Strategic Research and Innovation Agenda

Draft for consultation

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

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Executive summary

The decarbonisation of the energy sector to achieve the Paris objectives by the EU and its member states will drive a switch in electricity and heat generation technologies from fossil fuels to renewables including geothermal. Over the last 10 years, the geothermal industry has matured and the market enlarged, but to achieve a significant cost reduction and to increase performance of technologies further research and innovation actions are key. A larger amount and a better allocation of private and public (EU, national and regional) research and innovation funds are therefore required.

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

As international competition increases, **maintaining European technological leadership** is key to preserving our competitive advantage in the sector.

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

Technological

1) Prediction and assessment of geothermal resources
2) Resource access and development
3) Heat and electricity generation and system integration

Transversal challenges

4) From R&I to deployment (environmental, regulatory, market, policy, social, human deployments)
5) Knowledge sharing (data harmonization and coordinated organization of data and information, shared research infrastructures)

The overall **Mission** for Research and Innovation is to raise the Deep Geothermal sector to contribute to the City of the future where a combination of renewable energy sources, for local electricity, transport and heating/cooling supply to buildings, tertiary and industry, with underground thermal storage facilities, and electric vehicle are integrated into the system.

Figure 1 Vision of the city of the future (Source: ETIP DG, Vision for deep geothermal, 2018)

Introduction. Deep Geothermal: Designing the future of geothermal energy

Renewable, secure, clean, versatile, distributed, predictable: the energy future that we imagine for human societies in Europe is solidly grounded on geothermal energy. With its long tradition of electrical power production, developed in Italy at the dawn of XIX century, and of district heating, almost one century old in Iceland, geothermal has been a backbone of the renewable energy system in Europe. Yet, alongside its numerous and diversified applications the geothermal sector teems with further development.

This is what the **Vision of the European Technology and Innovation Platform on Deep Geothermal (ETIP-DG)** is meant to deal with. The actual status of geothermal production in Europe is synthetically presented in the Vision, followed by a discussion about the challenges ahead, to increase 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 organized will play an always bigger role in terms of social, environmental and economic sustainability of human societies. The Vision dreams about the "City of the Future": a combination of renewable energy sources, for local electricity and heating/cooling supply at house level, with or without storage facilities, and electrical cars integrated into the system. It envisions large heating networks fed by geothermal heat, with intelligent exchanges of energies between houses and the major supply pole. It will be a city that has 100% renewable power sources in terms of electricity, heating/cooling and mobility, 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 in Europe by geothermal energy. And it goes beyond the urban areas, by exploring the numerus applications already in operation to produce heat for industrial and agricultural processes, for balneology and health spas all over Europe.

It explains that the Levelised Cost of Electricity, LCoE, is one of the lowest in the renewable energies realm, and that heat applications largely contribute to energy efficiency. If we compare the potential for geothermal energy to the potential of fossil fuel, we find that the 1% of the thermal energy contained within our planet is 500 time higher than the energy accumulated within the oil and gas reservoirs from all over the world. From this perspective, we could alternatively say that while "looking up" at the future, it would also be strategic to start "**looking down**". Beside the wordplay, a cultural shift is seriously fundamental in order to unleash the opportunities of geothermal energy.

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 use just a minimal part of the geothermal potential. With 163 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 applications (i.e. food industry or bio-refinery, etc.).

As the scientific knowledge and the technological developments are moving forward, augmenting the accuracy of resource development and management and the efficiency and the accuracy 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. The 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 with the help of heat pumps to lift the temperature. The increase of the numbers of wells means increasing the knowledge of the underground, improving the forecasting of underground condition, the performance of application, enhancing the resilience of the system.

Of course, not one of the abovementioned ambitions have the chance to be realized without a collective commitment. As we have learned in the last decades, energy transition is not only a matter of techno-scientific innovation, but also of cultural habits, social issues and political choices, which are strongly interconnected. In order to redesign the European energy systems towards a sustainable future, it is therefore fundamental to put in place an interdisciplinary, open, 360 degrees approach, which includes the heat flow running under our feet. To learn more about the ambitions regarding this renewable and indigenous energy in Europe, look at ETIP-DG Vision on Deep Geothermal.

A. Prediction and assessment of geothermal resources

Introduction

A comprehensive knowledge about the subsurface is a crucial point for choosing the most promising areas for detailed exploration and potential geothermal development, and then throughout the life of a geothermal project. A better knowledge contributes to minimize the exploration risk and the cost for reservoir development on one hand, and to maximize the profitability and the reservoir sustainability on the other hand.

The knowledge gained over the past 50 years of exploration for hydrocarbon, geothermal and mineral resources, allows a-priori definition of several prospective areas in Europe. However, an integrated approach for a comprehensive characterisation of such reservoirs and for the assessment of their geothermal potential at different depths is still lacking.

Geothermal exploration has made advancements in the last years, taking advantage of the progress of single methodologies and the opportunities to develop and test integrated approaches. Exploration is progressively targeted in areas with limited surface manifestations (e.g. in magmatic areas) or in sedimentary basin structures which cannot rely on existing subsurface data such as wells and seismic in mature oil and gas basins. Therefore, innovative surface measurement, remote sensing, and imaging and monitoring techniques from surface and borehole are required to detect reservoirs. The overall objective of R&I in exploration is to reduce the costs of exploration technologies and increase probability of successfully characterize the geothermal resources.

Topic 1: Advanced exploration prior to drill

Objective

Cost effective exploration methods, contributing to improved imaging of geothermal reservoir structure (geometry and size) and rock and fluid properties (thermal, flow, chemical, mechanical) are critical in reducing the exploration costs by reducing costs for detecting geothermal reservoirs and reducing the probability of non-successful exploration wells. Key innovations are novel methods capable of detecting the size and properties and thus reducing uncertainty (risk).

State of the art

Methodology for exploration and investigation of geothermal resources are numerous, and well described in literature (e.g. Best practices guide for geothermal exploration, by IGA and IFC). The FP7 funded project IMAGE (Integrated Methods for Advanced Geothermal Exploration) has developed various novel exploration techniques

http://www.image-fp7.eu/reference-documents/deliverables/IMAGE-D2.05-2017.11.02-IMAGE-final-book-public.pdf

Exploration risk remain, however, high till the first exploratory well is drilled and direct data can be achieved. 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 methodologies to reduce the uncertainty of the resource's location, size, and productivity characteristics.

Potential for technological development

Technological development options include:

- Reduce cost of surveys and improve resolution of underground imaging by geophysical exploration techniques (e.g. Gravity, EM, passive seismic, 2D-3D-4D seismic), beyond industry standards
- Improve remote sensing techniques for detecting surface anomalies
- Improve multidisciplinary of exploration methods (Geological, geophysical, geochemical)
- 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.

Target

(Link: Declaration of Intent)

Reducing exploration costs, by reducing costs of exploration technologies and increasing probability of success

Topic 2: Advanced investigation and monitoring technology

Objective

Improve characterization of reservoir performance before, during and after geothermal exploitation

State of the art

Numerous exploration techniques are used to characterize the resource during and after the first wells are drilled to test the existence of a geothermal reservoir capable of sustaining commercial rates of fluid production and injection. They can be used during the drilling, to look ahead and reduce drilling risks (Logging While Drilling (LWD) and Measurement While Drilling (MWD)). Various technologies applied from surface/airborne and borehole provide input to numerical model for forecasting the performance of the geothermal reservoir during future production. By geophysical and geochemical methods it is also possible to monitor the underground physical and chemical changes during production, which is essential for the optimal and sustainable operation of the resource.

All methods require further improvement, so mitigating risks during the feasibility and operation phases of a geothermal project.

Potential for technological development

Technological development options include:

- Enhance reservoir information from time-lapse analysis of field data
- Improved (or more cost effective) borehole based geophysical techniques (e.g. VSP, CSEM, fibre optic methods)
- Improve well bore measurements (in situ property measurements on the borehole wall and at high temperature), including LWD and MWD tools[1]
- cross-interpretation of well logging
- cross-interpretation with surface survey
- in situ fluid monitoring
- tracer technologies, including optimization of High-Temperature tracers
- Technological development taking advantage of existing data (e.g. smart reprocessing),
- Innovative sensor technology,
- Advanced data acquisition and handling, computational and processing capabilities, new breakthrough technologies,
- joint inversion and modelling, and combining exploration and field monitoring purposes. Closed loop approaches also allow to improve incremental (near) field development

1 Cross-cutting with Topic 7 of “Resource access and development”

Target (Link: Declaration of Intent)
Reducing exploration costs, by reducing costs of exploration technologies and increasing probability of success

Topic 3: Exploration workflows - Conceptual models, reservoir characterization, performance and decision models

Objective

Geothermal resources can be classified in different types. In order to reduce cost and improve robustness we need open evolutionary and transparent workflows, customized and optimized to these specific resource types, as well as improved multi-scale and multi-disciplinary approaches to infer conceptual models and reservoir characterization, underpinned by fundamental process and property understanding and validation.

The workflows are aimed at enhancing the knowledge and the interpretation of the geothermal systems. Consequently, the goal is to reduce capital expenses (CAPEX) and still reduce risk and include uncertainty analysis based on performance models, decision and risk methodologies to enhance chances of success.

For areas with little information we aim to develop and test novel methodological approaches to unlock hidden geothermal potential. These can be improved from adopting portfolio and option theory approaches developed for the hydrocarbon industry, dedicated exploration techniques and synergy in exploring geo resources (double plays).

State of the art

GEOTHERMAL EXPLORATION BEST PRACTICES: A GUIDE TO RESOURCE DATA COLLECTION, ANALYSIS, AND PRESENTATION FOR GEOTHERMAL PROJECTS

https://www.geothermal-energy.org/fileadmin/user_upload/documents/best_practice_guide/IFC-IGA_Geothermal_Exploration_Best_Practices-March2013.pdf

H2020 IMAGE book

http://www.image-fp7.eu/reference-documents/deliverables/IMAGE-D2.05-2017.11.02-IMAGE-final-book-public.pdf

Geothermal potential assessment

https://www.researchgate.net/publication/299347329_Geothermal_potential_assessment_for_a_low_carbon_strategy_A_new_systematic_approach_applied_in_southern_Italy

https://pubs.geothermal-library.org/lib/grc/1032377.pdf

Multidisciplinary approach

https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/11068.pdf

Geothermal exploration is progressively targeted in areas with limited surface manifestations (e.g. in magmatic areas) or in sedimentary basin structures which cannot rely on existing subsurface data such as wells and seismic in mature oil and gas basins.

Hidden potential in such areas can add significantly to the geothermal resource base, but require innovative technical workflows and risk management approaches.

https://www.researchgate.net/profile/Whitney_Trainor-Guitton/publication/255822386_Value_of_spatial_information_for_determining_geothermal_well_placement/links/547e314b0cf2c1e3d2dc1bc0/Value-of-spatial-information-for-determining-geothermal-well-placement.pdf

https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2016/Shervais.pdf

https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/11110.pdf

Potential for technological development

Technological development options include

- Development of standard terminology for conceptual and reservoir characterization models – from lithosphere to reservoir scale[2].
- Development of predictive models, processing of existing data and workflows for reservoir characterization for different reservoir types, focussed on multi-disciplinary integration and interpretation.
- Develop public and transparent performance models, decision and risk management (DRM) approaches for optimal decisions in the exploration workflow and provide tools and methodological framework for the techno-economic performance assessment.
- Demonstrate portfolio approaches, and apply value of information approach.
- Adaptive technical and organisational approaches to re-use failed wells for other usage (double play)

Target

(Link: Declaration of Intent)

Reducing exploration costs, by improved workflows reducing uncertainty and enhancing resolution

2 Starting point is the conceptual model – starting from learnings from corresponding areas – and EU catalogues of temperature, stress, rock composition and properties (etc.) to define regional parameters at the first order. The next step is to develop regional evaluation of geothermal resources – need key data to be able to do this successfully – this allows for identifying areas worthy of additional exploration.

Topic 4: Exploration catalogues – reservoir analogues, rock properties and model constraints

Objective

Evolutionary improvement of multiscale (tens of km to meters) and multi-disciplinary regional and site conceptual models and reservoir characterization capabilities, through sharing learnings from comparable productive reservoirs (also hydrocarbon) and geological analogues, as well as building catalogues of rock properties (from integrated site and borehole geophysical methods and lab investigations on key-samples), fracture network characterization and fluid-rock interaction features. Fallout is improved reservoir characterisation in absence of data, and multiscale reference models and maps to feed constraints for regional and site models.

State of the art

http://www.image-fp7.eu/reference-documents/deliverables/IMAGE-D2.05-2017.11.02-IMAGE-final-book-public.pdf

- https://www.geo.tu-darmstadt.de/media/geowissenschaften/fachgebiete/angewandtegeothermie/pdf_2/P3_-_PetroPhysical_Property_Database_short_description.pdf

Potential for technological development

Technological development options include:

- Build and extend relevant rock property databases in synergy with legacy from hydrocarbon exploration and production.
- Develop reference set of lighthouse reservoir models and analogues for different geothermal reservoir types.
- Develop new upscaling approaches from rock sample properties to borehole geophysical logging to integrative exploration geophysics.
- Use empirical correlations of different properties at different scales for geostatistical reservoir parametrization/characterization
- Build multiscale reference maps and models to provide constraints for regional and site models, integrating geophysical, lab and structural models.
- Build a relevant database on the fluid-rock interaction, providing constrains on the variation of rock properties in presence of hydrocarbon/geothermal fluids.

Target (Link: Declaration of Intent)

Reducing exploration costs, by improved regional and site characterization models dealing with relationships among geological structures, rock properties and fluid flow.

