000 m in depth.

The development of UTES is linked to a multidisciplinary understanding of the whole system, including waste-heat source, exploration and subsurface characterisation, production, implementation, and distribution systems, as well as the adaptation of the regulatory framework and social acceptance.

The recently approved ERA-Net GEOTHERMICA HEATSTORE project is an excellent example of how all these tasks will be tackled by a transnational consortium of 24

groups from 9 countries, in order to provide practical solutions for the implementation of P&D projects in different contexts.
A wide variety of materials can be used for thermal energy storage. TES materials must possess suitable thermo-physical properties such as a favourable melting point for the given thermal application, high latent heat, high specific heat and high thermal conductivity. Other desired properties of thermal energy storage materials include low supercooling, low cost, easy availability, thermal stability, chemical stability, low volume change, non-toxicity, low vapour pressure, congruent melting and low flammability. TES systems can be broadly classified into three categories based on the type of TES material being selected for heat or cold storage: sensible heat storage, latent heat storage and chemical heat storage systems. Geothermal power plants are not yet equipped with thermal energy storage. Proper storage types for geothermal plants in the short term are sensible heat storage (water, thermal oil, etc.) and latent heat storage.

Potential for technological development

Potential technological development covers two aspects:

- Integration of thermal energy storage to cope with daily, weekly and seasonal variations in heat demand and available heat from the geothermal power plant

- Development of appropriate control systems to manage heat and electricity production, heat demand and storage connected to the installation. Use of both the flexibility of the centralised thermal energy storage systems and flexibility in the network (e.g. thermal use of building mass, water storage tanks, electrical cars, etc.). Connection with the district heating controller, process controller, grid controller and market interface.

In terms of production, HT-UTES faces many challenges shared by other well-established industrial geothermal applications such as heat production from sedimentary aquifers and power generation in general. The main technical challenges can be summarised as follows:

- Adapting the return temperature from the surface site to the subsurface temperature and to the regulatory frameworks

- Identifying, characterising and monitoring reservoirs for UTES

- The geo-mechanical effects of the reservoir linked to the seasonal injection/production operations

- Characterising and monitoring water-rock interaction at reservoir level

- Hydrogeochemical problems associated with scaling and corrosion of the piping system

- Integration of a medium/long term storage system in compliance with the technological and economic constraints of the plant

- Design and optimisation of the distribution network

TOPIC 7: DEVELOPING HYBRID PLANTS

Objective

he goal is to improve the coupling of geothermal energy with other renewable energy sources and waste heat in both hybrid plants and new combined heat and power plants:

- By combining the generation technologies of different profiles at one production site, energy availability is increased and energy intermittency reduced. At the same time, sharing existing infrastructure reduces costs and the plant's environmental impact per unit of energy produced and delivered.

- By coupling geothermal energy with other renewable sources, the supply temperature can be increased, making low temperature geothermal power plants feasible.

- By combining geothermal heat with other heat sources, smart thermal grids can be created.

The goal is also to demonstrate the technical and economic feasibility of responding to commands from a grid operator at any time.
Research priorities concern:

- Reducing heat loss in new and existing District Heating and Cooling (DHC) networks and low temperature DHC networks

- Advanced integration of geothermal power plants with other renewable sources

- Integrating conventional and binary geothermal power plants

- New technologies for direct energy production from unusable steam or water.

Current status

Geothermal and solar (thermal and photovoltaic) are complementary, meaning that production from solar is higher during the sunniest and hottest days of the year, when the thermal efficiency of the geothermal plant is lower. The increased delivery of power during peak hours also enables a more load-following production profile.
Cove Fort, Utah, is the world's first large scale power generation facility to successfully combine geothermal with hydropower technology: Enel GP added fully submersible downhole generator technology to a geothermal injection well, combining geothermal and hydroelectric power at one site. Cove Fort began operation in 2013 and can generate up to 160 GWh of energy per year: the new downhole generator adds an additional 5 GWh per year.
The Stillwater solar geothermal hybrid project located in Fallon, Nevada (USA) is the first plant in the world to combine the continuous generating capacity of medium temperature, binary cycle geothermal power with solar photovoltaic and solar thermal. Between 2012 and 205, Enel GP added a 26.4 MW solar PV unit to the geothermal plant and developed a solar thermal system to operate in conjunction with the existing Stillwater geothermal power station. It combined three renewable sources at the same location for the first time. Research findings between March and December 2015 confirm that the combination of a 2 MW solar thermal facility with a 33.1 MW geothermal plant increased

overall output at Stillwater by 3.6% compared with production from geothermal only.
Cornia hybrid biomass/geothermal: In 2014, Enel GP built a hybrid biomass extension for one of its plants, an extension to the Cornia 2 geothermal plant in Tuscany, Italy. This plant works as supplement to an existing industrial site, and the 5 MW of capacity from biomass will be added to a geothermal plant that currently has an installed capacity of 13 MW. The geothermal plant's annual power output is therefore enhanced by around 30 GWh. The extension feeds from biomass from nearby forests. The steam entering the power plant is heated from an initial temperature of between 150° and 160° C to 370°-380° C, increasing the net electricity generation capacity thanks to both the increased enthalpy of the steam and the improved efficiency of the cycle, the latter of which is due to lower moisture levels during generation.
District heating and cooling systems which currently combine different sources, including geothermal, already exist but not as part of a smart thermal grid.

Potential for technological development

The development of this technology covers the following areas:

- New and unprecedented plants using residual heat or non-geothermal RES to increase the temperature of the geothermal brine

- Using geothermal to stabilise the supply of variable sources: Hybrid plants (e.g. com-bining geothermal with waste heat, biomass, concentrated solar thermal or green gas) can optimise efficiency, repeatability and consistency, while minimising the uncertainty of well heat flux when ordering the surface equipment

- Demonstrating the applicability of geothermal combined with other sources for district heating and cooling at industrial and/or residential sites, including the use of high-temperature heat pumps and Underground Thermal Energy Storage (UTES) at elevated temperatures, and for integration into smart thermal grids.

TOPIC 8: EXPLOITING MINERAL PRODUCTION FROM GEOTHERMAL SOURCES

Objective

The objective is to develop novel and potentially disruptive technological solutions that can help satisfy European needs for energy and strategic metals as well as other economical non-metallic materials in a single interlinked process. Geothermal plants can optimise the production of both energy and metals/materials according to market demands by exploiting deep geological formations. The exploitation of mineral production can also help geothermal plants become more economically competitive.

Current status

Several pilot plants worldwide have been built to extract salts, silica, lithium and specific metals from brines, but industrial production has only taken place at a few locations and has been limited to the production of silica, Li, Br, J and Sn. In most cases, however, brines have been regarded as wastewater either requiring treatment to meet the imposed environmental discharge limits, discharged as is, or left to evaporate, instead of being regarded as a source for non-metallic and metal elements. This is mainly due to the dilute metal concentrations of the brines, as well as their complex nature. High metal concentrations (e.g. >10 mol/m3) can usually be handled with conventional physicochemical, adsorption and electrochemical separation technologies. Dilute metals in solutions, on the other hand, require special methods. Moreover, geothermal brines are complex mixtures that make removal of specific components difficult.
A European project, CHPM2030, is currently working on the exploitation of mineral production from geothermal sources. Their first results include the following elements: Different technologies are being used or investigated for metal removal from aqueous matrices, like biological treatments, membrane processes, advanced oxidations, chemical and electrochemical methods. More conventional methods include ion exchange, reduction, oxidation, solvent extraction, precipitation, electro-driven separations and adsorption. These technologies are typically investigated at relatively low temperatures (~50-60 °C) whereas deep geothermal fluids are typically in the range 70 - 300 °C. Hence, there is substantial scientific and engineering knowledge to be gathered in order to advance to more industrially relevant conditions for metal recovery of geothermal fluids. Each of these methods also needs further development to integrate them into geothermal plants, to increase the separation efficiency, to enlarge the capacity, to improve selectivity and to lower the separation cost. Moreover, new solutions may be developed that transform the extracted components into more valuable forms, adding to the economic profitability of the recovery process.

Potential for technological development

The following technological developments are envisioned with respect to recovering chemical components from geothermal brines:

- Increasing the selectivity and efficiency of the separation techniques

- Developing new, potentially disruptive technologies to separate and transform chemical components from geothermal brines into more valuable products

- Developing technologies that take advantage of the chemical energy potential of geothermal brines

The following developments are envisioned with respect to integrating separation technologies into geothermal plants:

- Extending the operation conditions of existing separation technologies to the pressure and temperature conditions of geothermal plants

- Developing technical solutions to increase the separation capacity in order to deal with the high flow rates typically encountered in geothermal plants

- Developing conceptual designs for a new type of future facility that is designed and operated as a combined heat, power and mineral extraction system from the outset

TOPIC 9: GENERATING AT DIFFERENT VOLTAGES FOR SMART GRIDS

Objective

The objective is to integrate geothermal power plants into a redesigned electricity system using smart grids. Geothermal power plants need to generate electricity at different voltages: high and medium-low voltage. The aim is to develop geothermal systems able to tackle the following issues:

- Transmission grid: balancing supply/demand and frequency control at various time scales, transmission grid line congestion

- Distribution grid: voltage control issues

The research priorities are the following:

- Developing systems for high and medium-low voltage, while being able to offer ancillary services

- Medium/Long-term Energy Storage (heat/electricity, hydrogen) coupled with geothermal power plants in order to support smart grid ancillary services

- Digitalising geothermal power plants to support operation, maintenance, and integration into smart grids.