Topic 5: Resource assessment

Objective

Approaches are needed that allow reliable estimate resource estimates before the resource has been drilled and flow tested. These approaches are needed for site development and bankability of projects, but also for regional assessment of potential, in view of societal development policies and industrial play based development. To this end a reliable methodology and tools to perform resource assessment have to be developed, as well as communication and reporting protocols.

State of the art

Reserve assessment in the oil and gas industry uses a standard evaluation method. In the geothermal world, the current standard practice is to calculate field capacities based on numerical simulation, once sufficient data are available. There isn't, however, a standardized data set to make these viable. There is a need to have harmonized methods for doing this – Australia and Canada have adopted geothermal reporting codes – but these countries don't have any developed resources – this was required by the local stock markets.

Current partial methods for geothermal are, moreover, existing for a limited set of different types of geothermal resources. There are tested concepts for sedimentary systems (porosity vs. permeability) that could be applied to these types of clastic systems. One complicating factor is diagenesis – this is just a qualifying factor. Other geologic environments could be very different – they should be evaluated in different ways

https://www.unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/UNFC2009_publcom.geoth.2016/20160930UNFCGeothermalSpecsFinal.pdf

https://www.geoth-energ-sci.net/2/55/2014/

https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0407.pdf

https://www.researchgate.net/publication/299347329_Geothermal_potential_assessment_for_a_low_carbon_strategy_A_new_systematic_approach_applied_in_southern_Italy

Potential for technological development

Technological development options include:

- Development of differentiation of resource and reserves estimates based on geologic setting and quantitative methods based on critical performance parameters, using demonstration sites and calibration with developed resources.
- public transparent performance analysis tools for resource potential and site assessment.

- Development of methods and protocols for communication and documentation, including mapping, of the resource and robustness of estimation (at different stages of the project) to stakeholders – for different application, also taking into account economic, environmental and social aspects /risk management.

Target

(Link: Declaration of Intent)

Reducing exploration costs, by improved resource assessment and reporting protocols.

The topic therefore contributes to the firsts of two non-technical factors: Transparent and harmonized methods and instruments for technical and financial risk management.

Topic 6: Beyond Conventional Resources

Objective

Unconventional geothermal resources such as super-hot geothermal systems (SHGS), Enhanced Geothermal Systems (EGS), offshore resources, can significantly contribute to geothermal energy growth in the future.

To develop SHGS (> 400°C), the major exploration objective is capability to detecting suitable reservoirs in terms of temperature, fluid bearing and permeable zones, with acceptable fluid chemistry for production.

EGS are marked by enhanced flow rates through innovative borehole design, reservoir stimulation (e.g. fracking, jetting, chemical treatment, thermal cracking). EGS is key to unlock low permeable geothermal reservoirs, or to improve poor performing wells. EGS is considered an important option to develop intermediate temperature resources (ca 125-250°C) at large depths (4-8km) for direct heat or power production outside magmatic areas. Major exploration challenges relate to predicting reservoir structures and properties.

State of the art

The challenges for the exploration resources can be most effectively be addressed in a global cooperation perspective to optimally benefit from sharing knowledge and access to costly natural laboratories. R&D for unconventional resources is currently performed in H2020 projects GEMEX, DESCRAMBLE, DEEPEGS, DESTRESS, and has been studied in FP7 project IMAGE:

http://www.image-fp7.eu/reference-documents/deliverables/IMAGE-D2.05-2017.11.02-IMAGE-final-book-public.pdf

Potential for technological development

Technological development options include:

• Exploration methods for roots of SHGS geothermal systems, and in depth understanding and predictive models for properties and processes beyond conventional temperature. • Develop theoretical and experimental methods to estimate physical and mechanical properties of rocks near Brittle/Ductile conditions. • Analyse deep super-hot fluids. • Exploration methods for roots of EGS geothermal systems, and in depth understanding and predictive models for properties and processes beyond conventional depth. • Development and testing exploration methods to detect the right reservoir conditions. • Research on novel resources, including offshore, geopressurized and coproduced, magma…
Target (Link: Declaration of Intent)
Reducing exploration costs for unconventional geothermal resources

B. Resource Access and Development

Introduction

Up to 2/3 of the levelized cost of energy (LCoE) of geothermal projects is related to drilling and maintenance of the well field. Therefore, a major objective of the strategic research and innovation agenda is to provide technologies that can result in a substantial reduction of the costs to drill geothermal wells and to reduce maintenance costs. The latter can either be achieved by using alternative materials or by better protection of casings and production equipment against corrosion and scaling. Another basic challenge is to drill deeper reaching higher temperatures. Besides technical limitations of currently available sensors and tools, temperatures above 175 °C in combination with aggressive fluids pose new challenges to the materials used to complete the wells and to the equipment used during drilling and operation. A number of approaches were proposed either to significantly improve respectively to adapt existing technologies. The research spectrum covers all technology readiness levels to provide options for breakthroughs in medium-long term in the field.

The proposed topics or items start with drilling system approaches, which lead to potential improvement in many parts of the processes by considering the drilling process in a holistic way. The topics discussed afterwards may be part of such new drilling systems or can be stand-alone. Less common or innovative technologies for breaking the rocks, e.g., thermal drilling, hammer drilling, electro pulse drilling or laser drilling, are options to be utilized in long-term or medium-term. They require additional research to become applicable for drilling deep geothermal wells. Reliable drilling fluids are extremely important for safe drilling operation. Special challenges are given for high temperature application. High temperatures and corrosion are also bottlenecks for bottom hole assemblies, especially downhole motors and measurement while drilling (MDW) devices.

Reliable well construction and integrity of geothermal casing for special applications at low temperature wells and in general for high temperature well are prerequisite for environmental safe geothermal exploitation. Research approaches are presented within several items. Identifying and surveying these systems needs reliable electronics above 175 °C, which may be applied in measurements while drilling or in monitoring approaches for future geothermal applications.

Topic 1: Optimized drilling technologies

Objective

The objective is to develop and make available fit-for-purpose means and methods for a higher degree of drilling process automation that considerably reduce the lost time and well integrity problems that typically occur when drilling geothermal wells under unknown geological settings. Methods should be based on learnings from the oil and gas industry, but be shaped to the special requirements of geothermal drilling in medium-low permeability, hot and hard rock conditions. At the same time, the to be developed technologies need to match stringent economic constraints that apply to geothermal projects, as compared to the oil and gas environment. Geothermal drilling automation technologies shall reduce cost, increase wellbore integrity and improve Health, Safety, and the Environment (HSE) at the well site.

State of the art

The hydrocarbon industry and mining industry over the past decade has made tremendous progress in developing new downhole sensors, downhole-to-surface communication channels and algorithms to analyze and interpret raw data from drilling devices and the borehole. There are also early approaches to use 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 also the type of sensors does not match the differing needs in geothermal projects.

Potential for technological development

Methods and means 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 focus on European locations. Technology development areas will be among others downhole sensors, bi-directional communication channels, data analytics, learning data bases, automation algorithms and surface control processing hard- and software. Rig mechanization, such as pipe handling machines, will not be developed under this item.

Possible technological developments include new hard- and software devices that reflect the specific needs of geothermal drilling, and automation of the geothermal drilling process through integration of downhole measurements and surface control. The benefits of the new technologies should be demonstrated through laboratory simulation and testing in pilot field projects (in conjunction with geothermal operators).

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.

Target

- Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015.
- Reduce the exploration costs by lowering the costs to drill exploration wells.

Topic 2: Innovative drilling methods

Objective

The objective is to develop proven or new rock destruction mechanisms into highly efficient and versatile rock destruction processes for geothermal applications. The goal envisions maximizing energy transfer effectiveness used to destruct the rock, thereby improving the overall energy efficiency of making hole and incorporating downhole measuring techniques. This should result in realistic solutions to raise the attractiveness of drilling for geothermal wells in soft to hard rock formations is desired.

State of the art

Rotary drilling is the dominant drilling method in the geothermal sector today. However, over the past decades several alternative methods to break rocks haven been developed and tested. These include breaking (hard) rock via thermal alteration, high-pressure fluid injection, spallation or electric discharge in the rock. Some of these methods have are already being used in other sectors. Percussion drilling or hammer drilling is commonly used in the mining sector. 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 soft through soft sediments. Other techniques such as spallation, flame-jet and electric discharge drilling have only be tested at lab scale. The experience and test data point out that under certain geological conditions these drilling methods can result in higher rates of penetration (ROP), less wear and – in some case – a lower energy use than traditional rotary drilling. In addition, they may be effective for operations to increase or restore the productivity of geothermal wells: examples are the drilling of radials by jetting and the use of laser drilling to remove scaling.

Innovative drilling methods can also be combined. First lab and field results show that a combination of 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 of the equipment and can lead to fewer round trips to replace worn drilling bits.

Potential for technological development

With conventional mechanical drilling methods one reaches drilling speeds of up to 3 m/h in hard rock, meaning that rock breaking and rock removal should be greatly improved to reduce cost of drilling. The above mentioned technologies have been tested on lab scale or in the field under full size drilling conditions, but need further development to be applicable for drilling deep geothermal well. 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, developments are needed with respect to the bottom hole assembly (BHA) that is needed for the ‘full size drilling conditions’. These developments should lead to effective solutions to deal with drag, to remove of cuttings, and to allow directional drilling and measurement while drilling (MWD) (ID drift and hydraulics).

Perhaps the most promising aspect is the integration, fusion and optimization of separately existing technology with proven performance in drilling, thereby reducing research and development risks and increasing project attractiveness and enhancing the chance of the technology to go market.

The R&D should aim to:

• Develop new drill methods for hard rocks without bit wear and high ROP (> 5 m/h);

• Research and optimize the rock destruction principles;

• Develop hybrid drilling systems to drill with higher ROP, lower WOB and less torque;

• Design and test adequate BHAs;

• Demonstrate benefits of technology under field conditions.

Target

- Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015;
- Reduce the exploration costs by lowering the costs to drill exploration wells.

Topic 3: High temperature Bottom Hole Assembly (BHA)

Objective

Development of high performance drilling systems enabling directional drilling of deviated wells in formations with a temperature of 150°C to 300°C.

State of the art

State-of-the-art directional drilling with standard elastomer based stators of downhole motors and MWD systems is limited to a temperature 150°C or 175°C.

Potential for technological development

Develop and test of a commercial 300°C directional drilling system based on a 300°C downhole motor and MWD System. Improvement of cost efficiency of drilling systems for geothermal applications.

Target

- Reduce the exploration costs by 25% in 2025, and by 50% in 2050 compared to 2015 (4)
- Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015 (5)
- Enable directional drilling in high enthalpy reservoirs

Topic 4: Innovative drilling fluids

Objective

Noel technologies and eco-friendly materials for the formulation of suitable drilling fluids that are stable under the conditions met in (ultra-)hot geothermal reservoirs or that can be used in combination with new drilling methods (see topic D.2)

The solutions should be able to provide a good compromise between cooling power, temperature drop, rheology and operation time (cost effective). They can also be used to protect against corrosion from mineralized (hot) water or acid gasses.

State of the art

A series of potential additives for enhanced thermal and rheological properties exist, e.g.:

- Nanoparticles: Nano zinc oxide, carbon nanotube, silica Nano particles, aluminum oxide Nano particles, graphene, and hollow glass spheres;
- Traditional additives for water based drilling fluid potentiated with the above mentioned additives: Bentonite, Xanthan Gum, Starch, Synthetic polymers, copolymer and tetra-polymers;

- Non-conventional drilling fluids: carbon dioxide (gas) as circulation fluid, ionic liquid, vegetable oil (crude palm oil chemically modified), active cooling methods based on phase change from solid to liquid as well as from liquid to gas;
- Green and eco-friendly products or additives (mainly filtration controlling purpose): pistachio shell, sugar cane ash, tamarin gum, ground coca bean shells, rice fractions, cotton seed hull, coconut coir, fibers (natural), ground peach seeds, ground nut shells and nut flour.

Potential for technological development

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

- Design of new drilling fluids that are stable under high-temperature, chemically aggressive conditions;
- Develop drilling fluids with improved rheological properties to drill faster and cheaper in hard rocks and hard environments;
- Develop drilling fluids that protect drilling equipment and casing against corrosion from mineralized (hot) water or acid gasses;
- Develop effective methods to control mud losses in geothermal reservoirs.
- Attention should be paid at the rheological properties of the new drilling fluids, their environmental characteristics such as biodegradability and recyclability, and their potential to increase wellbore stability and add corrosion protection.

Target

- Reduce the exploration costs by 25% in 2025, and by 50% in 2050 compared to 2015;
- Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015.

Topic 5: Innovative casing and cements

Objective

- Improve casing material to guarantee integrity and fatigue life under challenging conditions in geothermal applications
- Investigation, Research and demonstration of cost and performance effective (i) corrosion resistant materials including cladded materials, (ii) casing stress and strain reduction to below yield stress, (iii) flexible couplings that allow axial casing movements, casing-cement layer to prevent sticking of casing in warm up.

Despite handful of great advantages brought up by casing drilling in terms of saving time and technical problems, there are still open questions regarding integrity and fatigue life of wells drilled under challenging geothermal conditions (i.e., ultra-high temperatures and pressure, aggressive fluid composition). Reconstructing the complex loads acting on casing string while drilling and during the productive life of a geothermal well in laboratory scale, is a very powerful tool to respond those questions and therefore the objective of this research. These 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 reduce the stress and strain below yield stress, modify the casing-cement layer to prevent sticking of casing during warm-up, allow effective hardening of cement in contact with hot, aggressive fluids, and improve the resistance of casing and cement against corrosion and disintegration.

State of the art

First in situ results show that high austenitic stainless steel types and nickel alloys have promising resistance against corrosion by hot, mineralized fluids encountered in Icelandic geothermal fields. Aging and possible phase changes due to high temperatures have to be verified before standardized for high temperature geothermal use. Moreover, test are needed to see how these materials behave under other reservoir conditions (chemical and temperature).

The application of a protective coating is an alternative for the use of high grade steel types and alloys. This typically is done through deposition or cladding; Cladding for economical use of high cost materials have to evolve to lower the material cost to 25-35% of full thickness use of these materials while the state of the art is around 70%.

Success of high temperature wells (>300°C) with “locked” casing are as low as 50% due to structural failures resulting from plastic deformation and collapse of the casings. Work on Flexible Coupling concept where the axial movement of the casing is allowed give hope to have controlled below yield stress situation in casings.

There have been so far several prevalent standard laboratory facilities in industry to carry out the analysis of response of tubulars under complex loads. These facilities despite being accepted, have not been able to reconstruct a comprehensive working conditions for casing string’s global loads. These facilities lack one or more loading conditions. This means less accurate understanding of the material behaviour under real and harsh conditions encountered in geothermal application.

Potential for technological development

With conventional design and completion techniques high costs are related to well failures, often with need for permanent plugging or reduced flow of wells due to mechanical instability or plastic deformation. Corrosion of industry standard materials for casings due to sour fluids in deep drilling needs to be solved both economically and practical.

The conventional test facilities have been limited in realizing the loading conditions on tubulars encountered in (ultra-hot) geothermal wells. New comprehensive lab facilities that allow full scale testing of casing string's material and connections are needed in order to more accurately estimate component behaviour. This will provide well-engineers and operators better guidance for selecting connections and materials depending on the (expected) reservoir and production conditions and will increase the environmental safety and cost efficiency of drilling operations.

The innovation potential and technology development include:

- New economical solution for corrosion resistant casings;
- Cladding has to be developed to lower the cost;
- New coupling techniques have to be verified and demonstrated to lower the casing failures due to plasticity or mechanical instability;
- New cement formulations need to be developed to lower stress & strain on the casing during warm-up and to guarantee efficient hardening and stability under harsh conditions;
- Research and detailed analysis of circumstances that casing string has to go through in geothermal applications;
- Providing more effective approach to study and analyse material and connection behaviour;
- Providing more efficient vision for proper selection of material i.e. efficient estimation of economical and operational aspects;
- Develop a test facilities to reconstruct real conditions in casing drilling for geothermal applications.

Target

- Reduce the exploration costs by 25% in 2025, and by 50% in 2050 compared to 2015;
- Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015;
- Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) below 10 €ct/kWh for electricity and 5 €ct/kWh for heat by 2025.

Topic 6: Measurement & logging while drilling (incl. looking ahead of the bit)

Objective

Enable and improve while drilling information (e.g. to evaluate the formation, anticipate over pressure formations, position the drill bit, predict risk, look ahead and around, support for drilling in critical condition i.e. supercritical and melting zones and brittle-ductile transition) in geothermal environments by innovative methods, including improved downhole recording and communication.

In order to monitor, analyse, control and optimize operational processes related to drilling and well performance, it is necessary to create new technological systems that allow timely anticipation on changes in operating conditions. Traditional technology to monitor 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, environmental aspects of geothermal resource utilization play an ever increasing role which has to be conscious fulfilled. Availability of relevant data, together with a deep process understanding, allows rig and field operators to adjust drilling procedures, production and injection schemes and production strategies to optimize the performance of geothermal wells and fields. Proper planning and improved real time decisions will allow to manage the geothermal resources better and achieve costs minimization of operational and maintenance activities.

Parameters to be monitored with the innovative technologies include drilling parameters (e.g., the position of the bit, vibrational load, WOB, torque, mud weight and flow), reservoir and production conditions (e.g., P, T, pH, EC, TDS) and well integrity (e.g., cement and casing mechanical integrity monitoring, zonal isolation).

In addition, tools should be develop to ‘look ahead’ of the bit. These tools will allow rig operators to early detect over-pressure, to evaluate the formation and to predict bottom hole temperatures. Moreover, being able to image formations around and ahead of the bit (2D and 3D) will provide precious information about the characteristics of the geothermal reservoir.

State of the art

Recently, single well imaging techniques (SWI) including seismic sources and receivers close to the BHA have been tested. Examples of such techniques are seismic while drilling (SWD) and vertical seismic profile while drilling (VSP-WD). These systems use either standard acoustic LWD’s or new developed tools to image the borehole surroundings with signal frequencies in the kHz range. SWI approaches take advantage of the complete recorded seismic wave field to image surrounding structures up to tens of feet. Advantages of this approach are e.g. the depth independent resolution and low extra costs for data acquisition. High spatial wave field recording is enabled due to the quasi-continuously recording without coupling to the borehole. Limitation can be low signal-to noise ratio in particular for later recorded events 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). Potential technological developments include, e.g.:

- Under high temperature and/or high pressure conditions;
- In heavily deviated to (sub)horizontal wells;
- For measurements between surface and positions in the well during drilling, e.g. the Drill bit SWD System or;
- Analysis of the borehole waves and reverberations, linked also to the mechanical properties of the drilling system;
- Technologies to provide cross-well data, e.g., in joint use with DAS, Drill Bit SWD in conjunction with seismic interferometry;
- Producing better images, and perform rock characterization close to the target, with high resolution data considering e.g., complementarity of lower frequency drill bit SWD data with other higher frequency steering methods;
- Methods to adjust the well trajectory to a more precise target during drilling, e.g., through operational organization such that the results can be processed and interpreted “real-time”;
- Real-time downhole-surface transmission, e.g., mud pulse, EM, acoustic drill pipe;
- Surface-synchronized down-hole memory recorders to provide While Drilling (WD) results which can be synchronized after tool retrieval with surface system data;
- Minimizing vibrations of the drilling string for an optimize and readable signal to noise ratio by using recent cutting-edge shock absorber technology above the BHA;
- 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.

Target

- Reduce the exploration costs by 25% in 2025, and by 50% in 2050 compared to 2015;
- Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015;
- Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) below 10 €ct/kWh for electricity and 5 €ct/kWh for heat by 2025.

Topic 7: New monitoring tools – HT-electronics

Objective

The aim is to develop electronics and sensors to be used in in high-temperature geothermal wells during drilling operation in order to ensure reliable MDW and to enable logging while drilling (LWD), to be used during well construction and testing, and to perform (continuous) integrity checks of the wellbore and wellbore equipment.

Drilling of high-temperature and high-pressure geothermal wells requires sensors and electronics with a high temperature and pressure rating. For tools that are used during drilling operation improved cooling solutions by circulation of drill-mud can be developed.

State of the art

Many sensors to measure drilling parameters such as BHA shock and vibration are limited to 175°C. Tools to monitor/optimize the drill string at real time at higher temperature are few. Currently tools from O&G industry is adopted to drilling geothermal wells. Honeywell reported in 2013 demonstration of a 300°C capable steering tool.

Logging tools and sensors for slickline operations are available up to 450°C (DESCRAMBLE-project), but the available MWD and LWD tools are very few and limited in use. Moreover, communication over wireline (E-line) is not available above 300-350°C.

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

- Little knowledge of predictive models of BHA performance in high temperature;
- Hardly any real time downhole monitoring during injection and production. p/T sometimes available at ESP/injection string;
- For high temperature wells (>150°C) only limited number of tools available for well logging and evaluation, mostly p/T memory gauges;
- Little knowledge of intelligent completion hardware and software tools and devices: inflow devices, production logging, monitoring. Real-time monitoring downhole in low temperature wells along the production string, hardly ever in the reservoir interval.

Potential for technological development

The envisioned technological developments include, e.g.:

- High temperature electronic components capable used above 175°C up to 300°C;
- E-lines capable used above 300-350°C;
- Improved heat shields (Dewars);
- Improved cooling techniques of electronics and sensors. This will allow use of standard electronics below 175°C;
- New sensing technologies (e.g. fiber optics);
- Integration of the new sensing tools into the well design for efficient monitoring of reservoir and well performance at real time.

Target

Based on the predefined targets in the declaration of intent:

- Increase reservoir performance resulting in power demand of reservoir pumps to below 10% of gross energy generation and in sustainable yield predicted for at least 30 years by 2030;
- Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) below 10 €ct/kWh for electricity and 5 €ct/kWh for heat by 2025.

Topic 8: Optimized and disruptive technologies for enhancing energy extraction

Objective

In general, hydraulic stimulation can be described as injection of fluids at high flow rates into reservoirs to develop new fractures or reactivate existing fractures. The aim is to enhance the productivity of low permeability rock for extraction of hydrocarbons or energy extraction for geothermal use. In geothermal applications these stimulation treatments are required to develop suitable heat exchangers to extract economic amounts of heat and are referred to as Enhanced Geothermal Systems (EGS).

The general aim of hydraulic stimulation is to develop an advanced injection strategy to control the fracture propagation and simultaneously reduce the risks of unwanted seismic events beyond a certain threshold depending on the vulnerability and exposure of people, buildings and infrastructure. In this context many efforts have been made to develop stimulation concepts to mitigate the risk of unwanted high seismicity and simultaneously enhance the permeability of the rock. One option to optimize the development of fracture networks based on hydraulic fracturing treatments are advanced protocols like cyclic or pulsed injection schemes. Other ways to improve heat exchange and transport should be also developed.

State of the art

Hydraulic stimulations in EGS systems are carried out selectively, uniquely and controlled to achieve sufficient flow rates for the economic utilization 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 optimization of stimulation treatments with respect to unwanted effects like induced seismicity and hence the reduction of the probability of felt events. Designing a special concept of the well path, 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.

Potential for technological development

Enhanced geothermal systems (EGS) are engineered reservoirs developed to extract economic amounts of heat from low permeability and/or porosity geothermal resources. To enhance the productivity of reservoirs, a site specific concept is necessary to actively make reservoir conditions profitable 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. These stimulation treatments enhance the productivity of low permeability geothermal reservoirs by inducing new fluid pathways. The overall goal is to develop a sufficiently large heat exchanger at depth to extract the necessary amount of heat. In addition to a pure hydraulic stimulation, it can be combined with a chemical treatment and/or thermal fracturing (i.e. cold water injection). This is achieved adding acids to extend hydraulic pathways by dissolving minerals or due to thermal induced fracture development.

Another option is the Radial water Jet Drilling (RJD) technology to increase inflow into insufficiently producing geothermal wells and thus enabling a more sustainable utilization of geothermal resources. RJD uses the power of a focused jet of fluids, applied to a

reservoir rock in order to create several horizontal holes. These laterals from an existing well into the reservoir aim to drain initially not connected high permeable zones to the main well. A combination of chemical treatment and radial jet drilling can be also envisaged. The radials increase the pay-zone and overcome the near wellbore skin. The chemical treatment will increase the hydraulic performance in the vicinity of the wellbore and the radials.
Target (Link: Declaration of Intent)
According to the declaration of intent, the target of stimulation is to increase reservoir performance resulting in power demand of reservoir pumps to below 10% of gross energy generation and in sustainable yield predicted for at least 30 years by 2030. Based on these constraints, the general aim is to reduce overall costs by actively developing geothermal reservoirs. It follows the ambition to reliably increase system performance of EGS, making the improvements sustainable and at the same time minimize environmental impact, in particular the level of induced seismicity. These issues have been at the center of public concern, leading to widespread opposition to EGS project developments. The specific challenge in this approach lies in the generation of the desired permeability by hydraulic stimulation methods, which requires elevated injection pressures, while to minimize the magnitude of unwanted seismicity. These two goals seem to be mutually exclusive, requiring a compromise. The innovative aspect is the concept for stepwise hydraulic stimulation, which is designed to reconcile these two goals and to overcome the deadlock on in EGS developments in that way.

Topic 9: Total re-injection and greener power plants

Objective

Improved environmental performance of high- temperature geothermal power generation systems, avoiding the release of steam and potentially hazardous chemical compounds into the atmosphere and ecosystems.

The objective is to develop viable, safe, and cost-efficient technologies to improve the environmental performance of geothermal systems by avoiding the release of steam and potentially hazardous chemical compounds into the atmosphere and ecosystems. This should result a sustainable use of geothermal resources, by total reinjection of fluids into the reservoir total and complete control of the condensable gases (if any):

- Development of coupled well-reservoir multiphase flow model, taking into account the interactions between chemical and physical properties of geothermal fluids and the geo-mechanical behavior of the reservoir rocks.
- Development of technology for Non Condensable Gases (NCGs) capture, sustainable use, abatement or reinjection, including the selection of the most advanced materials able to operate in harsh environment.
- Demonstration of the competitiveness of the new cost-efficient developed technologies at field test sites including monitoring of the performance of the plants and comprehensive economic analysis.

State of the art

Total reinjection is not a pervasive practice in high-temperature geothermal power generation systems yet, mostly due to the high concentration (>2% in some areas) 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 the reservoir permeability, and promotes the fixation of the dissolved gases by mineralization. This technique is not immediately applicable in case of sedimentary or crystalline reservoir rocks and for high rate of CO2.

However the reinjection of CO2 and other NCGs is quite common practice in petroleum industry (EOR) having been used for 30 years, to increase the 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. Fluids chemistry and its interactions with rocks have a crucial importance in reinjection projects, minimizing operational risks and improving geothermal sustainability.