Current status

Typically, geothermal power is used as a base load for the supply of electricity in the grid. The power transformer transforms the voltage from the generator to the required voltage necessary to connect to the distribution/transmission network. Flexible operation of geothermal plants is not a part of current operation modes, as it can compromise the well field and the steam production equipment. Besides, current regulations and market strategy allow for the full load operation of geothermal power plants.
Current geothermal power plants are not equipped to operate in flexible mode nor to

deliver ancillary services. Voltage control is one of the ancillary services required to maintain reliable operation of an interconnected transmission system. Other kinds of ancillary services include scheduling and dispatch, reactive power, loss compensation, load following, system protection, and energy imbalance.

Potential for technological development

Several developments are required:

- Development of a power system converter and a corresponding control system allowing flexible geothermal systems to connect geothermal plants to the low-voltage and medium-voltage grid

- Integration of medium/long-term storage systems (both electrical and thermal) in order to comply with plants' technological and economic constraints (see also Topic 6: High-Temperature Thermal Energy Storage)

- New concepts for small and distributed geothermal power plants using small and waste streams, to be connected to a low voltage network, and creating a geothermal district for electricity and heat production

D. FROM R&D&I TO DEPLOYMENT

Introduction

Introducing and deploying deep geothermal technologies at large scales entails a number of technical and non-technical challenges, notably as regards their initial high investment cost, the acceptance of technologies in the developing areas, the involvement of consumers in the production chain so as to enhance the role of prosumers, and the legal and financial barriers. The aim is to develop regulatory, financial, political and social solutions that can be implemented in order to overcome barriers to deploying innovation in the sector, as well as barriers to the broader deployment of geothermal energy solutions and their increased uptake all over Europe. This must be done in parallel to the technological research described above if geothermal energy is to be one of the main contributors to European climate and energy targets.

Harmonisation or the exchanging of best practices for administrative procedures are required, in addition to a stable and reliable policy framework, if the investor and end-user confidence is to increase. The sector's growth also requires positive and effective communication amongst stakeholders in order to build up geothermal systems which are sustained by all participating actors.

Nowadays, market conditions in the EU electricity and heat sectors prevent geothermal from fully competing with conventional technologies which have historically been developed under protected, monopolistic market structures where cost reduction and risks were borne by consumers rather than by plant suppliers and operators. The internal market is still far from transparent. Firstly, electricity and gas prices are regulated in many countries, meaning that they do not reflect the full costs of generating electricity and/or heat. Secondly, there is a lack of market transparency, including a lack of information provided to customers and tax-payers in addition to clear billing. Support measures for geothermal technologies are therefore required in order to favour progress towards the cost-competitiveness of a key source in the future European energy mix and to compensate for current market failures.

It is also necessary to go beyond the 'one-size-fits-all' approach. The development of geothermal energy is driven by a number of interacting factors and the relationship between market and policy can be critical. For instance, electricity can be produced from geothermal resources through many different processes and with varying efficiency. Recently demonstrated geothermal technologies such as EGS will become competitive in a near future. However, policy recognition of all these differences and variations is somewhat lacking, resulting in the design of generalised incentives which do not reflect the large variety present in the scale of the technology, final utilisation, or degree of maturity. This means that incentives may ultimately fail to provide any real benefit for geothermal actors. A different approach is therefore needed so as to tailor the market and policy environment to a suitable model which optimises the development of geothermal resources.

Smart, sustainable and inclusive geothermal energy growth, following the aims of the Europe 2020 and 2030 strategy, should be centred around the concept of improving quality of life, quality of the environment and social inclusion, as well as cohesion and solidarity within and amongst EU countries. The environmental and societal aspects involved in the deployment of geothermal systems, which are reaching the same level of importance as economic and technical aspects within the energy debate, are currently subject to very little monitoring, organisation, and communication. The proper management of these aspects requires administrative procedures which are harmonised at EU level. The Deep Geothermal sector also aims to guarantee the protection and empowerment of customers, offering them meaningful and efficient choices, expecting their increasing participation in the market both as consumers and prosumers, and embedding procedures for public engagement when designing geothermal energy systems.

The smart and sustainable use of geothermal energy also implies maintaining and optimising the value of products and materials. This concept of the "circular economy" means that waste and resource use are minimised and that resources are kept within the economy when a product has reached the end of its life, so that it can be used again and again, creating further value through the more efficient production and use of goods and services, with the aim of increasing the resilience or sustainability of these resources.

As international competition increases, maintaining European technological leadership is key to preserving the current competitive advantage in the sector. In this respect, ensuring access to first-class skills and human resources is also key to further geothermal developments in the future. As the total installed capacity grows, there will be a new need for human resource development within the geothermal energy sector. This skills shortage across the whole geothermal value-chain will become the greatest source of new geothermal energy jobs.

Targets

- Set ambitious policies at EU and national levels to allow the development of the geothermal market and the penetration of innovation in the sector

- Adapt policies and markets. Research and assess the economic incentives and support mechanisms for geothermal (as well as legal and regulatory frameworks) that will enable fast deployment at a low price

- Minimise the uncertainty associated with geothermal energy by addressing and quantifying exploration risk, and develop financial tools that help mitigate such risks

- Integrate geothermal into the natural environment

- Comply with the European concept of the "circular economy"

- Ensure public engagement and acceptance. Further research is needed to understand the drivers of public engagement and develop a more effective way to communicate key aspects for public acceptance such as environmental and economic elements

- Ensure access to first-class skills and human resources and consolidate the scientific base for geothermal energy in order to cement progress and educate the next generation of geothermal pioneers

TOPIC 1: SETTING THE RIGHT POLICIES

Objective

In order to develop deep geothermal in Europe, whether for juvenile or mature national markets, geothermal stakeholders need a European and national political framework for the short, medium and long term, which:

- Sets up a level playing field at the European and national levels in order to help the development of geothermal energy in Europe, therefore allowing for overall consistency with the vision for geothermal energy in Europe

- Has a clear understanding of the agenda for the development of geothermal energy at EU and national level and commits to the harmonisation of policies and regulations on deep geothermal

- Establishes dedicated policies that allow 2050 Paris climate objectives to be achieved through the use of carbon-free technologies in the energy supply such as deep geothermal

- Establishes a long-term vision and strategy for the development of deep geothermal in Europe

- Defines the role of geothermal within the energy system, notably in the electricity market and the supply of heating and cooling
  For the 2020-2030 framework, reference would be made to geothermal in the National Climate and Energy Plans (NECPs).

Current status

In terms of policies and regulations contributing to the development of geothermal energy, there are European (and some national) climate and energy frameworks established for 2020, 2030 and 2050. In addition, at the European level, there is a long-term objective to reduce emissions by 80% to 95% by 2050, to which the Paris agreement adds the objective of achieving carbon neutrality by the middle of the century. This long-term objective is being pursued through intermediary targets, notably for 2020 and 2030. These targets are the cornerstone of the support schemes and focus given to RES which has enabled the recent development of geothermal energy in Europe over the past decade.
While there are few records of existing welfare analysis specific to geothermal energy, there is a significant body of existing literature addressing welfare analysis for other renewable energy sources. These studies are mostly qualitative, which makes quantitative assessments and comparisons with geothermal difficult.
The consideration of societal benefits is of paramount importance to welfare within the current organisation of energy markets in Europe, in which the market price, settled at the marginal value, does not enable the recovery of investment costs, particularly for renewable energies with high CAPEX and low OPEX. A comprehensive knowledge of the external factors would considerably help the design of appropriate support schemes.
As regards the identification of the regulatory and policy framework for deep geothermal, the current status has been presented by GEOTHERMICA and its predecessor Geothermal

ERA NET projects, as well as the EU projects GEOELEC and GEODH. Building on this work, the mapping of EU and national policy and regulations carried out by the ETIP DG project is another valuable publication.