Potential for technological development

- Laboratory tests and modeling of the re-injection systems.
- Global computational tools like coupled well-reservoir simulator with the aim of optimizing and calibrating the injection in both surface and subsurface domain.
- Proper well completion with site-specific design.

- Development of innovative system to avoid/reduce discharge of geothermal fluid into atmosphere during outages of power plant.
- Treatments of radioactive materials.
- Metallurgic studies and new materials development for the equipment in sour HPHT environment.

Target

(Link: Declaration of Intent)

- Increased social acceptability and mitigation of unsolicited side effects (induced seismicity, emissions to the environment).
- New technologies should be developed to improve the environmental performance of high- temperature geothermal power generation systems, avoiding the release of steam and potentially hazardous chemical compounds into the atmosphere from the cooling tower, as well as non- condensable gases (NCGs) like carbon dioxide.
- In particular the feasibility of closed-loop reinjection of liquid and NCGs for gas-reach resources should be demonstrated

Topic 10: Optimized monitoring for resource development

Objective

Corrosion, erosion and scaling are solved for geothermal industry, but technologies are non-optimized. Optimization would produce:

- Safer operation. Avoid unexpected plant accidents associated to equipment failure due to corrosion or scaling.
- Maximize plant reliability. Avoid unplanned downtime due to unexpected corrosion or scaling issues.
- Asset protection. Minimize corrosion to maximize life of all equipment in the plant (wells and surface equipment) which are a significant percentage of plant investment.
- Maximize energy recovery. By maximizing heat transfer on exchangers and minimizing energy losses due to e.g. bubble pressure control.
- More environmentally friendly operation. Use less chemicals to control scale and corrosion, use greener chemistries.

State of the art

Corrosion protection in geothermal plants is a well stablished technology. The use of filming corrosion inhibitors is generalized, leveraging from experience developed over decades of corrosion control in oil & gas business. Films and coating however suffer from physical erosion.

Scale control in geothermal plants is a well stablished technology too. There is virtually no geothermal plant right now suffering a scale problem that can't be solved. Chemical treatment companies have leveraged from boiler, cooling towers, seawater evaporators and oilfields scale control technology to solve scale issues in the geothermal plants.

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

Scale predictive models are also well stablished. Opposite to corrosion modelling, scale modelling in geothermal has been a research field for years and several modelling software like WATCH or Nalco's Geomizer. These tools are already commonly used to predict risk of scaling in new project or existing plants.

Scaling and Corrosion prevention is usually done while planning the system, using well designed plant scheme that allow control of bubble pressure (e.g. CO_2) along all the plant, wellhead and reinjection pressure and temperature control, specific material designed for the operating conditions and chemicals injection lines designed for the expected scaling.

Erosion is typically solved now by upgrading metallurgy which is an expensive solution. Here is an overlap with material study, due to physical erosion, sulphydization, hydrogen cracking, dusting and many other mechanisms involving chemical and physical coupled effects.

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

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 being used to evaluate flow path, to determine reservoir rock volume and water-rock heat transfer surface in geothermal reservoirs. The available tracers however are not stable at high temperatures or may interact with components with the geothermal fluid.

Environmental impact:

- Currently mining authorities give approval for the addition of chemicals into the geothermal fluid to avoid scale or corrosion.
- Typically, the approval or assessment is based on Biodegradability by OECD tests or based on CEFAS classification of products. None of these criteria represents a thorough understanding of the impact of chemicals usage in geothermal reservoirs.

Potential for technological development

Corrosion management is not optimized yet. Optimization of the assessment - monitoring and control scheme can reduce the use of chemicals and the minimize environmental impact. This includes reliable, models for corrosion forecasting. Here lessons can be learned from O&G. Predict corrosion control is needed early on during project development.

Greener Corrosion Inhibitors can reduce the environmental impact. Today, all filming corrosion inhibitors are surfactants and pose a risk to the environment.

Alternatively, new coatings and corrosion-resistant materials can be developed that would no longer ask for to use chemical treatment programs. Moreover, functional coatings of material surfaces can help to reduce or even avoid the formation of scale.

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

On-line scale cleaning as an alternative or complementary solution to continuous scale inhibitor use.

The fate in of chemicals used for scale and corrosion prevention in geothermal reservoir and surrounding environment need to investigated, e.g., through simulation and/or model, as well as lab and field experiments.

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

Target

(Link: Declaration of Intent)

- Reduce by 50% average downtime of geothermal plants in EU due to scale or corrosion. (Benchmark study to be done to define base average case).

- Reduce by 25% average maintenance costs for equipment replacement or cleaning. (Benchmark study to be done to define base average case).
- Move 100% of EU Corrosion Inhibitor applications to WGK1 technologies.
- Reduce Corrosion Inhibitor use by 25%. (Benchmark study to be done to define base average case).
- Increase Brine energy recovery by 10% in ORC units.

Topic 11: Optimized management techniques for geothermal systems

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 point of view, this objective implies a reduction of costs during both design and implementation phase. Such a goal may be achieved by developing innovative full-cycle prediction models to face one or more of the following issues: (a) Couple the estimate of reservoir potential with near-well phenomena and well-flow stability. (b) Assure the flow stability in the distribution network in terms of pressures and temperatures. (c) Control and predict scaling or corrosion phenomena in pipelines. (d) Estimate various scenarios during the network design, to get the optimal network configuration. (e) Control and reduction of plant emissions and chemical consumption minimization through optimized process control and management, to reduce environmental impact.

State of the art

The analysis of the technical and scientific literature has highlighted the enormous efforts made to understand the mechanism of energy transport in geothermal piping networks. Several studies have been performed to evaluate, identify and solve the issues related to the simulation of heat and mass flow in network and process plants, with emphasis on the following aspects:

- characterization of the flow of the fluid affected by uncertainties of 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 are reported in the technical literature, as well as for those related to reservoir and process plants, including advanced fluid cycles [GarcíaValladares et al., Energy Conversion and Management (2006); Liu et al., Networks Journal of Hydrodynamics, Ser. B 21 (2009); Hasan and Kabir, Journal of Petroleum Science and Engineering, 71 (2010); Sancheza et al., Mathematical and Computer Modelling 57 (2013); Verma, Revista Mexicana de Ciencias Geológicas, 30 (2010), Huang and Freeston, Proc. 14th New Zealand, Geothermal Workshop (1992), Peluchette and Anderson, Thirty-Eighth Workshop on Geothermal Reservoir Engineering (2013)]. Conversely, the state-of-the-art concerning integrated models covering all the aspects of a geothermal installation, in terms of physical capabilities, production issues, management operations and production optimization is quite poor. Excluding the codes used for nuclear power plants licensing (which are very complex, but not available for the market, and subject to strong restrictions in terms of licensing and user qualification), the other tools are limited in physical description and capabilities. They are based on broad simplification of real behaviour of components and this implies strong impacts in the accuracy of system design. Most of the models available for geothermal networks are confined to the study of stationary flow, neglecting impact on production of fluid composition, operational transient and interaction with electrical grid and process plant. In addition, despite the large amount of work available in literature regarding scale impact in geothermal pipes and components, corrosion issues due to aggressive gases (J.Nogara,S.J.Zarrouk,2017 Renewable and Sustainable Energy Reviews, G.Allegrini, G.Benvenuti, Geothermics,1970), few research initiatives have been carried out to couple the above phenomena with geothermal fluid mechanics development. In No significant activities neither available tools are so far well developed in coupling design, management and long-term operation of geothermal plants, which are the strategic points to make geothermal energy more profitable in economic terms, more environmental friendly and more standardized to be easily replicated across the world.

Potential for technological development

The strong differences in terms of temperature, pressure and chemical composition of the geothermal reservoir with the surface equipment (especially when dealing with deep geothermal plants), the interactions among physical behavior and operational requirements of geothermal installations, the impact of working conditions on component materials and lastly the requirements in reducing environmental impact of these plants, require a predictive capability addressing: (i) the multiphase flow behavior on wells, pipes and other components; (ii) issues generated by geothermal fluids on components performances; (iii)the impact of new materials, equipment or operative methodologies in future geothermal plants. This aspect is essential for the design and operations of a complex system that integrates different elements with dynamic behaviour. The integration of several scientific areas typically isolated each other's (reservoir, well engineering, fluid dynamic and pipeline transportation, fluid chemistry, power plants and production cycles, safety analyses) will allow to identify interactions, feedback and impacts of each area over the others, to define new working methodologies, to develop new knowledge to manage phenomena occurring in the crossing areas and interfaces among geothermal environment. Finally, thanks to a predictive approach regarding the behaviour of a complex system as a geothermal plant, it will allow to integrate the specific efforts on different disciplines in a common frame, to take into account interaction and feedback from different production aspects. This approach will boost the design of optimized 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 optimization and environmental impact minimization
- design of unconventional and hybrid systems, and prediction of performances
- integrated electrical grid-power plant design and management
- cost–benefit forecasting analyses based on a deterministic scenario approach

Target

(Link: Declaration of Intent)

Based on declaration of intent on strategic targets for Deep Geothermal Energy and the agreed strategic targets, the following milestones will be achieved by the present research topic:

- Increase overall energy requirements for geothermal power generation resulting in power demand to below 10% of gross energy generation and in sustainable yield predicted for at least 30 years by 2030;

- Improve the overall plant efficiency, including wells, pipelines and plant equipment at different thermodynamic conditions by 10% in 2030 and 20% in 2050;
- Reduction of geothermal plants OPEX in terms of improvement of plant operation schedule, manage aggressive fluids to limit equipment failure, optimize fluid treatment to comply with environmental constraint using tailored production cycles, to reach energy costs below 10 €ct/kWhe for electricity and 5 €ct/kWhth for heat by 2025;
- Demonstrate the technical and economic feasibility of responding to commands from a grid operator, at any time, to increase or decrease output ramp up and down from 60% - 110% of nominal power.

Topic 12: Optimized production pumps

Objective

During operation, energy demand for pumping as well as maintenance and replacement of production and injection pumps can be a burden on overall plant efficiency and profitability. Hence the overall objective is to improve pump efficiency and longevity, to secure production reliability, to develop tools for avoiding two-phase flow in wells, etc., in order to upgrade exploitation economics. The two goals are to:

- Improve submersible pump operational efficiencies and longevities securing sustainable single phase liquid (i.e. gas/steam free) production at optimum power ratings within the 150-200°C binary cycle geopower temperature range.
- Bridge the higher temperature 200-300°C technology gap expected from Oil and gas Electrical Submersible Pump (ESP) steam flood practice and Line Shaft Pump (LSP) in house manufacturers' experience addressing sensitive fluid environments.

State of the art

Of the three submersible pump concepts eligible to deep seated, hot and thermochemically sensitive reservoir environments, namely electrosubmersible (ESP), (enclosed) lineshaft (LSP) and turbopump (TP) the two first quoted widely dominate the geothermal production market. The once popular within the geothermal district heating TPs have been progressively abandoned owing essentially to their structurally lower efficiencies and occasionally to inhole packer shortcomings.

LSP and ESP artificial lift, currently operates at temperature, depth and power ratings standing within the 150°C-180°C, 500 m, 1 000-1 200 HP ranges.

Pros and cons of LSP vs ESP technologies, often opposed in the past, tend nowadays to shade off as a result of the newly set performances ambitioned by both parties. The higher efficiencies claimed by LSPs (surface motor) over ESPs (in hole elongated motor) would be somewhat offset by the larger submersion depth and subsequent shaft length (750 m) challenged by LSP manufacturers and its presumably higher reliability and longer life expectation mitigated by a complex enclosing tubing/shaft/bearing assembly, compared to a simpler ESP shaft transmission design.

The booming development of the widespread medium enthalpy (100°C-180°C) resources and combined geopower/geoheat (CHP) production is acting as a strong stimulus among the pumping and power (ORC turbine) industries adding thousands of megawatts to the presently installed capacities. This trend noticed in Turkey (Anatolian Aegean façade), Western USA (Southern California, Nevada), Europe (Southern Germany, Molasse Basin, Rhine Graben), it leads the pump industry to rise in the very near future its operating standards to 200°C, 750 m and 1 500 HP.

The LSP leading position on the market is getting challenged by long hesitating ESP manufacturers, a competition beneficial to the geothermal community.

Future RD&D developments should be directed towards the dominating high enthalpy geopower sector and related pressurised liquid reservoir settings, exhibiting fluid temperatures close to when not exceeding 300°C.

Presently high temperature serviced ESPs currently operate at ca 250°C in steam flooded horizontal wells aimed at recovering heavy crude via the so called SAGDS (Steam Assisted Gravity Drainage) process. However should be borne in mind (i) power ratings limited at ca 250 HP, and (ii) a 300°C induced motor winding temperature.

Such operating conditions would elsewhere require dramatic efforts designing high temperature resistant enclosed line shaft/bearing assemblies and stable shaft lubricating mixtures.

Extending both limetimes and power ratings would require two prerequisites in producing thermochemically hostile fluid environments, first robust downhole chemical injection lines and second authorisation from concerned mining/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 two phase geothermal reservoir and deserve accordingly a specific technological research of technological.

Potential for technological development

- Development of high temperature resistant, high efficiency ESP;
- Improvement of enclosed LSP technology in producing high to very high temperature pressurised liquid resources.

Target

(Link: Declaration of Intent)

- Increase reservoir performance resulting in power demand of reservoir pumps to below 10% of gross energy generation and in sustainable yield predicted for at least 30 years by 2030.
- Reservoir performance includes underground heat storage.

C. Heat and electricity generation and system integration

Introduction

This chapter focuses on energy conversion processes, surface systems of geothermal plants and the integration to the energy system of the geothermal heating, cooling and electricity supply.

The challenge is to improve and made affordable generation technologies by:

- Increasing the efficiency, and reducing losses and internal consumption on energy conversion processes;
- Improving reliability and durability (resistance to corrosion, abrasion) of surface system equipment;
- Reducing the overall cost for heat and power generation;
- Adapting plants to be base load and dispatchable for an integration to the energy system.

Deep geothermal adds stability and flexibility to the future energy system, interconnected at local level, fed by a variety of local (renewable) energy sources and coupling various energy sectors (i.e., electricity, heating & cooling and transport).

Deep geothermal is also a unique heating and cooling source for fourth generation district heating & cooling (DHC) networks, for the tertiary sector and for industrial processes.

Through underground thermal energy storage it will be possible to balance heat demand and supply in the smart thermal grid.

Topic 1: Advanced Binary plants

Objective

The objective is to develop advanced low to medium temperature binary plants. The goal is to minimize the second law efficiency losses; on the other hand, from a techno-economic perspective, cost-efficiency is pursued depending on the economics of each project. Thus, the primary aim are techno-economic tailored solutions reducing the overall plant costs or maximizing the efficiency of the plant. Moreover, since the thermal source is continuously available, reliability and availability are key factors that should reach the highest possible percentage through implementing redundancies on critical items and using high quality components.

State of the art

Today most of the installed geothermal binary power plants utilize 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 engineering size and features of technical components which include auxiliary systems, such as firefighting and operational issues. In fact, there are only few installed geothermal power plants which use organic non-flammable working fluids i.e. refrigerants. Only with a technical and commercial development of new and more readily available refrigerants, the number of installed geothermal plants utilizing such working fluids would increase. 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 related to a well defined ambient and a resource with a given temperature), the actual installed binary plants are close to the maximum efficiency, almost reaching 75% when exploiting fluids at different pressure levels with cascaded heat transfer processes. Pushing the plant efficiency at its highest level however is not recommendable as it would lead to cost increases that would jeopardize the project feasibility.

The actual state of the art includes also supercritical cycles, such as the ones using CO_2, even if all the available working fluids do not respond to the required boundary conditions, i.e. the geothermal resource does not allow to reach the critical temperature of the working fluid. In fact, thermal efficiencies are very low, because of the small temperature difference between the hot and the cold sources. Today all the projects employing CO_2 as working fluid are in an R&D phase and funded by specific research programs. Also, the use of hybrid renewable systems that could significantly improve the thermal efficiencies, are in an R&D stage.

Potential for technological development

Since one of the most impacting variables is the working fluid, technological development aims at defining its thermodynamic conditions to improve plant performances.

Features to be considered for these improved fluids are:

- Saturation conditions
- Thermal stability
- Flammability
- Explosivity
- ODP
- GWP
- Costs

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

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

Another technological challenge is to improve specific components of the binary cycle: design of improved heat exchanger, selection of material, surface structure and coating to enhance heat transfer and minimize scaling, increase efficiency of cooling system by enhancement of air-cooler/condenser and matching to cycle efficiency of components (also developed in other topics below); hybrid cooling of binary cycles working with low temperature geothermal source, integration with heat or cold supply via novel cascading concepts. Lastly, a standard technology suitable for Non-Condensable Gases (NCG) could reduce the overall carbon footprint of the geothermal binary plants.

Target

The energy cost reduction of binary systems will pass by:

- Reducing the plant footprint by 15% and the overall plant costs by 10%, 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 the average turbine efficiency throughout a continuous development in the Computational Fluid Dynamics (CFD) technology;
- Increasing the net cycle efficiency with the use of new fluid mixtures both in subcritical and supercritical configurations;
- Reducing the thermal wastes by 10%, without increasing the rotating components nor the plant complexity, by designing new multilevel configurations also allowing the decrease of the irreversibilities between the thermal cycle, the resource, the environment and the end use;
- Reducing the Balance of Plant (BOP) costs by 10%.

The quantitative targets from the SET Plan declaration of Intent on deep geothermal are:

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

#3. Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other

renewable energy sources) below 10 €ct/kWhe for electricity and 5 €ct/kWhth for heat by 2025

Topic 2: High temperature binary power plants

Objective

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

Binary plants are in fact environmentally much more 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 substances potentially unfavorable to the environment can be prevented, thus virtually eliminating pollution problems. Moreover, if no condensate or liquid fraction of the geothermal fluid is used for the heat rejection to the ambient, full reinjection of the geothermal fluid is feasible, and no depletion of the geothermal reservoir occurs. Since the geothermal fluid flow is restricted in a closed loop, high resistance materials or filming corrosion inhibitors are then required only for the heat exchangers in contact with the geothermal fluid, giving way to a possible plant cost reduction.

Alongside the positive environmental performance, increasing energy conversion efficiency and improving cost effectiveness of the binary plant remain fundamental objectives.

State of the art

Binary technology for high temperature applications, like biomass and waste heat recovery, is currently adopted and considered “state of the art”, with more than 400 plants in 40 different countries. However, in geothermal applications, 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 the conventional flashed steam cycles, for resources at moderate temperatures (up to 150 °C). Production of electricity from geothermal high enthalpy resources 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, etc. An average weighed the data of 16% is a reasonable estimate.

In the range 150-170°C, binary technology is often but not exclusively adopted, 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 selection of the binary technology, which has been done in a very few cases (e.g. Las Pailas plant, Costa Rica), implies a so called high temperature / high enthalpy binary plant with a somewhat different plant scheme and the following features:

- Is capable to exploit both the separated hot brine & steam (two phase flow)
- Allows zero emission operation, if no geothermal fluid is used for the heat rejection process, and full reinjection of geothermal fluid and gases is possible
- Makes no depletion of the geothermal steam as the traditional single flash plants
- Can generate earlier energy to the grid, thanks to the faster implementation time
- Can be relocated, because it has no complicate steam gathering system and can be a modular assembly
- Has low requirement for land (wellhead generation)
- Is a stable base-load energy generation system
- Can be operated in remote areas and isolated grids
- Is scalable to utility size (thanks to the modular technology)

Potential for technological development

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

By the exploitation of high enthalpy, steam dominated resources, key feature of the 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 utilization of the resource. Power plant scheme and material selection for the component need however to be carefully considered in order to exploit the whole resource potential.

The thermodynamic cycle optimization typically involves minimizing the 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 application, the geothermal fluid is generally an all 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 sophisticated optimization and a convenient power plant scheme. The investigation of the geothermal fluid chemistry and properties is crucial for the successful design of power plant. If NCG are present, they must be considered in the heat exchangers design process. A number of series & parallel preheating heat exchangers are suitable in order to extract the heat from the steam, which is condensed and cooled down to the reinjection temperature, i.e. the lowest allowable temperature, compatible with possible scaling problems. In ORC plants, the reinjection brine temperature can also be controlled over the saturation level before scaling can occur by means of a recuperative cycle, adopting 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 fulfill 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, the performance can be more efficient with respect to a flash plant only if a significant portion of heat is extracted from the separated brine. In such way, depending on the brine chemistry, a risk of silica or other species (e.g. stibnite) precipitation can occur, as the saturation condition of the brine may be encountered at low temperature. 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 or filming corrosion inhibitors are then mandatory for the components in contact with the geothermal fluid in order to ensure long operation and high availability of the components.

In the light of the above, an efficient exploitation of the high temperature binary plant is possible only with a careful and thorough plant design, a deep investigation of the geothermal fluid chemistry, the adoption of suitable high resistance material to prevent corrosion and with the implementation of a scaling mitigation procedure (e.g. by means of scaling inhibitors dosing or pH control, or design of the system above the saturation point).

Target

Extend the advantages of the binary technology to high temperature geothermal sources, with particular reference to:

- Enable the whole exploitation of the geothermal fluid
- Enable the containment of the geothermal fluid in a separate loop
- Increase the First law conversion efficiency of the cycle above 20% for high temperature binary plants (i.e. T > 180 °C or enthalpy 1500 kJ/kg)
- Reduce the reservoir geofluid depletion virtually to 0% in the long term (as compared to the single flash plants where all the geothermal steam is continuously lost through the cooling towers i.e. 30% to 50% according to the resource enthalpy).
- increase the wells life thanks to adoption of continuous monitoring systems of the chemistry quality, so as to avoid scaling.
- increase the component life thanks to adoption of a convenient prevention method against corrosion.

The quantitative targets from the SET Plan declaration of Intent on deep geothermal are:

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

#3. Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) below 10 €ct/kWhe for electricity and 5 €ct/kWhth for heat by 2025

Topic 3: Power cycles and mitigation for super high enthalpy 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 (ultra hot or partially molten magma and/or supercritical geothermal resources).

State of the art

Superhot geothermal resources are magma and/or supercritical geothermal systems that have much higher enthalpy and pressures than the geothermal systems that are currently utilized to generate electricity today. They are encountered at 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 favorable 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 takes place due to the highly corrosive and abrasive nature of the produced fluids, attributed to entrained acid gases (HCl, HF, and H_2S) coupled to 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 utilized for power generation) has been tested on surface by a 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). IDDP-1 well had to be abandoned after 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). A new IDP-2 project is currently in drilling phase.

Potential for technological development

Key challenges for further technological development are:

- To demonstrate reliable fluid treatment and steam purification methods, so that the purified steam can be delivered to the turbines in order to generate electricity
- To demonstrate reliable surface equipment suitable for commercial exploitation
- To demonstrate reliable electricity generation from a superhot geothermal well
- The wet scrubbing steam purification method needs to be demonstrated during power generation.
- Further field experiments and demonstration should also include:

- Optimizing the wet scrubbing method in terms of scrubbing water chemistry, heat recovery and step power generation in order to improve overall heat o 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 it is the fluid/steam purification method that results in the highest energy efficiency of the power plant.
- Testing or developing new materials and corrosion resistant surface equipment for extreme high temperature and pressure operation.

Target

As a first step: Develop, install and operate a direct steam expansion power generation plant of at least 25 MWe capacity from a single superhot geothermal well.

Long term vision: Exploit the vast superhot geothermal resources, which are estimated as 10 times higher than hydrothermal resources and of the same order of magnitude with the EGS resources.

The quantitative targets from the SET Plan declaration of Intent on deep geothermal are:

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

#3. Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) below 10 €ct/kWhe for electricity and 5 €ct/kWhth for heat by 2025.

Topic 4 : Flexible production of heat and power

Objective

The increasing amount of very intermittent solar PV and Wind makes that back-up power plants are needed and that geothermal power plants have to be more flexible.

In contrast to those 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 a lot of geothermal systems, the design of the binary geothermal power plants has been optimized for purely electricity production.

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 “recovery” of the higher-temperature “waste” heat in a CHP configuration will result in better economics and higher exergetic efficiency. However, in most cases, the heat demand fluctuates strongly throughout the year, meaning that a flexible CHP plant that fulfills the heat-demand, is called for.

With a growing share of intermittent renewable power, in particular when having priority access to the grid, other types of plants will have to increasingly provide fluctuating back-up power to meet unpredictable demand peaks. Geothermal plants can play an important role in providing back-up power by adjustment of the power production in various response time-frames to assist in the stabilization of the grid. In order to meet the requirements in a grid, the geothermal plant needs to be transformed in a flexible one.

State of the art

Most of ORC systems today are predominantly not so flexible since they are only efficient in one or a few operating point – 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 tight coupling with the heat production. The ORC turbine is treated as a sub-system of the heat and power plant and integrated into its control system without connection to the overall energy grid.

Therefore, it can only be operated according to the heat provision, not according to the heat and electricity demand within the overall energy grid.

Some manufacturers are starting up research and development to increase the flexible operation of the ORC based on novel or adapted turbines and expanders or to go to a more modular approach (smaller units cascaded controlled).

Potential for technological development

Increase the flexibility of electricity production from geothermal wells by

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

- Improved modular design of power plants to adapt better towards electricity needs and heat demand without reducing the overall electrical efficiency and yearly production.
- Optimisation of the connection configuration between the geothermal source, the binary plant and the district heating network (eg parallel connection, serial connection, combinations, etc.) to increase the electricity production taking into account the heat profile and temperature regimes of the district heating network.
- Generation with different voltage for smart grids in specific applications as island or island mode is key for a flexible geothermal power production.

Target

- Development of new type of ORC systems / modules capable to modulate between 20% and 100% and with high ramp-up and ramp-down ratio (eg 10% of power / minute)

The quantitative targets from the SET Plan declaration of Intent on deep geothermal are:

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

Topic 5: High Temperature Thermal Energy Storage (HT-TES)

Objective

In order to fulfil the mismatch between (electricity and heat) production and demand, not only a flexible power plant can play a role, but electrical and thermal energy storage can play an important role.

Most of the power plants until now have no storage included. Regarding thermal energy storage both low and high temperature systems can play a role.

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

State of the art

The deployment of renewable energy sources for both power and heat production is accelerating in Europe, a trend that will continue. However, the variations in both the availability and demand of energy and their integration into the existing energy infrastructure raise challenges in terms of operational variability and balancing. Peak shaving and heat storage can help to balance demand and supply 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 as well as storage in the building mass or the DH infrastructure itself. Different types of electric storage would further increase the system's flexibility.

TES allows converting the waste heat discharged into the environment by industrial processes into a resource. In addition, TES can contribute in developing innovative projects for CHP coupling geothermal to fossil fuels power stations, and renewable energy source such as PV or waste-to-power plants. Finally, TES can contribute to reducing the GHG emissions into the environment, both by partially replacing fossil fuels and by developing solutions for coupling CO_2 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 mainly rely on rather low temperature and shallow depth for local uses. High-Temperature UTES (HT-UTES) cover the 25˚-90˚C temperature range, and the targets of interest can reach up to 2000 m in depth.