Potential for technological development

In order to attract the attention of decision makers, and particularly to get them dedicating resources for technological R&D&I on geothermal energy, it is valuable to provide evidence of the benefits of geothermal energy. With this in mind, four research priorities have been identified:

1. Developing a welfare analysis of the increase of deep geothermal energy in the energy mix through a comprehensive assessment of the impact of geothermal energy on economic growth, social welfare, employment, environmental benefits (LCA: life cycle assessment), and trade balancing

2. Screening and mapping, exchanging and replicating best practices on policies relevant for R&D&I in deep geothermal energy

3. Establishing a systematic approach to policies for deep geothermal which have the potential to enable more integrated development of innovative technologies and increase cooperation across the value chain as well as the diffusion of technology innovation

4. A long-term vision and strategy for deep geothermal, as well as following up on deve-lopments and market evolution, are crucial elements to guiding policy-making and ensuring the consistency of a sound integrated framework

TOPIC 2: ENGAGING WITH THE PUBLIC AND OTHER STAKEHOLDERS

Objective

In order to make sure that deep geothermal energy can play its role in Europe's future energy supply in a sustainable fashion, it is essential to engage in strong interactions with strategic groups and:

- Further analyse the socio-scientific understanding of a range of social and cultural aspects and factors which shape individual and community acceptance of geothermal technologies for electricity production and heating and cooling pu rposes, as well as how they interact as part of the energy transition

- Improve scientific literacy around geothermal energy and foster mutual learning amongst different stakeholders, enhancing contributions from all societal actors and unleashing the potential of geothermal energy

- Develop tools to include perspectives from the public and other stakeholders as part of the innovation process for geothermal energy technologies, preventing possible social conflicts around the development of geothermal technology

• Experiment with new forms of societal consultation/participation when defining research and development objectives within the geothermal field, reconnecting citizens to science and to scientific institutions

Current status

Although social and non-technical aspects are increasingly considered key determinants in the transition towards a low-carbon society, studies on the social acceptance of geothermal energy in Europe are still scattered and often a lack a uniform approach. At the same time, the geothermal community seems to have shown a growing interest in this issue in recent years, probably as a result of new forms of opposition emerging from different countries.

Various methodological approaches and research techniques have been applied in order to engage the public with geothermal issues, including surveys, interviews with key stakeholders, focus groups, media analyses, roundtables, public events, workshops, local referendums, seminars, information campaigns and education activities. The Geothermal ERA-NET project organised a joint action named PR-GEO which, in 2015, discussed some of the studies on the social acceptance of geothermal energy and public engagement exercises in relation to geothermal developments, conducted in some countries around Europe (i.e. France, Germany, Italy, Switzerland). One deliverable of the GEISER Project introduced a strategy for fostering public acceptance of EGS activities, which was applied in two EGS case studies. A risk governance strategy, including perception of public acceptability for various socio-economic conditions and sites, is planned as part of the (ongoing) DESTRESS project.

Several other interesting experiments with societal dialogue within the geothermal field have been conducted in Europe and beyond, as described in the literature and partly collected in Springer Nature Lecture Notes. A wide variety of countries, from both a social and geothermal perspective, have gathered experience assessing social acceptance and public engagement within the field, proving that the role of society as whole is gaining importance to the energy transition.

It often also appears that the general public is not well-informed about geothermal technologies and is not able to distinguish between different geothermal energy systems and related environmental and technological issues. As underlined by the DESTRESS project, increased public awareness and "transparent and open communication is key to the dialogue between science, industry and society on how geothermal technology can be advanced to a higher technology readiness level".

Another way to ensure social acceptance of geothermal projects is to share the benefits with customers and citizens. The objective is to develop organisational models and best practices of geothermal energy projects sharing the economic or other benefits created by the projects with local communities. Examples of this include local co-ownership and local crowd funding, (financial) compensation mechanisms or the creation of local green jobs.

Benefit Sharing Mechanisms like the approach taken by the NER300 Geothermae project in Croatia show a repeatable approach of integrating public opinion through financial benefits and selling the heat at a very attractive price (30 – 50% lower than what they pay at present).

Potential for technological development

Overcoming non-technical issues such as social acceptance is required in order to successfully develop energy technologies, and these issues require a highly interdisciplinary approach. This should be borne in mind by researchers, policy makers and funding providers when considering the allocation of resources, research and development strategies and project evaluations.
Four main constraints on successful societal engagement have been identified, as well as their potential counter-measures requiring development and implementation by key stakeholders:

Identified issues	Potential counter-measures	Key stakeholder(s)
Information gap between geothermal experts and the public and a lack of access to knowledge preventing understanding and perhaps acceptance.	Definition of guidelines for systematic information activities. Education and information campaigns about geothermal energy technologies and developments.	Experts from companies and academia Lay people from society Public communication from Science and Technology (PCST) experts
Scarcity of social engagement and inclusive geothermal projects. Need for genuine public participation in geothermal planning.	Definition and testing of public engagement strategies and practices in the geothermal field.	All stakeholders
Diverse strategies for societal engagement are being implemented worldwide; however, such knowledge is not so easily accessible that others can benefit from it.	Development of a permanent and constantly updated trans-European observatory on engagement strategies adopted in the field of renewable energy technology, including geothermal.	European commission Energy companies Civil society organisations Local public administrations Policy makers
The potential socio-economic and cultural impacts of distributed power generation, and the role of new social actors like prosumers, are still uncertain.	Furthering research and establishing new methodologies to assess the socio-economic and cultural impacts of distributed power generation while identifying the interrelations between these impacts and technology, investments and regulations.	Researchers Consumers Producers Civil society organisations Public administrations

TOPIC3:REINFORCINGCOMPETITIVENESS

Objective

The competitiveness of the deep geothermal sector has to be consolidated by:

- Developing a fair basis of cost comparison between energy sources, beyond a unique LCoE approach, taking into actual account system costs and external factors

- Analysing the ability of energy market models to properly remunerate the various benefits of geothermal energy in a industrial context of intensive capital investment (CAPEX) and marginal operational costs (OPEX)

- Establishing fair competition globally with the geothermal stakeholders from across the world

Considering that the rest of the world is moving towards geothermal energy at an accelerated pace, these efforts need to be maintained and made subject to ambitious further expansion in order to maintain Europe's leading position in developing the geothermal industry of the future, both for research and commercial development.

Current status

LCOE is one of the criteria most used to compare the competitiveness of different energy sources, notably in policy making. It is a very partial indicator, however, as there is no consi-deration of system costs such as the cost of transmission, or other network costs such as impact on system balancing, impact on state/system energy security, and the costs of external factors such as government-funded research, residual insurance responsibilities borne by the government, external costs of pollution damage or external benefits (e.g. the value of knowledge for future generations).
Current market models are unable to remunerate energy sources with low operational costs, hence there is a need for 'out-of-market' remuneration (feed-in tariffs, contracts for difference, premiums, capacity remunerations).
Europe has pioneered the exploitation of geothermal resources for power generation for over 100 years in Larderello, and the EU still maintains a leading role in electricity due to the development of EGS technology in many parts of the EU with the integration of national projects (in France and Germany) into a European Project at Soults-Sous-Forêts (France). In addition, the EU has the first successful commercially funded EGS project in Landau (Germany) and an EGS for industrial use (ECOGI project in France). 15% of installed geothermal power capacity is located in Europe. European companies are often technology leaders.
With more than 200 geothermal DH (District Heating) systems in operation, Europe is also the global leader for geothermal DH. Global competition exists mainly for heat exchangers and pipes. The use of geothermal heat in industry, the agri-food sector and services also started in Europe.

Potential for technological development

• Develop a model providing proper comparison of the full costs of competitive heat and power energies; this is necessary for a rational allocation of resources between energies.

• Establish carbon pricing with taxation tools and a new ETS which also tackles large heat installations in order to integrate the costs of external factors into the full costs of an energy source.

• Develop new business models for geothermal developers and operators, allowing them to sell their heat and power on different markets.

• Support the export of European geothermal technologies via trade missions and policies to open third markets.

• Set standards and establish high quality: European industry is defined by high standards, it is important to benefit from this fact internationally.

• Promote innovation: Develop new technologies and bring them to market (innovation in energy is a long process, and is quite risky for companies); promote "Competitiveness clusters" dedicated to geothermal, recognise potential for the reconversion of professionals and industry from other energy sectors such as coal mining and oil and gas, and liaise with other sectors such as the agri-food industry, data science and robotics.

TOPIC 4: ESTABLISHING FINANCIAL RISK MANAGEMENT SCHEMES

Objective

The goal of Financial Risk Management is to mitigate resource risk, which is the major barrier to entry for geothermal project developers in Europe. This also seriously hampers market uptake worldwide. The aim here is to develop financial schemes that manage to transfer the geology-related resource risk to other bodies in such a manner that project developers can accept their fair share of the resource risk, lowering their financial exposure should the development of a geothermal reservoir fail while also minimising societal costs. It must also open avenues towards a Europe-wide system.
This includes:

• Harmonisation of evaluation standards

• Integration of exploration costs into the business model: portfolio management model versus insurance scheme

• Addressing the moral hazard issue in an insurance scheme

• Creation of a risk sharing facility at national level and across borders (Pan-European)

• Encouraging the exchange of data and experience

Current status

A Geothermal Risk Insurance Fund is seen as an appealing public support measure for overcoming geological risk. As costs decrease and markets develop, the private sector will be able to manage project risks with, for example, private insurance schemes, and attract private funding.

With the notable exception of a few European market participants operating in well-developed geothermal regions, project developers have very little ability to manage the financial risk associated with poor knowledge of the deep subsurface, a lack of technological progress and high costs. As a matter of fact, the presented probability of weighted net success/failure values for project cash flows tends to be overly negative, effectively shutting out private capital from investing in geothermal energy.