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

The ERA-Net GEOTHERMICA HEATSTORE project recently approved is an excellent example of how all these tasks will be tackled by a transnational consortium of 24 groups from 9 countries, to provide practical solutions for the implementation of P&D projects in different context.

For thermal energy storage a wide variety of materials can be used. TES materials must possess suitable thermos-physical properties like favourable melting point for the given thermal application, high latent heat, high specific heat and high thermal conductivity etc. Other desired properties of thermal energy storage materials are low supercooling, low cost, easy availability, thermal stability, chemical stability, low volume change, non-toxic, low vapor pressure, congruent melting and low flammability etc. TES systems can be broadly classified into three classes 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 on the short time are sensible heat storage (water, thermal oil, etc.) and latent heat storage.

Potential for technological development

- Integration of thermal energy storage to cope with daily, weekly and even seasonal variations in heat demand and available heat from the geothermal power plant.
- Development of appropriate control systems to manage both heat and electricity production and connected storage to the installation. Using both the flexibility of the centralized thermal energy storage systems and flexibility in the network (e.g., thermal use of building mass, water storage tanks, electrical cars, etc.). Connection with district heating controller, process controller, grid controller and market interface.

In terms of production, HT-UTES face many challenges, common to 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 Identification and characterization/monitoring of the reservoir
- Reservoir geo-mechanical effects associated to the seasonal injection/production operations
- Characterization and monitoring of the water-rock interaction at reservoir level
- Hydrogeochemical problems associated to scaling, corrosion of the piping system
- Presence of hydrocarbon pockets
- Design and optimization of the distribution network

Therefore the technological development that can be investigated are:

- THMC reservoir modelling
- Installation of wellbore equipment (i.e, Distributed Acoustic Sensing DAS) for time-lapse production monitoring
- Heat-exchanger design and optimisation
- Development of environmentally friendly tracers (i.e. DNA or other nano-particles) for reservoir characterization, well production and interferences
- Multi-lateral drilling
- Re-utilization of non productive geothermal or hydrocarbon wells

Target

The main targets are local utility operators and more in general industries, which aim at improving the environmental sustainability of their processes. This can be achieved mainly by reducing the GHG footprint and HT-TES can contribute where the subsurface and the surface boundary conditions are favourable. As HT-TES are still immature, research activities has to be done by academic institutions to answer industrial requirements.

- Demonstrations of fast responding thermal energy storage systems integrated in the geothermal plant to respond on the needs in the thermal and electrical grid (storage capacity of at least 12h of the thermal output of the geothermal wells).

Topic 6: Innovative design and integration of binary cycle technology in existing and new flash plants

Objective

Improve geothermal heat to power conversion efficiency by integration of binary plants as bottoming units to geothermal flash plants.

State of the art

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. Such 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, in order to continuously adjust their power output very fast responding to the grid requirements.

Despite these benefits, at present only a few binary plants have been integrated as bottoming units into flash plants. The main reasons are the much higher costs of the binary plants (1923 €/kWe capital cost and 1.70 c€/kWh(e) operational) compared to the ones of the second flash unit (1102 €/kWe capital cost and 1.28 c€/kWh(e) operational), the lower capacity of the binary plants than the 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 above market penetration barriers. Key challenges are to effectively reduce costs, increase binary plant capacity, develop control methods for grid integration according to instant load requirements and remote control by the grid operator, as well as establish standard scaling inhibition methods for the integration of binary plants into flash plants.

At component level they may include reengineering materials, turbine and lubrication system, cooling system, integrated power plant automation, fluid handling and scale inhibition system.

Large scale market penetration can be facilitated by studying, evaluating and optimizing alternative concepts and by developing the business case.

Target

1st step: demonstrate a reliable combined flash-binary plant, of improved conversion efficiency, reduced costs and flexible power output remotely controlled by the grid operator.

Long term vision: All geothermal flash plants are equipped with bottoming binary units.

Topic 7: Integrated analysis and optimization based on reservoir, wellbore, steam system and power plant models.

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 point of view, this objective implies a reduction of costs during both design and implementation phase. Such a goal may be achieved by developing innovative full-cycle prediction models to face one or more of the following issues:

(a) Couple the estimate of reservoir potential with near-well phenomena and well-flow stability.

(b) Assure the flow stability in the distribution network in terms of pressures and temperatures.

(c) Control and predict scaling or corrosion phenomena in pipelines (see above topic 10).
(d) Estimate various scenarios during the network design, to get the optimal network configuration.

(e) Control and reduction of plant emissions and chemical consumption minimization through optimized process control and management, to reduce environmental impact (see above topic 9).

State of the art

The analysis of the technical and scientific literature has highlighted the enormous efforts made to understand the mechanism of energy transport in geothermal piping networks. Several studies have been performed to evaluate, identify and solve the issues related to the simulation of heat and mass flow in network and process plants, with emphasis on the following aspects:

- characterization of the flow of the fluid affected by uncertainties of 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 are reported in the technical literature, as well as for those related to reservoir and process plants, including advanced fluid cycles [GarcíaValladares et al., Energy Conversion and Management (2006); Liu et al., Networks Journal of Hydrodynamics, Ser. B 21 (2009); Hasan and Kabir, Journal of Petroleum Science and Engineering, 71 (2010); Sancheza et al., Mathematical and Computer Modelling 57 (2013); Verma, Revista Mexicana de Ciencias Geológicas, 30 (2010), Huang and Freeston, Proc. 14th New Zealand, Geothermal Workshop (1992), Peluchette and Anderson, Thirty-Eighth Workshop on Geothermal Reservoir Engineering (2013)]. Conversely, the state-of-the-art concerning integrated models covering all the aspects of a geothermal installation, in terms of physical capabilities, production issues, management operations and production optimization is quite poor. Excluding the codes used for nuclear power plants licensing (which are very complex, but not available for the market, and subject to strong restrictions in terms of licensing and user qualification), the other tools are limited in physical description and capabilities. They are based on broad simplification of real behavior of components and this implies strong impacts in the accuracy of system design. Most of the models available for geothermal networks are confined to the study of stationary flow, neglecting impact on production of fluid composition, operational transient and interaction with electrical grid and process plant. In addition, despite the large amount of work available in literature regarding scale impact in geothermal pipes and components, corrosion issues due to aggressive gases (J.Nogara, S.J.Zarrouk, 2017 Renewable and Sustainable Energy Reviews, G.Allegrini, G.Benvenuti, Geothermics,1970), few research initiatives have been carried out to couple the above phenomena with geothermal fluid mechanics development. In No significant activities neither available tools are so far well developed in coupling design, management and long-term operation of geothermal plants, which are the strategic points to make geothermal energy more profitable in economic terms, more environmental friendly and more standardized to be easily replicated across the world

Potential for technological development

The strong differences in terms of temperature, pressure and chemical composition of the geothermal reservoir with the surface equipment (especially when dealing with deep geothermal plants), the interactions among physical behavior and operational requirements of geothermal installations, the impact of working conditions on component materials and lastly the requirements in reducing environmental impact of these plants, require a predictive capability addressing: (i) the multiphase flow behavior on wells, pipes and other components; (ii) issues generated by geothermal fluids on components performances; (iii)the impact of new materials, equipment or operative methodologies in future geothermal plants. This aspect is essential for the design and operations of a complex system that integrates different elements with dynamic behaviour. The integration of several scientific areas typically isolated each other's (reservoir, well engineering, fluid dynamic and pipeline transportation, fluid chemistry, power plants and production cycles, safety analyses) will allow to identify interactions, feedback and impacts of each area over the others, to define new working methodologies, to develop new knowledge to manage phenomena occurring in the crossing areas and interfaces among geothermal environment. Finally, thanks to a predictive approach regarding the behaviour of a complex system as a geothermal plant, it will allow to integrate the specific efforts on different disciplines in a common frame, to take into account interaction and feedback from different production aspects. This approach will boost the design of optimized 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 optimization and environmental impact minimization
- design of unconventional and hybrid systems, and prediction of performances
- integrated electrical grid-power plant design and management
- cost–benefit forecasting analyses based on a deterministic scenario approach

Target

Based on declaration of intent on strategic targets for Deep Geothermal Energy and the agreed strategic targets, the following milestones will be achieved by the present research topic:

1. Increase overall energy requirements for geothermal power generation resulting in power demand to below 10% of gross energy generation and in sustainable yield predicted for at least 30 years by 2030;

2. Improve the overall plant efficiency, including wells, pipelines and plant equipment at different thermodynamic conditions by 10% in 2030 and 20% in 2050;

3. Reduction of geothermal plants OPEX in terms of improvement of plant operation schedule, manage aggressive fluids to limit equipment failure, optimize fluid treatment to comply with environmental constraint using tailored production cycles, to reach energy costs below 10 €ct/kWhe for electricity and 5 €ct/kWhth for heat by 2025;

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

Topic 8: Develop Hybrid plants

Objective

The goal is to improve coupling of geothermal energy with renewable sources and waste heat for hybrid plants and new geothermal combined heat and power plants and optimization of new and existing DHC networks.

- By combining generation technologies of different profiles at one production site, energy availability is increased and energy intermittency reduced. At the same time, sharing existing infrastructure enables costs-savings and reduction of the plants environmental impact per unit of energy produced and delivered.
- By coupling geothermal energy with other renewable sources, it can increase temperature of the brine and make economic low temperature geothermal power plant.
- Usage of storage systems of different nature is needed to optimize the system from a technical and economic point of view (details in fiche 'Storage' -> chapter C Topic 5.
- By combining geothermal Heat to other heat sources, smart thermal grid can be created.

The research priorities are about:

- Reduction of heat losses in new and existing DHC networks and low temperature DHC networks
- Advanced integration of geothermal power plant with other renewable sources
- Integration of conventional and binary geothermal power plants.
- New technologies for direct energy production from not usable steam or water.

State of the art

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: EGP added a fully submersible downhole generator technology to a geothermal injection well, combining geothermal and hydroelectric power at one site. Cove Fort began operations 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 enthalpy, binary cycle geothermal power with solar photovoltaic and solar thermal. Between 2012 and 205, EGP added a 26.4 MW solar PV unit to the geothermal plant at the time one of the largest PV systems of its kind in the United States, and developed a solar thermal system to operate in conjunction with the existing Stillwater geothermal power station. By combining three renewable sources at the same location for the first time, EGP was able to fully capitalise on already installed assets, creating a more efficient and productive overall plant. 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: EGP built in 2014 an hybrid biomass extension for one of its plants, an extension to the Cornia 2 geothermal plant in Tuscany, Italy. This plant supplements 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 enhanced by about 30 GWh. The extension feeds from biomass from nearby forests and quotes. 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 systems currently combine different sources, including geothermal, already exist but not in a smart thermal grid.

Potential for technological development

- First of a kind plant using other sources to increase temperature of the geothermal brine.
- Use geothermal to stabilize supply of variable sources: Hybrid plants (Geothermal with waste heat, biomass, concentrated solar thermal or green gas) to optimize efficiency, repeatability and consistency and minimize uncertainty of well heat flux when ordering the surface equipment.
- Demonstrate applicability of geothermal combined with other sources for district heating and cooling on industrial and/or residential sites, including use of high-temperature heat pumps, UTES at elevated temperature, and for integration in smart thermal grids
- Thermoelectric Seebeck effect for energy production not usable steam or water.
- Advanced integration of conventional (steam) geothermal power plants with binary power plants to optimize geothermal brine usage.
- Integration of medium/long term storage system to comply with plants technological and economic constraints

Target

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

Topic 9: Exploit Mineral production from geothermal sources

Objective

The objective is to develop novel and potentially disruptive technological solutions that can help satisfy the European needs for energy and strategic metals in a single interlinked process. Geothermal plants have to optimize the production of both energy and metals according to the market demands, and deep geological formation will be exploited to allow the co-production of energy and metals.

State of the art

Worldwide several pilot plants have been built to extract salts, silica, lithium and specific metals from brines, but industrial production is only taken place at a few place and limited to the production of silica, Li, Br, J and Zn. In most case however the brines have been regarded as wastewaters in need of treatment to meet the imposed environmental discharge limits, discharged as is or left to evaporate instead of being regarded as a source for both non-metallic and metals elements. This is mainly due to the dilute metal concentrations of the brines and their complex nature. High metal concentrations (e.g. >10 mol/m3) can usually be handled with conventional physicochemical, adsorption and electrochemical separation technologies. Yet, dilute metals in solutions require special methods. Moreover, geothermal brines are complex mixtures that make removal of specific components difficult.

An 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 use 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. The 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 gather towards the advancement into more industrially relevant conditions for metal recovery of geothermal fluids. Each of these methods also need further development to integrate them in geothermal plant, 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

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

- Increase the selectivity and efficiency of the separation techniques;
- Develop new, potentially disruptive technologies to separate and transform chemical components from geothermal brines into more valuable products;

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

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

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

Target

- Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) below 10 €ct/kWhe for electricity and 5 €ct/kWhth for heat by 2025

Topic 10: Generation with different voltage for smart grids

Objective

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

- For transmission grid: balance of supply/demand and frequency control at various time scales, congestion of transmission grid line
- For distribution grid: voltage control issues.

The research priorities are the following:

- Development of systems for high and medium-low voltage, able to offer ancillary services
- Medium/ long term Energy Storage (heat/ electricity, hydrogen) coupled with geothermal power plants to support smart grid ancillary services
- Digitalization of geothermal power plants to support operation and maintenance and integration in smart grids.