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

The newly launched GEORISK project aims at supporting the establishment of insurance schemes in Hungary, Greece and Poland, and envisages the transition towards public-private or fully private insurance schemes from previously established public schemes in France, Germany, Switzerland and Turkey.

Potential for technological development

- Development of a specific resource assessment standard. Shared resource assessment methodologies exist in the oil and gas sector, which facilitate dialogue between companies and financial institutions.

- Performance of surveys on exploration or pre-cost risk in other industries (notably but not exclusively hydrocarbons) and how cost and risk are managed and integrated into the overall business model. Benefit/drawback analysis of a portfolio model as opposed to insurance schemes. Analysis of the specific issue of moral hazard in insurance schemes.
    - Establish schemes allowing for the exchange of geological data, knowledge and experience between geothermal, oil and gas and other subsurface service companies.

- Creation of a simulation model for establishing a sustainable risk mitigation scheme with a medium-term perspective.

TOPIC 5: GEOTHERMAL DEPLOYMENT SUPPORT SCHEMES

Objective

Support schemes are crucial public policy tools for geothermal in order to compensate for market failures and to allow the technology to progress along its learning curve. The objective is to:

- Facilitate the financing of R&D&I in deep geothermal energy, most notably for deep geothermal demonstration projects. Specifically, this would involve:
  - Facilitating access to financing for projects (i.e. information on funding facilities etc.)
  - Reducing the cost of financing for innovation in deep geothermal energy: identifying and reducing the capital costs incurred by non-technological risks

- Improve the bankability of geothermal projects throughout their development time through the identification of suitable financing instruments

- Remove barriers and improve the regulatory framework to facilitate the uptake of geothermal Power Purchase Agreements (PPA) for heating and electricity

- Balance the financial uncertainty linked with geological risk during the resource evaluation stage while maximising certainty from a technical perspective

- Adapt the current state of R&D&I in geothermal projects to attain an acceptable risk threshold for private funding (banks, investors) and proper technology readiness level

- Develop a long-term vision of the financing needs for R&D&I in deep geothermal energy, and identify the role of public authorities in providing financing and setting financing instruments enabling investments in R&D&I in deep geothermal and for scaling technological innovations in the energy system

Improving the accessibility of financing for deep geothermal R&D&I helps to remove major barriers to technological development across the whole value chain. It also reduces the delay in scaling technology innovation up to market readiness.
Financial instruments fit for the specific constraints of deep geothermal allow more projects to be undertaken and innovation to be achieved.

Current status

Public support for geothermal energy is such that it is necessary to mobilise private financing in a difficult investment climate. The economic and financial crisis has certainly affected investment in clean energy. The picture is already a complicated one, and it should be noted that Geothermal is a capital-intensive technology that takes some years to develop. Such a barrier can be tricky to overcome, especially when European stock markets are still uncertain and banks are looking exclusively for zero-risk investments.
The European climate and energy policy framework is a major element driving financing to deep geothermal R&D&I. The European Union in general has set up many facilities that direct financing to innovation in deep geothermal at every stage, from early research

to the demonstration of deep geothermal energy projects at scale. Identification and the assessment of the European policy and regulatory framework and the financing facilities is a starting point for the estimation of R&D&I needs in deep geothermal. This is an exercise that has notably been conducted by the DG ETIP project in mapping policies and regulation for deep geothermal.

It is also valuable to assess national schemes dedicated to financing deep geothermal projects. At the international level, multilateral financial institutions have developed valuable instruments such as the World Bank' ESMAP, the scheme from the EBRD and the World Bank in Turkey, or the Geothermal Development Fund by kfW in Latin America. There is a valuable body of literature on the specific issue of financing deep geothermal energy, particularly when it comes financing R&D&I and early developments. Key examples include the GEODH and GEOELEC projects. The Geoheatpol project also includes an extensive chapter on the specific financing needs of an emerging market for deep geothermal, notably regarding risk mitigation and the reduction of the cost of capital.

Potential for technological development

Research areas on this topic include:

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

- Developing innovative financing mechanisms adapted to the specificities of geothermal technologies and the maturity level of markets and technologies, notably to allow market deployment of innovation.

- When designing a support scheme or a sustainable financing programme, policy-makers should take a holistic approach which goes beyond the LCoE and includes system costs and all external factors with a LCA approach. Alternatively there is the possibility of offering geothermal a bonus for the benefits it provides to the overall electricity system both in terms of flexibility and base load. The base load characteristics of geothermal and its contribution to electricity grid stability should be adequately remunerated, as should the production and use of heat.

- Public support schemes covering different financial needs such as R&D, demonstration, the exploration phase identifying areas of interest, and the drilling/production phase (market conditions) in order to support technological progress throughout the learning curve.

TOPIC 6: ESTABLISHING A LEGAL AND REGULATORY FRAMEWORK

Objective

The goal is to establish a legislative framework allowing for geothermal deployment, its penetration, and profitability, while guaranteeing that resources are properly managed. This includes the establishment of appropriate European and national legislation and regulations by:

- Mapping the regulatory issues affecting the geothermal sector and best practices at each step of a deep geothermal project, from exploration to decommissioning
- Assessing and optimising the environmental, social and economic footprints of deep geothermal
- Establishing a position for geothermal energy in various codes (Mining, Environment, Water, etc.)
- Introducing a unifying process for geothermal projects (one address for all ministries)
- Licensing processes (first-come, first-served, licensing rounds, competition window, etc.)
- Works authorisation processes

Current status

Deep geothermal energy is a heavily regulated sector and typically requires a specific support framework. When considering the European regulatory and policy framework, various interlinked regulations and policies create a complex regulatory background. Although this complex regulatory framework may not necessarily result in the over-regulation of geothermal projects, and may indeed provide a consistent and robust framework allowing for confidence in deep geothermal energy projects, its lack of readability may be a deterrent for the emergence of new geothermal markets.
The most important pieces of European legislation underpinning the regulatory framework for deep geothermal are:

- Emissions Trading Scheme/Effort Sharing Decision Regulations for the non-ETS sectors
- Electricity market rules
- Renewable Energy Directive (2009 and 2018 recast)
- EU Environmental Directives (2020 Climate and Energy Package, 2030 Climate and Energy Framework, Air Quality Directive, Water Framework Directive, Environmental Impact Assessment Directive, National limitations on air pollutants, Radiation Protection Legislation)

Introducing third-party access to the heat network could prove fatal for geothermal heat, for example, as investors would become more reluctant to spend the high capex of geothermal sources, which could end up stranded later.
Additional associated guidelines:

- State aid guidelines on energy and the environment

- Network codes (Grid connection to the generators etc.)

In addition to the European framework, each European country has set its own national legal and regulatory frameworks regulating the geothermal sector.

In Perspective for geothermal energy in Europe[17] , key regulatory issues compiled from several studies (GEOELEC, 2013; GEODH, 2014; REGEOCITIES, 2015) are described and categorised into five main topics: definition, classification and resource ownership, licensing and authorisations, sustainability, and spatial planning and grid access.
The GEOENVI project aims to provide recommendations for harmonising environmental regulations across Europe, and developing a life cycle approach to assessing the environmental impact of geothermal.

Potential for technological development

Geothermal deployment would be accelerated by:

- Improving the legal and regulatory framework covering deep geothermal and its applications

- Providing recommendations for European harmonisation, including mutual recognition of environmental regulations, as well as for financial institutions

[17] Ruggero Bertani (2017), Perspectives for geothermal energy in Europe, World scientific, ISBN 9781786342317

TOPIC 7: EMBEDDING GEOTHERMAL ENERGY INTO THE CIRCULAR ECONOMY

Objective

The circular economy is a core topic for geothermal development. This means developing a system of production and trade in which durability and recyclability are built into products and components from the design stage onwards so that they can be reused or made into new raw materials, thus reducing waste volume and energy consumption while preserving natural resources.
The integration of geothermal into the circular economy would involve components, products and systems which are optimised, used and re-used, repaired, redistributed, refurbished, and/or remanufactured.
Another aim is to develop a quality label for the geothermal products, components and systems, becoming greener and eco-friendlier.

Current status

In 2016, the European Commission published a Circular Economy Package for a more sustainable economy. This package sets out a plan and targets for EU waste that should be achieved by 2030 in order to make the transition to a resource-efficient economy.
Many manufacturers, designers and developers in the geothermal sector have endorsed this initiative and are working on producing greener products, but the sector is not yet organised such that it can be fully integrated into the concept of the circular economy with all of its components.