State of the art

Typically, Geothermal power is used as a baseload 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 part of current operation modes, as it can compromise the well and the equipment for steam production. Besides, current regulation and market strategy allow the full load operation of geothermal power plants.

Current geothermal power plants are not equipped to operate in flexible mode nor to deliver ancillary service.

The varying output from Wind and PV can cause voltage swings in transmission lines, potentially creating power surges and blackouts.

Voltage control is one of the ancillary services to maintain reliable operations of the interconnected transmission system. Other kinds of ancillary services are: scheduling and dispatch, reactive power, loss compensation, load following, system protection, and energy imbalance.

Potential for technological development

- Develop power system converter and a corresponding control system for flexible geothermal systems to interconnect geothermal plants to the low-voltage and medium-voltage grid.
- Integration of medium/long term storage systems (both electrical and thermal) to comply with plants technological and economic constraints (see also topic 5)

• New concepts for small and distributed geothermal power plants, using small and waste streams, to be connected at low voltage network and to create a geothermal district for electricity and heat production.
Target
Demonstrate the technical and economic feasibility of responding to commands from a grid operator, at any time, to increase or decrease output ramp up and down from 60% - 110% of nominal power

D. From R&I to Deployment

Introduction

Introducing and deploying at large scale geothermal technologies entails a number of non-technical challenges, notably as regards their initial high investment cost, the consumer acceptance and the legal and financial barriers. The aim is to develop regulatory, financial, political and social solutions which can be implemented for overcoming barriers to the broad deployment of geothermal energy solutions.

Topic 1: Set the right Policies

Objective
To develop deep geothermal in Europe, for juvenile or mature markets, stakeholders need a political frame which: • Set up a level playing field at the European level to help the development of geothermal energy in Europe, and therefore allows for overall consistency with the vision for geothermal energy in Europe. • Have a clear understanding of the agenda of the EU and national levels to the development of geothermal energy and engage in the harmonization of the policies and regulations on deep geothermal. • Establish dedicated policies that allow reaching the 2050 climate Paris objectives with of carbon free technologies in the energy supply like deep geothermal. • Establish a long-term vision and strategy for the development of deep geothermal in Europe. • Define the role of geothermal in the energy system, notably in the electricity market and the supply of heating and cooling.
State of the art
In terms of policies and regulations contributing to the development of geothermal energy, European and some national climate and energy frameworks are established for 2020, 2030 and 2050. In addition, at the European level, there is a long-term objective to reduce emissions by 80% to 95% by 2050, to which the addition of the Paris agreement raises the objective to the achievement of carbon neutrality in the middle of the century.This long-term objective is pursued through intermediary targets, notably the 2020 and 2030 renewable energy targets. These targets are the cornerstone of the support schemes and the focus given on RES which enabled the recent development of geothermal energy in Europe in the past decade. There are few records of existing welfare analysis specific to geothermal energy, however there is significant existing literature addressing welfare analysis for other

renewable energy sources. These studies are mostly qualitative, which makes quantitative assessments and comparisons with geothermal more difficult.

This is of paramount importance within the current organization 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 “externalities” would considerably help the design of appropriate support schemes.

Regarding the identification of the regulatory and policy framework for deep geothermal, the state of the art is presented by GEOTHERMICA (ERA NET project), and the EU projects: GEOELEC, GEODH. Building on this work, the ETIP DG project’s mapping of policy and regulations is another valuable publication.

Potential for technological development

To attract the attention of decision makers, and particularly to get them dedicating resources for technological RD&I on geothermal energy, it is quite valuable to provide evidence as to the benefits of geothermal energy. For this, there are two research priority that 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, trade balancing…
2. Screening and mapping, exchanging and replicating best practices on policies relevant for RD&I in deep geothermal energy.
3. The establishment of a system approach to policies for deep geothermal has the potential to enable a 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 is a crucial element to guide policy making and ensure the consistency of a sound integrated framework.

Target

In order to reach the Strategic Targets of SET Plan – Declaration on Deep Geothermal Energy, and to increase the contribution of geothermal electricity and heat to the energy mix, technological advance must be supplemented and complemented by other factors. These include non-technological factors and the demonstration and deployment of innovative concepts to prove them and make them available for the market.

Topic 2: Public and other stakeholders engagement

Objective

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

- To further analyse the socio-scientific understanding of a range of social and cultural aspects and factors that shape the acceptance of geothermal technologies developments for electricity production and heating and cooling purposes by individuals and communities and their interactions in the energy transition
- To improve science literacy around geothermal energy and foster mutual learning among different stakeholders, enhancing the contribution of all societal actors and unleashing the potential of geothermal energy
- To develop new tools in order to include public and other stakeholders' perspectives in the innovation process of geothermal energy technologies, preventing the possible social conflicts around geothermal technology developments
- To experiment new forms of societal consultation/participation when defining the research and development objectives within the geothermal field, reconnecting the citizens to science and to scientific institutions

State of the art

Although social and non-technical aspects are increasingly considered key determinants towards the transition of a low-carbon society, the studies on social acceptance of geothermal energy in Europe are still scattered and often a lack a homogenous approach. At the same time, in the last years the geothermal community seems to have a growing interest on the issue, probably due also to new forms of opposition raising among 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 referendum, seminars, information campaigns and education activities.The Geothermal ERA-NET project organized a joint action named PR-GEO which on 2015 discussed some of the studies on social acceptance of geothermal energy and public engagement exercises with geothermal developments conducted in some countries around Europe (i.e. France, Germany, Italy, Switzerland). A Deliverable of the GEISER Project introduced a strategy for creating public acceptance for EGS activities, which was applied on two EGS case studies. A risk governance strategy including perception of public acceptability for various socio-economic conditions and sites is foreseen for the (running) DESTRESS project.

Several other interesting experiences on societal dialogue within the geothermal field have been conducted in Europe and beyond, as described in literature and partly collected in a Springer Nature Lecture Notes. Very different countries, both from a social and from a geothermal perspective, have experiences of assessment of social acceptance and public engagement within the field, proofing that the role of society as whole is gaining importance in the energy transition.

It often also appears that general public is not very informed about geothermal technologies, and is not able to distinguish among different geothermal energy systems and related environmental and technological issues. As also underlined by the DESTRESS project, an increased public awareness and a "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 benefits with the customers and the citizens. The objective is to develop organisational models and best practices with geothermal energy projects sharing economic or other benefits created by the projects with the local communities, e.g. through local co-ownership, & local crowd funding, (financial) compensation mechanisms or creation of local green jobs.

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

Potential for development

Non-technical issues, including social acceptance, are a recognized prerequisite for a successful development of energy technologies and they require a highly interdisciplinary approach. This should be considered by researchers, policy makers and funders, when it comes to the allocation of resources, research and development strategies and projects evaluations.

Four main constraints for a successful societal engagement have been identified, as well as their potential counter-measures that need to be developed and implemented by the key stakeholders:

No.	Identified issues	Potential counter-measures	Key stakeholder(s)
1	Information gap between geothermal experts and public, and lack of access to knowledge.	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 of Science and Technology (PCST) experts
2	Scarcity of social engagement and inclusive geothermal projects. Need for a true public	Definition and test of strategies and practices of public engagement in the geothermal realm	All stakeholders

	participation to geothermal planning.		
3	Diverse strategies for societal engagement are being implemented worldwide, however, such learnings are not easily accessible, so others can profit from them.	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 organizations Local public administrations Policy makers
4	The potential socio-economic and cultural impacts of a distributed power generation, and the role of new social actors like the *prosumers*, are still uncertain.	Furthering research and establishing new methodologies to assess the socio-economic and cultural impacts of a distributed power generation identifying the interrelations between these impacts and technology, investments and regulations.	Researchers Consumers Producers Civil society organizations Public administrations

Target

Based on Declaration of Intent, in order to reach the strategic targets for Deep Geothermal and to increase the contribution of geothermal electricity and heat to the energy mix, technological advance must be supplemented and complemented by other factors. Among these non-technical factors, a main target is an increased social acceptability mainly through mitigation of unsolicited site effects. The present research topic, which goes beyond mitigation of environmental effects, has at its core the social engagement as recognized prerequisite for a successful development of geothermal energy technologies.

Topic 3: Reinforce Competitiveness

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 the system costs and the externalities.
- Analysing the ability of energy market models to properly remunerate the various benefits of geothermal energy in a context of CAPEX intensive and marginal OPEX industry.
- Establishing a fair competition at the global level with the geothermal stakeholders from the rest of 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 further expanded ambitiously in order to keep this leadership in developing the geothermal industry of the future, both for research and commercial development.

State of the art

LCOE is one of the criteria most used to compare the competitiveness of different energy sources, notably in policy making. It however is a very partial indicator as there is no consideration of system costslike transmission and other network costs such as impact on system balancing, impact on state/system energy security, and of costs of externalities like government funded research, residual insurance responsibilities that fall to government, external costs of pollution damage or external benefits (e.g. value of learning to future generations).

Current markets models are unable to remunerate energy sources with low operational costs, hence there is the need for remuneration "out of the market" (FiT, CfD, capacity).

Europe has pioneered in 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 Soultz-Sous-Forêts (France). In addition, the EU has the first successful commercially funded EGS project in Landau (Germany) and EGS for industrial use (ECOGI project in France). 15% of the geothermal power installed capacity is in Europe. European companies are often technology leaders.

With more than 200 geothermal DH systems in operation, Europe in also the global leader for geothermal DH. Global competition exists mainly for heat exchangers and pipes. Use of geothermal heat in the industry, agri-food sector and services also started in Europe.

Potential for technological development

- Develop a model for the right comparison of the full costs of competitive energies: heat & power, is necessary for a rational allocation of resources between energies,

- Establish carbon pricing with taxation tools and a new ETS tackling also large heat installations, for the integration of costs for externalities in the full costs of an energy source,
- Support the export of European geothermal technologies via Trade missions and policy to open third markets
- Set Standard & high quality: European industry is defined by high standards, it is important to benefit from this fact internationally.
- Promote Innovation: developing 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 and see potential for reconversion of professionals and industry from declining or non sustainable sectors: coal mining, oil& gas exploration, and liaise with other sectors: agro-food industry, digitalization (big data)…

Target

In order to reach the Strategic Targets of SET Plan – Declaration on Deep Geothermal Energy, and to increase the contribution of geothermal electricity and heat to the energy mix, technological advance must be supplemented and complemented by other factors. These include non-technological factors and also demonstration and deployment to prove innovative concepts and make them available for the market

The definition of LCoE is the following:

$$LCOE = \frac{total\ lifetime\ expenses}{total\ expected\ output} = \frac{\sum_t^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}$$

With :

- LCOE = Levelized cost of energy
- I_t = Investment expenditures in the year t
- M_t = Operations and maintenance expenditures in the year t
- F_t = Fuel expenditures in the year t
- E_t = Electricity generation in the year t
- R = Discount rate

Figure 2 Definition of LcoE

Therefore, the LcoE approach usually does not capture the following components:

- Systems factors like transmission other network costs such as impact on system balancing, impact on state/system energy security
- Externalities like government funded research, residual insurance responsibilities that fall to government, external costs of pollution damage or external benefits (e.g. value of learning to future generations)
- Business impacts like effects of fuel price and future revenue volatility, future changes in legislation, risks.

Topic 4: Establish Financial Risk management schemes

Objective

The goal is to mitigate the resource risk which is the major barrier to entry for geothermal project developers in Europe but also worldwide and seriously hampers its market uptake via Financial Risk management schemes. It aims to develop financial schemes that manage to transfer the resource risk (geology) to other bodies in such a manner that project developers can accept their fair share of the resource risk whilst lowering their financial exposure in case of failure to develop a geothermal reservoir. It includes the:

- Harmonization of evaluation standards.
- Integration of exploration costs in 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 over the borders (Pan-European)

State of the art

A Geothermal Risk Insurance Fund is seen as an appealing public support measure for overcoming the 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 capability to manage the financial risk owing to the poor knowledge of the deep subsurface, lack of technological progress and high cost. In effect the probability of success/failure weighted net present values of project cash flows tend to be overly negative, thus effectively shutting out private capital from investing in geothermal energy.

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

The newly launched GEORISK project aims at supporting the establishment of insurance schemes in Hungary Greece, Poland, and will envisage the transition towards public-private or fully private insurance schemes of existing public scheme sin France, Germany, Switzerland and Turkey.

Potential for technological development

- Development of a specific resource assessment standard. Shared resource assessment methodologies exist in oil & gas business. They facilitate the dialogue between companies and financial institutions.

- Survey of exploration or pre-cost risk in other industries (notably hydrocarbons but not only) and how cost and risk are managed and integrated in the overall business model. Benefits/drawbacks analysis of portfolio vs insurance schemes. Analysis of the specific issue of moral hazard in insurance schemes.
- Create of simulation model for establishing sustainable risk mitigation scheme, with a medium-term perspective.

Target

In order to reach the Strategic Targets of SET Plan – Declaration on Deep Geothermal Energy, and to increase the contribution of geothermal electricity and heat to the energy mix, technological advance must be supplemented and complemented by other factors. These include non-technological factors and also demonstration and deployment to prove innovative concepts and make them available for the market.