Potential for technological development

The next steps should be:

- Adopting geothermal standardisation procedures and quality branding focused around the circular economy in order to improve the confidence of consumers and legal authorities regarding sustainable geothermal products and promote mutual understanding in the geothermal sector through agreed terminology, sharing vocabulary and definitions in order to have an agreed and consistent approach

- Improving the applicability and use of recycled/secondary materials/waste in geothermal plants

- Monitoring the use of raw materials in geothermal, especially the critical materials in terms of availability. Identifying, classifying and quantifying the data regarding raw materials, promoting interoperability and comparability with other materials

- Developing new business models with eco-friendly geothermal actors

- Performing research and innovation to develop new technologies for waste and water management

- Develop innovative greener and eco-friendly geothermal products, components and systems, transitioning to the use of sustainable materials

- Monitoring the entire process using digital applications

TOPIC 8: HARMONISED PROTOCOLS FOR DEFINING THE ENVIRONMENTAL AND HEALTH IMPACTS OF GEOTHERMAL ENERGY AND MITIGATION PLANNING

Objective

The aim is to create a robust strategy to respond to environmental concerns (by which we mean environmental impacts, incidents and risks) and highlight the benefits of the deep geothermal market uptake, focusing on the environmental and health impacts. This would include a harmonised and modelled LCA (Life Cycle Assessment) on environmental impacts, strengthening knowledge of the environmental and health impact of geothermal activities in the scientific community and developing knowledge about preventive measures in connection to risk communication and enhancing the environmental health literacy of communities living in geothermal areas.

Current status

Amongst the potential environmental impacts we can list the following:

- Surface-visual effects (land use, landscape, flora and fauna)
- Physical effects (induced seismicity, micro-seismicity related to each operational phase of exploitation (including reservoir connection and fluid reinjection into the reservoir), subsidence, geological hazards, groundwater resource depletion and natural radioactivity)
- Acoustic effects (noise during drilling, construction and management)
- Thermal effects (release of steam into the air, ground heating and cooling for fluid withdrawal or injection)
- Chemical effects (gaseous emissions into the atmosphere, incondensable gases, pollution and emissions, reinjection of fluids, disposal of liquid and solid waste)

Determinants and risk factors linked to geothermal production impacting health have been analysed in a few studies in Europe (Italy and Iceland) and in New Zealand. There is not, however, a harmonised protocol for assessing and comparing data.
The GEOENVI project aims to provide recommendations for harmonising environmental regulations in Europe and develop a life cycle approach to assessing the environmental impact of geothermal.

Potential for technological development

- Create a simplified and configured life cycle assessment (LCA) model and elaborate a general protocol for the delivery of simplified LCA models for geothermal installations
- Develop suitable studies investigating links between geothermal plants, exposure to chemicals and effects upon health
- Develop tools beyond the Richter scale in order to monitor seismicity and evaluate the degree of damage

- Apply cumulative risk assessment methods and tools, accompanied by case studies
- Develop knowledge about preventive measures
- Develop a Health Impact Assessment to strengthen Environmental Impact Assessment
- Assess the environmental impacts and risks of European geothermal projects which are currently operational or in development
- Communicate effectively with the general public regarding environmental and health concerns

TOPIC 9: HUMAN DEPLOYMENT

Objective

The development of a significant number of new projects will trigger a real boom in labour-intensive activities such as exploration, drilling, construction and manufacturing. The two main objectives are:

- Training a growing and skilled workforce for the Deep Geothermal sector to face the present and future energy challenges of Europe and to maintain the quality of energy delivery
- Ensuring the knowledge and investments of other sectors (e.g. oil and gas, nuclear, coal) is shared with Deep Geothermal

Ensuring the existence of necessary skills in the sector requires action at all levels of education and training, meaning technical and scientific education, training and continuous learning. In order to achieve proper education reform, cooperation between all of the organisations involved is required.
Cooperation between education and training institutes and companies is necessary to create a network allowing for faster and more efficient satisfaction of labour market needs while providing students with the appropriate skills and knowledge.

Current status

Amongst the actions required, a key issue is cooperation between education and training institutes and companies in order to create education and training networks involving industrial platforms, universities and research centres. Further ideas include the development of geothermal energy studies within existing university courses, launching new courses, absorbing the workforce of declining industries, and promoting the mobility of workers in Europe. Support for these actions should be sought nationally, in H2020 (and subsequent framework programmes) Concertation and Support Actions, as well as from existing EC programmes aimed at supporting knowledge transfer and human mobility, such as (Marie Curie, Erasmus +, ERC grants).
Dissemination activities are programmed and developed as part of most EU research projects, but much of this material does not reach wider society, including universities

and education centres. In order to integrate the latest knowledge gained from research into education, a coordinated effort from European academic and research centres is necessary. Training and links with industry have been launched as part of the GEOELEC project relating to power production and GEODH for heat production. Various universities around Europe, first listed in GEOELEC and then further analysed in the Geothermal ERA-NET projects, provide bachelor, graduate and post-graduate geothermal courses, usually provided in the local language. International geothermal schools are available in Switzerland.

Training has not been organised, and this would be beneficial both for increased specialisation and for outreach and job creation.

In 2018, there were more than 10.000 jobs directly related to deep geothermal in Europe. Geothermal energy jobs can be broken down into different types, from engineers, drillers and workers in equipment factories to project managers. Geothermal also generates indirect jobs such as with suppliers of raw materials and induced jobs. The estimated total number of deep geothermal jobs in 2018 stands at more than 20,000 jobs.

Potential for technological development

The potential of the geothermal power industry can only be achieved by attracting, retaining and renewing the workforce. Companies and research organisations need to adopt a range of measures if they are to access the highly skilled workforce they need. Several actions are required:

- Enhancement of the educational and training process while planning instructional education for the geothermal market: Develop courses on geothermal with existing university courses in fields such as engineering, bio-sciences, earth sciences, business administration and finance, and launch new courses combining geosciences and mechanical engineering
- Create Networks for Geothermal Energy Education and Training involving industrial platforms, universities and research centres with expertise in geothermal energy-related disciplines – geosciences, material sciences, mechanical engineering, computational sciences, economic and legal sciences
- Develop an Employment action plan in order to transfer knowledge and absorb the workforce of declining industries while promoting the mobility of workers in Europe
- Launch international cooperation, especially for EGS

E. KNOWLEDGE SHARING

Introduction

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

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

It is also vital to demonstrate capacity building, industrial technology transfer and expertise-based scientific and academic partnerships throughout Europe, with the shared goal of developing high quality, competitive and sustainable geothermal energy projects. This includes supporting the existing pan-European infrastructure for experimental testing and monitoring facilities and infrastructure such as laboratories[18], and using them in an efficient and coordinated fashion. In several EU countries, research infrastructure for basic and applied research in the geothermal field is fairly well established. There is definitely a need for a well-organised exchange on the testing standards used for various technologies spanning from exploration, drilling, and generation to operation. A joint effort towards large-scale demonstration is needed to ensure successful market introduction. At the same time, the next phase of development will require a focus on technology transfer and widespread demonstration projects. This cross-cutting action also aims at training and educating new geothermal professionals (see details in Chapter D: Topic 9: Human deployment).

Targets

- Improve access to relevant data and derived models in order to reduce exploration costs and manage technical and financial risks

- Large scale demonstration and deployment in order to provide proof of innovative concepts and their integration in the energy system

[18](Geo Energy Test Beds, GETB - see also https://www.epos-ip.org/data-services/community-services-tcs/geo-energy-test-beds-low-carbon-energy)

TOPIC 1: SHARING UNDERGROUND DATA - UNLOCKING EXISTING SUBSURFACE INFORMATION

Objective

Facilitate open access to subsurface data from geothermal and hydrocarbon exploration, production, and mining.
Promote access to geothermal information at European level via the development of an Information Platform, creating a standard and common data model at EU level and harmonising national data in order to speed up data discovery and mining. This is an important step to helping scientists, stakeholders, investors and geothermal developers, and it provides the basis for more accurate resource assessment and feasibility studies.

Current status

A wealth of information on geothermal prospects is available from past subsurface exploration and production. For exploration, it is estimated that at least 1000 billion euros have been invested into exploring oil and gas reservoirs over the past 50 years. Data covers well bore cores and logs, geophysical surveys including seismic images and other geophysical datasets, and also temperature and stress measurements. In most European countries, this data is not easily accessible and/or not in a format suitable for geothermal exploration. Geothermal data and mining are also highly relevant.
Various national initiatives are highlighting the importance of data sharing, geothermal databases and resource mapping: ThemoGIS in The Netherlands[19], GEOTIS in Germany[20], GEOTHOPICA in Italy[21], Thermo2D and Geothermie Perpectives in France[22], DOV in Flanders[23], and Switzerland's web-gis platform.[24] The format and structure of current databases are defined at national level.
The need for common data sharing is also well-recognised at EU level. For example, as part of Geothermal ERA-NET[25], the concept of a European Geothermal Information Platform was developed in light of interest from research and industry. At present, only a small pilot has been implemented[26] in order to test the concept. Both the concept and the pilot were tested and evaluated by stakeholders, who showed considerable interest in the matter.
Geological data is freely available to project developers in some countries like the Netherlands, where it is compulsory to release data after a five-year period.

Potential for technological development

Technological development options include:

- Definition of standards (e.g. for database formats and services using data automatically) and data models

[19] www.thermogis.nl
[20] https://geotis.de
[21] http://www.geothopica.igg.cnr.it
[22] http://www.thermo2pro.fr/ - http://www.geothermie-perspectives.fr/
[23] https://www.dov.vlaanderen.be/
[24] https://map.geo.admin.ch
[25] http://www.geothermaleranet.is
[26] Described in Trumpy et al., Building a European geothermal information network using a distributed e-Infrastructure, International Journal of Digital Earth, 2015

- Establishing the principle of geological data being made freely available after a period of time in national regulations (details in Chapter D: Topic 6: Establishing a legal and regulatory framework)

- Data preparation, harmonisation and publication through national web services.

- Development of the Geothermal Information Platform, providing services for open-access data harvesting, data mining and data management (e.g. graphs, statistical tools, etc.)

- Inclusion of geothermal properties and resource mapping, taking advantage of a common geothermal exploration protocol (see item on Resource assessment)

TOPIC 2: ORGANISING AND SHARING GEOTHERMAL INFORMATION

Objective

The ability to rapidly search for valuable information, as well as transparent and harmonised methods and instruments for technical and financial risk management, contribute to market uptake and accelerated innovation. The main aims in this regard are:

- Facilitating access to geothermal information at European level via the development of an Information Platform, creating a standard and common data model at EU level, harmonising national data so as to facilitate information discovery and data mining, and fostering the exchange of technical and non-technical knowledge at European level

- Establishing a web-based knowledge transfer system related to technical and non-technical aspects of interest in different European countries while simultaneously creating a community that fuels this system

Current status

While there is an abundance of information already contained within many websites, databases, and more, accessing the right information quickly and easily can prove difficult. Currently, geothermal information (including technical topics as well as national energy policies, economic and regulatory information, geothermal energy production, market and social requests, and training offers) is organised separately by each Member State, and only a few types of information are organised and coordinated at European level (e.g. energy production and installed capacity for Eurostat). The strategic importance of sharing knowledge was demonstrated within the context of the Geothermal ERA-NET project and two joint activities were proposed for this challenge.
One activity examined the concept of a European Geothermal Information Platform (EGIP), a Web tool gathering data and knowledge from national and scientific providers following the European INSPIRE directive, i.e. that data remains the property of the providers hosting it. The current status and requirements of geothermal data and the existing tools to manage them were described, the level of interest towards various topics was prioritised by way of a questionnaire, and the concept and its application were described in various documents. EGIP is meant to be interoperable with other pan-European data platforms such as EGDI. At the moment the concept has not been

explored further than 1) a Pilot Platform for sharing a few sets of underground data and documents, and 2) the Search Engine for European project documents created for the ETIP-DG website.
Another knowledge-sharing concept developed by Geothermal ERA-NET was OpERA-pedia, which would aggregate the operational issues of European geothermal installations in order to contribute to optimising the availability of information regarding operational issues, which were identified as some of the main barriers to the development of geothermal energy and as an urgent R&I need. This activity was funded by some countries and a wiki-style knowledge platform on operational issues is currently in development.

Potential for technological development

The building of knowledge sharing tools, following the track laid out by Geothermal ERA-NET, requires the following:

- Definition and prioritisation of technical and non-technical topics and issues to be organised (finishing the work begun by Geothermal ERA-NET)

- Coordination of European and national contracts/subsidies on chosen topics, to be handled nationally by the national ministries/governmental agencies, bringing together national experiences

- Creation of working groups of national experts and stakeholders (industry, research, public, and administration, depending on the topic) to provide a collection and overview of documents and technical issues, and their applied and potential solutions

- Definition of standards (e.g. for database formats and services using data automatically) and data models

- Data preparation, harmonisation and publication through national web services

- Development of the Geothermal Information Platform, providing links to tools (e.g. common wiki-style tools) and services for open-access data harvesting, data mining and data management (e.g. graphs, statistical tools etc.)

- Exploration and testing of new tools (e.g. available energy signposting) and development of innovative tools for sharing information

TOPIC3:SHAREDRESEARCHINFRASTRUCTURES

Objective

Achieve excellence in highly-demanding scientific fields related to geothermal energy and its development, and simultaneously contribute to the European Research Area (ERA) and Innovation Union.
Enable ground-breaking discoveries in geothermal technology, attract researchers from around the world, and build bridges between research communities.

Current status

Research infrastructures (RIs) are facilities, resources and services used by the science community to conduct research and foster innovation. They traditionally consist of major scientific equipment, resources such as collections, archives or scientific data, e-infrastructures such as data and computing systems, and communication networks. In the geothermal sector the availability of demonstration sites with access to wells and plants for testing and developing innovative concepts and technologies is crucial, but only a few are currently available.
While research centres working in the geothermal sector may already be involved in large RI in various fields (e.g. EPOS), there is no shared RI specifically dedicated to geothermal topics.

Potential for technological development

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

F. CONCLUSIONS AND MISSION

Geothermal is a key technology in the vision highlighted by this Strategic Research and Innovation Agenda. The development of large geothermal power plants, which tap into ultra-hot, supercritical heat reservoirs in order to supply a large part of Europe's base load electricity, will be required by 2050. In areas where the geothermal resources are at a lower temperature, the electricity potential is boosted by combining geothermal with other renewable resources such as solar-thermal, salt-gradient power, photovoltaics or local biomass. These large, centralised power plants are linked with CO2-capture and power-to-gas or power-to-fuel facilities that produce synthetic fuels and base chemicals at times of low electricity demand.

At the local level, geothermal Combined Heat and Power (CHP) plants are used for grid balancing services through voltage and frequency regulation and by supplying fast ramping, dispatchable energy. Additional flexibility is created by exploiting the vast thermal storage potential of fourth-generation district heating and cooling (DH&C) networks, including low and high temperature underground thermal storage, tank and pit storage using advanced storage media, and storage in the building mass and the piping of the DH&C network. Fourth-generation DH&C networks work in a temperature range of 55 – 25°C or lower. This allows for the utilisation of low temperature residual heat derived from industrial processes and buildings and improves the efficiency of the connected RES. Intelligent supply-and-demand management based on predictive, self-learning control algorithms and fast data communication enables efficient utilisation of flexibility and ensures optimal use of all energy sources connected to the network. This leads to the creation of a hybrid energy infrastructure connecting DH&C networks with the electric grid and other energy vectors through various coupling points.

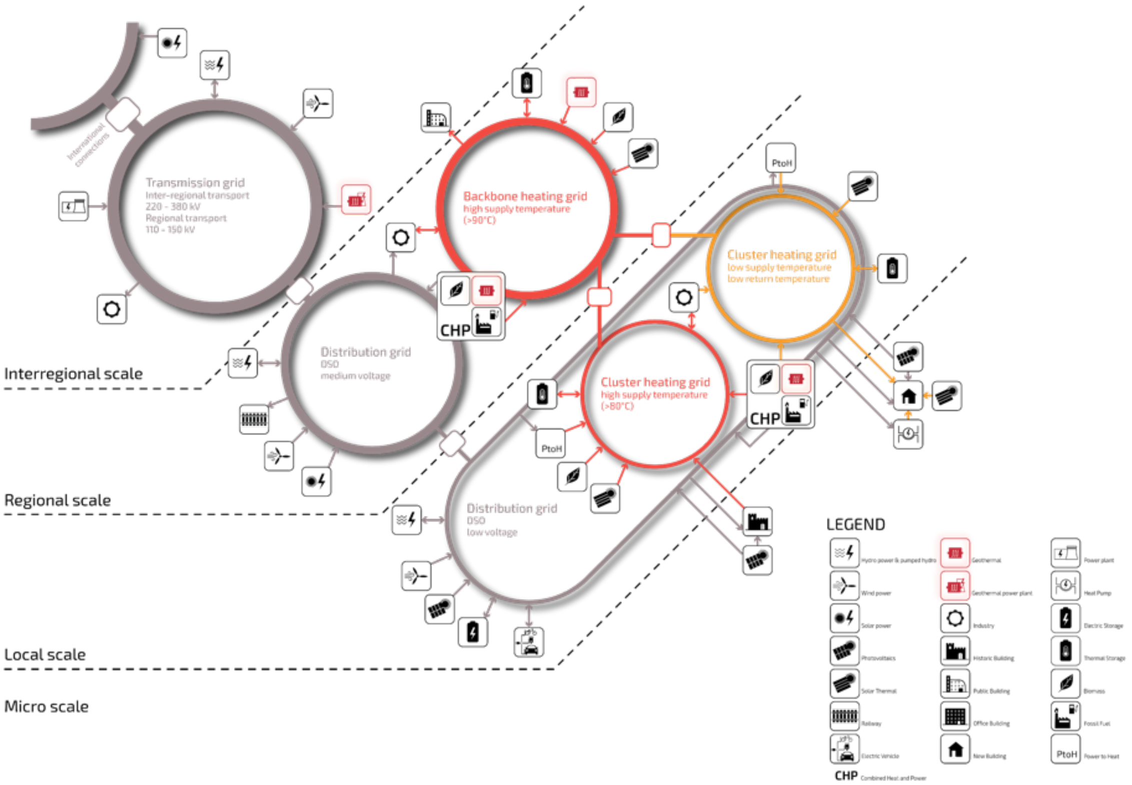

Figure 2 Hybrid energy infrastructure composed of interconnected energy networks based on renewable energy sources (courtesy of DNV GL, based on: NoordhoffUitgevers B.V., 2012) – extended version of VISION Fig. 10, including synthetic fuel and gas.

The creation of a hybrid energy infrastructure calls for technological developments and innovations extending far beyond the strategic research agenda for deep geothermal. Through an open dialogue with other energy sectors, the geothermal sector can assure that its technology developments are in line with roadmaps for:

- Hybrid power generation
- Smart networks for energy transition
- Energy efficient buildings
- Short and long-term energy storage solutions
- Renewable heating and cooling such as (high-temperature) heat pumps, solar thermal, innovative cooling devices and hybrid systems
- Fourth-generation district heating and cooling networks
- Sustainable chemistry
- Technologies for the production of synthetic fuels and gas from residual power and heat
- Data communication, the internet of things and artificial intelligence

Deep geothermal can also benefit from developments and innovations in other sectors such as oil and gas and (metal) mining. One example is the development of combined heat, power and metal extraction from deep geothermal brines. Exploiting the energy potential present in many geothermal brines can increase the energy output and profitability of the geothermal plant, while at the same time lowering Europe's dependency on foreign metal resources. In coming decades, securing the supply of critical raw materials, in

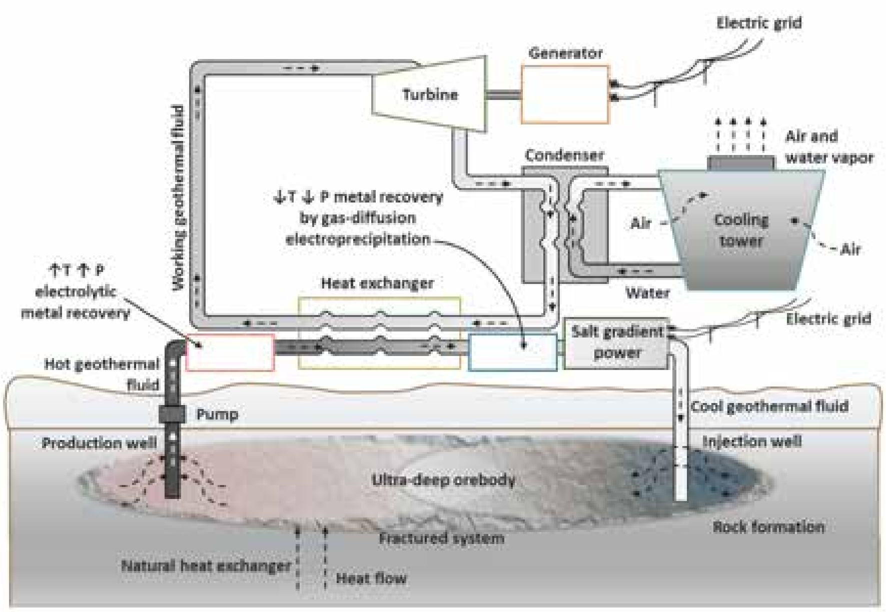

Figure 3 Concept of a combined heat, power and metal extraction geothermal plant (based on horizon 2020 project CHPM2030: https://www.chpm2030.eu/introduction/).

particular metals, will be a major challenge for European industry and society. Our dependency upon importing metals is growing every year, despite significant efforts made to develop recycling technologies and in material sciences.[27]

More information about cross-cutting R&D&I needs for deep geothermal and other sectors can be found in D 5.3 External stakeholders, Common R&D&I Needs and Complementary Actions.

In addition to technological developments, the envisioned energy transition calls for strategic actions to create a supportive socio-economic environment. Long-term goals have to be embedded within a clear energy policy and should be supported through financial incentives, innovative approaches to business and long-term investment strategies. The new energy infrastructure will also have an impact on the landscape and the way we live. These concepts therefore have to be taken into account during spatial planning and should be incorporated into policies regarding mobility, housing, industrial development, and more. This vision for the future should therefore be shared and discussed with all stakeholders. The challenges at hand are too big an effort for any one sector. Only by working together in mutual respect and trust can we create a new world where life can be enjoyed by everyone.

Mission

As part of its proposal for the new framework programme for Research and Innovation 2021-2027, Horizon Europe, the European Commission included new overarching cross-sectoral R&I Missions to help achieve bold and inspirational goals with far reaching impacts for science and technology, society, and citizens at EU level. The purpose of these Missions is above all to help the average European citizen know and remember something of the broad thrust of Europe's science and innovation policy.

Amongst the themes under consideration, the Mission focusing upon Clean Cities (carbon-neutral, smart cities) represents a way to advance the energy, economic, and environmental sustainability and security of Europe and its citizens, providing the ideal framework to mobilise all actors across Europe, both public and private, with cascade effects for both the economy and living standards of the communities involved.

Innovation in renewable and efficient technologies, such as deep geothermal, is the key to enabling the decarbonisation of the European economy, while clean and efficient cities are ideal environments for the cross-sectoral integration necessary to achieve the European climate and energy objectives for 2030, as well as for adapting to the new long-term requirements for reaching a climate neutral economy by 2050 as envisioned by the European Commission Long-Term Strategy.

The mission of ETIP Deep Geothermal is to accelerate the development of deep geothermal technologies in Europe by focussing on overall cost reduction, including social, environmental, and technological costs. This mission complies with the six targets defined by the European Commission and stakeholders from the European geothermal sector for the advancement of deep geothermal in the SET-plan:

[27] Public Consultation on Commission Raw Materials Initiative, Background paper, P1, More information: http://ec.europa.eu/enterprise/policies/raw-materials/public-consultation/index_en.htm

1. Increase reservoir performance [including underground heat storage], reducing the power demand of reservoir pumps to below 10% of gross energy generation and achieving a predicted 30-year or greater sustainable yield by 2030

2. Improve the overall conversion efficiency, including the bottoming cycle, of geothermal installations at different thermodynamic conditions by 10% by 2030 and 20% by 2050

3. Reduce the production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) to below €0.10/kWhe for electricity and €0.05/kWhth for heat by 2025

4. Reduce exploration costs by 25% in 2025 and by 50% in 2050 compared to 2015

5. Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015

6. Demonstrate the technical and economic feasibility of responding at any time to commands from a grid operator to increase or decrease output ramp up and down from 60% -110% of nominal power.

Furthermore, additional exploitation revenues can be gained by drawing value from co-products such as lithium or critical metals, or through the production of base chemicals and synthetic fuels. The ultimate goal of these targets is to accelerate the deployment of geothermal energy in Europe. According to recent estimates, geothermal power production could rise from 15 TWh in 2017 to 540 TWh in 2050, as highlighted in the SET Plan - Declaration of Intent on Strategic Targets in the context of an Initiative for Global Leadership in Deep Geothermal Energy. This would correspond to 12.5% of EU electricity demand in 2050. In addition, geothermal could supply between 233 (conservative scenario) and 349TWh (enhanced market scenario) of heat and cold in 2020 and up to 1,745TWh in 2050. According to the ETIP-DG Vision, geothermal will be a key energy source in the "City of the Future": a place where life can be enjoyed by everyone while respecting the environment, a city driven by a combination of renewable energy sources for local electricity and heating/cooling supply at residential level, either with or without storage facilities, and with electrical vehicles integrated into the system. It envisions large heating networks fed by geothermal heat, with intelligent exchanges of energies between houses and the major supply poles. It will be a city using 100% renewable energy sources with zero impact on the environment (no pollution, no greenhouse gas emission, no long-distance transportation of fossil fuels), and where citizens will act as "prosumers" in a smart, clean, renewable and sustainable system.
This dream can only be achieved if it is shared by all stakeholders. As we have learned in recent decades, the energy transition is not only a matter of techno-scientific innovation, but rather one of cultural habits, social issues and political choices, all of which are strongly interconnected. If European energy systems are to be redesigned for a more sustainable future, it is fundamental that an interdisciplinary, open and comprehensive approach is established, an approach which cannot exclude the inexhaustible, renewable, and indigenous heat flowing beneath our feet.

G. NEXT GENERATION OF TECHNOLOGIES

While the amount of deep geothermal power and heat capacity in Europe has reached nearly 3 gigawatts electric and 5 GW thermal, a strong scientific foundation involving fundamental and pioneering research is needed in order to develop beyond the activities of today and tomorrow. This groundwork shall address long-term applications and stimulate breakthrough possibilities such as:

a. Geothermal resource assessment through deep probing earth observation
Satellite and airborne surface thermal data and multispectral imaging have been successfully applied to mapping geothermal resources. In addition, spectral analysis of aeromagnetic data has been used to map the Curie point depth and to calculate thermal heat fluxes, whereas gravimetric data has proven useful in locating fault zones which are prospects for further geothermal exploration. These examples show that remote sensing in combination with targeted ground observations may provide an efficient way to locate and quantify currently unknown geothermal resources. Unfortunately, the use of remote sensing in geothermal resource mapping is hampered by data resolution, the lack of a robust algorithm to extract non-geothermal components from the imagery (e.g. diurnal and seasonal thermal effects in thermal infrared images, surface cover, shallow geology) and a limited depth of observation. However, the combination of different geophysical datasets and data mining have the potential to develop reliable algorithms for characterising (ultra-)deep and ultra-hot geothermal resources.

R&D should aim to:

- Identify and test remote sensing imagery that can act as a proxy for deep geothermal processes (e.g. near-surface/soil gas concentrations, analyses of multi-spectral imagery, aeromagnetic data, gravimetry)

- Data mine remote sensing imagery and geophysical data from known geothermal fields and the surrounding areas

- Combine techniques to locate hot-spot areas at large depths

- Acquire geophysical datasets for known geothermal fields to be used for machine learning

b. Geothermal Energy Buffers (GEB)
A GEB is a hybrid energy system involving solar thermal and electricity storage to complete the geothermal heat flow by means of an energy carrier. A GEB targets a productive sedimentary reservoir at a depth level allowing for high pressure (gas) storage while at the same time presenting an interesting residual porosity matrix. An organic fluid (LPG) experiencing a phase change under atmospheric conditions is used as an energy carrier. The energy carrier is stored underground for a pre-determined period of time to allow heating and gasification. Subsequently, it is moved towards the surface where its valuable energy (cold & electricity) is exploited before it is finally preheated prior to its reinjection. Mechanical energy (power generation) and cold are produced by liquid to gas conversion. The LPG is circulated in a closed loop between the subsurface reservoir and the surface gas processing facilities. At the surface, renewable thermal energy such as from solar thermal and RES-driven heat pumps will contribute to the sustainability of energy production, making GEB power production available at all times to compensate for electricity grid fluctuations.

R&D should aim to:

- Address the integration and management of energy systems, as the energy carrier will be pre-heated by means of another energy vector: water. This water will probably be geothermal and overheated with solar and electricity (heat pump) inputs during GEB off-power production time. The injection of heated water and gaseous LPG will be performed via multiphasic pumps.

- Model the percolation/migration of recycled LPG to the upper storage zone. The objective is to ensure transit of hydrophobic LPG into aqueous (and therefore hydrophilic), porous media without traps interfering during the upward migration route.

- Design a high thermal conversion efficiency multistage flash system capable of extracting electrical energy from large volumes of hot and pressured LPG.

c. Develop biologically-inspired robots for revolutionary drilling: more efficient, less costly when automated, safer, environmentally friendly

Burrowing animals demonstrate overwhelming superiority when compared to present-day drilling and tunnelling equipment. They have evolved to thrive in and manipulate the underground environment according to their needs. Their relative strength can exceed the performance of the most powerful drilling and tunnelling machinery by a factor of one hundred, even while being energy-efficient, self-organising and capable of navigating subsoil environments. The objective here is to develop disruptive, highly autonomous concepts for breaking and removing rock from deep formations, drawing inspiration from underground biology. It could also go beyond drilling and develop other breaking and excavation techniques. Such systems could be expected to include increased flexibility and scalability, leading to the development of heat extraction systems (e.g. ultra-deep wells, multi-radial wells, closed underground heat exchangers) that are currently considered uneconomical. Beyond 2050, robot drilling technology should be available, ensuring full integrity of the system.

R&D should aim to:

- Map the underground animal kingdom in order to identify efficient ways of drilling and/or tunnelling, underground navigation, feeding and building, and improving resilience

- Develop highly (semi-)autonomous drilling machinery for deep vertical and horizontal wells

d. Create an underground energy system

Although the concept dates from the early seventies, and notwithstanding long-standing R&D efforts in the US, Europe, Japan and Australia, the development of EGS is slowed by uncertainties about long-term reservoir behaviour and impacts on the surrounding area such as seismicity and groundwater contamination. These uncertainties hold back acceptance of the technology and profitability. In order to unlock the large energy potential stored in hot rock, new concepts to extract heat should be developed. These novel energy extractions systems make use of one or more wells that are connected to an underground heat exchanger. The underground heat exchanger is either fully drilled/ excavated (e.g. multi-laterals, horizontal wells, stopes, shafts and related facilities) or uses a combination of drilling and focused fracking of the surrounding rock (e.g. hydraulic or thermal). The result is a (semi-)closed heat extraction system with a predictable thermal output and temperature evolution. These systems can be made viable through the introduction of new, cost-effective drilling technologies. The possibility of using enhanced fluids to reduce corrosion and scaling problems and increase heat extraction should also be examined, in particular for closed-loop systems.

R&D should aim to:

- Improve understanding of the thermal and mechanical properties of rock under varying thermal regimes
- Develop tools to predict the mechanical behaviour of rocks and the stability of excavated structures
- Develop predictive models to evaluate heat flow towards (semi-)closed heat extraction systems at large depths
- Perform laboratory and in-situ testing of working fluid to optimise performance.
- Develop thermosiphoning in closed-loop systems to take advantage of the different temperatures of the system fluids and eliminate the need for a circulation pump
- Perform conceptual design and field-testing and demonstrate (semi-)closed heat extraction systems

e. Use of IT tools based on data mining and machine learning for resource assessment, access to the resource and generating energy

A recurrent barrier to the development of geothermal systems is uncertainty about the output and long-term behaviour of the reservoir. In the future, new self-learning IT tools that unearth the knowledge buried in the exploration and production data of previous geothermal projects will be used to predict the thermal output and behaviour (e.g. evaluating the flow rate, thermal output, pressure, mechanical behaviour including induced seismicity) of the reservoir. These tools will help overcome both technical and non-technical barriers during the development of new projects. In addition, self-adaptive production models linked with real-time data about the state of the reservoir (e.g. formation temperature, pressure distribution, fluid composition) and the demand of connected energy networks will guarantee safe and efficient energy production.

R&D should aim to:

- Data mine exploration and production data from geothermal projects
- Develop self-learning models to predict reservoir output and behaviour
- Develop and implement self-adaptive control algorithms

f. Connecting the reservoir with the surface: reliable and resilient data transfer
Next generation communication solutions will be used to detect and control drilling and heat mining in ultra-deep or ultra-hot environments. The challenges faced include: provision of full coverage, connectivity of sensors with different bandwidth requirements, resilience, re-configurability, self-organisation, self-healing and easy deployment in a harsh environment.
R&D should aim to:

- Develop radically new ways of providing data communication and localisation capabilities directly through heterogeneous non-uniform materials and rock substrates (e.g. using radio, seismic or acoustic signals or high energy particles)

- Develop self-repairing systems (e.g. based on redundancy, rerouting)

g. Produce energy from offshore geothermal installations
Being able to utilise offshore geothermal resources will increase the availability of geothermal energy worldwide tremendously. Cross-fertilisation with oil and gas is the key to success here. The challenge is developing a completely new generation of geothermal technology.
R&D should address:

- Development of methods for offshore geothermal exploration, including knowledge transfer from the oil and gas industry.

- One of the key parts in a geothermal power plant is the insulation of the pipeline from the wellhead to the plant. It is vital that energy is not lost when transferring the steam/brine from the wellhead to the plant. In the case of offshore geothermal it is even more crucial to insulate the conductor as it passes from the sea floor to the surface. In order to prevent the sea's cooling effect on the conductor leading to lost energy, it is important that energy loss in this area be minimised. The insulation needs to be able to withstand the rough sea on the outside and heat on the inside.

GLOSSARY

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

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

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

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

Consumers
People purchasing and consuming energy (or any goods and services in other contexts).
District heating: A system using a network of pipes to distribute hot water generated in a centralised location for residential and commercial heating requirements such as space heating and water heating.

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

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

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

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

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

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

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

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

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

Prosumers
People that both consume and produce energy.

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

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

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

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

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

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

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

Terms and abbreviations

CCHP
Combined Cooling, Heat and electrical Power

DH
District Heating

DHC
District Heating and Cooling

EGS
Enhanced Geothermal Systems

EU
European Union

GeoDH
Geothermal District Heating

GETB
Geo Energy Test Beds

GHG
GreenHouse Gas

GSHP
Ground Source Heat Pump

H&C
Heating and Cooling

HT-TES
High Temperature Thermal Energy Storage

LCoE
Levelised Cost of Electricity

O&M
Operation and Maintenance

R&I
Research and Innovation

RES
Renewable Energy Source

RRI
Responsible Research and Innovation

SHGS
Super-Hot Geothermal Systems

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ETIP-DG
European Technology & Innovation Platform on **Deep Geothermal**

The European Technology & Innovation Platform on Deep Geothermal (ETIP-DG) is an open stakeholder group, endorsed by the European Commission under the Strategic Energy Technology Plan (SET-Plan), with the overarching objective to enable deep geothermal technology to proliferate and reach its full potential everywhere in Europe.

The primary objective is overall cost reduction, including social, environmental, and technological costs.

The ETIP-DG brings together representatives from industry, academia, research centres, and sectoral associations, covering the entire deep geothermal energy exploration, production, and utilization value chain.

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

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