Topic 5: Support schemes to deploy geothermal

Objective

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

- Facilitate the financing of RD&I in deep geothermal energy, most notably for deep geothermal demonstration projects. This notably entails:
    - Facilitated access to financing for projects (i.e. information on funding facilities…)
    - Reduction of 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 along their development time through the identification of suitable financing instruments.
- Remove barriers and improve regulatory framework to facilitate the uptake of geothermal Power Purchase Agreement (PPA) for heating and electricity
- Balance the uncertainty linked with the geological risk at the resource evaluation stage from a financial standpoint, while maximising the certainty from a technical one.
- Align the reality of RD&I in geothermal projects with the risk threshold for the acceptability of private funding (banks, investors).
- Have Long-term vision of the financing needs for RD&I in deep geothermal energy, and identifying the role of public authorities in providing financing and setting financing instruments that enable investments in RD&I in deep geothermal and for scaling technology innovations in the energy system.

Improving the accessibility of financing for deep geothermal RD&I removes major hurdles to technological development across the whole value chain. It also reduces the delay to scale technology innovation up to market readiness.
Financial instruments fit for the specific constraints of deep geothermal allow more projects to be undertaken.

State of the art

Public support for geothermal energy is that it is meant to mobilize private financing in a difficult investment climate. The economic and financial crisis has indeed affected investment in clean energy.The picture appears already to be complicated, and it should be added that Geothermal is a capital-intensive technology that takes some years to develop. Such a barrier can be tricky to overcome, especially with the European stock markets still uncertain and with banks exclusively looking for zero risk.

The European climate and energy policy framework is a major element driving financing to deep geothermal RD&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 project at scale. The identification and the assessment of the European policy and regulatory framework and the financing facilities is a starting point to estimating the needs of RD&I in deep geothermal and is an exercise that has notably been conducted by the DG ETIP project in the mapping of the 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 EBRD's and World Bank's scheme 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, notably on financing RD&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 reduction of the cost of capital.

Potential for technological development

Research topics on this topic include:

- Retrospective survey of developments post-final investment decision of geothermal projects in order to assess the nature and level of remaining uncertainties that can impact the profitability of investments.
- Develop innovative financing mechanisms adapted to the specificities of geothermal technologies and according to the level of maturity of markets and technologies
- While designing a support scheme, policy-makers should take a holistic approach, which goes beyond the LCoE and includes system costs and all externalities. As an alternative, there is the chance to offer a bonus to geothermal for the benefits it provides to the overall electricity system: flexibility and base-load. The base-load character of geothermal and its contribution to electricity grid stability should be adequately remunerated as well as the production and use of heat.
- Public support schemes covering different financial needs: R&D, demonstration, exploration phase to identify areas of interest, drilling/production phase (market conditions);

Target

"Geothermal installations are characterized by low OPEX but high CAPEX, used mostly to cover the costs of exploration and drilling and of the plant construction. In addition,

financing costs are high due to high geological risks associated with costly drilling during early-stage exploration. Market financiers generally are unwilling to take up these early stage risks and costs, which represents one of the major barriers for geothermal project developers. However, high capacity factors (far higher than for most other renewables) and low OPEX, near zero system costs and externalities, result in costs very similar to those of other renewable and low-carbon technologies especially when the heat is taken into consideration in the cost analysis."

Topic 6: Establish Legal and regulatory framework

Objective

The goal is to establish a legislative framework that will sustain geothermal deployment, its penetration and profitability while guaranteeing that resources are properly managed. This includes the establishment of proper legislations and regulations by:

- Mapping the regulatory issues affecting the geothermal sector and best practices, at each steps of a deep geothermal project, from exploration to decommissioning.
- Assessing and optimizing the environmental, social and economic footprints of deep geothermal
- Setting a position of geothermal energy in the different codes (Mining, Environment, Water, …)
- Introducing of a unifying process for geothermal projects (one address for all ministries)
- License granting processes (FCFS, license rounds, competition window, ...)
- Works authorization processes

State of the art

Deep geothermal energy is a heavily regulated sector, and usually requires a specificsupport framework.When considering the European regulatory and policy framework, the various interlinkedregulations and policies create a complex regulatory background. Although this complexregulatory framework may not necessarily result in an overregulation of geothermalprojects and may indeed provide a consistent and robust framework that allows confidencein deep geothermal energy projects, the lack of readability may be a deterrent for theemergence of new geothermal markets.

The most important European legislative pieces that underpin the regulatory framework for deep geothermal are:

- ETS / ESD Regulations
- Electricity market rules
- Renewable Energy Directive (2009 and 2018 recast)
- Environmental EU 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)

For example, introducing third party access to heat network could be fatal for geothermal heat as investor would become more reluctant to spend the high capex of geothermal sources which could be later stranded.

And associated guidelines:

- State aid guidelines on energy and the environment
- Network codes (Grid connection to the generators…)

In *Perspective for geothermal energy in Europe*, key regulatory issues compiled from several studies (GEOELEC, 2013; DEOGH, 2014; REGEOCITIES, 2015) are described and classified in five main topics: definition, classification and resource ownership, Licensing and authorizations, sustainability, spatial planning and grid access.

GEOENVIproject aims at providing rrecommendations for harmonizing environmental regulations in Europe, and at developing a life cycle assessment approach on environmental impact of geothermal.

Potential for technological development

- improve the legal and regulatory framework on deep geothermal and its applications.
- Provide recommendations for European harmonization of environmental regulations and for financial institutions.

Target

In order to reach the Strategic Targets of SET Plan – Declaration on Deep Geothermal Energy, and to increase the contribution of geothermal electricity and heat to the energy mix, technological advance must be supplemented and complemented by other factors. These include non-technological factors and also demonstration and deployment to prove innovative concepts and make them available for the market.

Topic 7: Embedding geothermal energy in 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 as from the design stage so that they can be reused or made into new raw materials - thus reducing waste volumes and energy consumption and preserving natural resources.

The integration of geothermal in the circular economy would include components, products and systems which are optimized, used and re-uses, repaired, redistribute, refurbished and or remanufactured.

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

State of the art

In 2016, the European Commission published a Circular Economy Package for a more sustainable economy. The package sets out a plan and targets for EU waste that should be achieved by 2030, and 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 organized to be fully integrated in the concept of the circular economy with all its components.

Potential for technological development

The next steps will be:

- Adopt geothermal standardization procedures and quality brand about the circular economy to make progress on the consumer or legal authorities confidence on geothermal sustainable products and promote a common understanding in the geothermal sector through agreed terminology, share the vocabulary and definitions in order to have an agreed and consistent approach
- Improve the applicability and use of recycled/secondary materials/waste in geothermal plants
- Monitor the use of raw materials in geothermal, especially the critical ones in terms of availability: identification, classification and quantification of data regarding raw materials and promote interoperability and comparability with other materials
- Develop new business models, with geothermal eco-friendly actors
- Research and innovation to have new technologies for waste and water management
- Develop innovative greener and eco-friendly geothermal products, components and systems, becoming using sustainable materials.
- Monitor the full process with digital applications

Target
In order to reach the Strategic Targets of SET Plan – Declaration on Deep Geothermal Energy, and to increase the contribution of geothermal electricity and heat to the energy mix, technological advance must be supplemented and complemented by other factors. These include non-technological factors and also demonstration and deployment to prove innovative concepts and make them available for the market.

Topic 8: Harmonised protocols for defining environmental and health impacts of geothermal energy and mitigation planning

Objective

The aim is to develop solutions and tools for addressing concerns and highlighting benefits for the deep geothermal market uptake focusing on the environmentaland health impacts. It goes through Harmonised and modelized LCA on environmental impacts, strengthening knowledge on environmental and health impact of geothermal activities in the scientific community and developing knowledge about preventive measures connected with risk communication and enhancement of environmental health literacy of communities living in geothermal areas.

State of the art

Among the potential environmental impacts, we can list the followings:

- surface-visual effects (land use, landscape, flora and fauna);
- physical effects (induced seismicity: micro-seismicity related to all the operational phases of the exploitation, including reservoir connection and fluid reinjection into the reservoir; subsidence; geological hazards; groundwater resource depletion; natural radioactivity)
- acoustic effects (noise during drilling, construction and management);
- thermal effects (release of steam in the air, ground heating and cooling for fluid withdrawal or injection).
- Chemical effects (gaseous emissions into the atmosphere, incondensable gases, pollution and emissions; re-injection of fluids, disposal of liquid and solid waste).

Determinants and risk factors linked to geothermal production impacting health are analyzed in a few studies in Europe (Italy and Iceland) and in New Zealand. There is not, however, a harmonized protocol for assessing and comparing data.

GEOENVI project aims at providing recommendations for harmonizing environmental regulations in Europe, and at developing a life cycle assessment approach on environmental impact of geothermal.

Potential for technological development
• Generation of simplified parameterized model of life cycle assessment and Elaboration of a general protocol to deliver simplified LCA models for geothermal installations • Develop studies with adequate design to investigate the association among geothermal plants, exposure to chemicals and health outcomes • Apply Cumulative risk assessment methods and tools, accompanied by cases-studies • Develop knowledge about preventive measures • Health Impact Assessment to strengthen Environmental Impact Assessment
Target
In order to reach the Strategic Targets of SET Plan – Declaration on Deep Geothermal Energy, and to increase the contribution of geothermal electricity and heat to the energy mix, technological advance must be supplemented and complemented by other factors. These include non-technological factors and also demonstration and deployment to prove innovative concepts and make them available for the market.

Topic 9: Human deployment

Objective
The development of a significant number of new projects will trigger a real boom in labor-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 • Transfer of knowledge and investments from other sectors (e.g. Oil&Gas, nuclear, coal) to 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 the proper education reforms, cooperation between all organizations involved is required. Cooperation between education and training institutes and companies is necessary to create a network allowing for a faster and more efficient satisfaction of the needs generated in the labour market, while students are provided with the appropriate skills and knowledge.
State of the art
Among the necessary actions, a key issue is represented by cooperation between education and training institutes and companies, creating networks for education and training involving industrial platforms, universities and research centers. Further ideas are to develop courses on geothermal energy within existing university courses and to launch new courses; to absorb workforce of declining industries; and to promote mobility of

workers in Europe. Support to these actions should be sought nationally, in H2020 (and subsequent framework programs) Concertation and Support Actions, and in existing EC programs or support of knowledge transfer and human mobility, such as (Marie Curie, Erasmus +, ERC grants).

In most EU research projects dissemination activities are programmed and developed, but most of this material does not reach the wider society, including universities and education centers. In order to transfer of latest research generated knowledge into education, a coordinated effort is necessary among European academia and research centers. Training and links with industry have been launched in the GEOELEC project, in relation to power production, and GeoDH (on heat production). Various universities around Europe, listed first 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 is not organized and would be beneficial both for higher specialization 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, for example with suppliers of raw materials and induced jobs. The estimated total number of deep geothermal jobs in 2018 is more than 20.000 jobs.

Potential for technological development

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

- Enhancement of the educational and training process and planning on instructional education for 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 of new courses combining Geoscience and Mechanical Engineering
- Create Networks for Geothermal Energy Education and Training involving industrial platforms, universities and research centres with competences in geothermal energy-related disciplines – geosciences, material sciences, mechanical engineering, computational sciences, economic and legal sciences.
- Develop an Employment action plan to transfer knowledge and absorb workforce of declining industries, promote mobility of workers in Europe.
- Launch international cooperation especially on EGS

Target

In order to reach the Strategic Targets of SET Plan – Declaration on Deep Geothermal Energy, and to increase the contribution of geothermal electricity and heat to the energy mix, technological advance must be supplemented and complemented by other factors.

These include non-technological factors and demonstration and deployment to prove innovative concepts and make them available for the market.

E. Knowledge Sharing

Introduction

The Deep Geothermal Temporary Working Group of the SET-Plan stressed the relevance of two cross-cutting issues, related to knowledge sharing, which are crucial for support to all research and innovation actions as well as non-technical barriers/enablers:

- Knowledge transfer + training (including peer-to-peer learning and research infrastructures)
It is important that the EC demonstrates throughout Europe capacity building, industrial technology transfer and science & academic partnerships via know-how, with the shared goal to develop high quality, competitive and sustainable geothermal energy projects. This includes supporting the existing pan-European infrastructure of experimental test and monitoring facilities and infrastructures (Geo Energy Test Beds, GETB - see also https://www.epos-ip.org/data-services/community-services-tcs/geo-energy-test-beds-low-carbon-energy) and making efficient and coordinated use of them. This cross-cutting action also aims at training and educating new geothermal professionals (details in chapter D: Topic 9: Human deployment).

- Recommendation of an open-access policy to geothermal information (including standard exchange formats)
The scope of this cross-cutting action is to facilitate access to geothermal information at the European level via the development of an information platform, creation of standard and common data models at EU level. This should be achieved through progressive harmonization of national data to facilitate data discovery and mining.

Topic 1: Underground data sharing - unlocking existing subsurface information

Objective

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

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

State of the art

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

Various national initiatives are highlighting the importance of data-sharing, geothermal databases and resource mapping: ThemoGIS in The Netherlands[3], GEOTIS in Germany[4], GEOTHOPICA in Italy[5], Thermo2D and Geothermie Perpectives in France[6], and the web-gis platform of Switzerland[7]. Actual databases have format and structure defined at national level.

Need for common data-sharing is also well recognized on EU level, e.g. in the frame of Geothermal ERA-NET[8] the concept of a European Geothermal Information Platform was developed following the interest of research and industry. At the moment only a small pilot is implemented[9] for testing the concept. Both the concept and the pilot were tested and evaluated by stakeholders, who showed high interest in the matter.

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

Potential for technological development

Technological development options include:

- Definition of standards (e.g. for database format, services which make automatic uses of data) and data models.

3 www.thermogis.nl
4 https://geotis.de
5 http://www.geothopica.igg.cnr.it
6 http://www.thermo2pro.fr/ - http://www.geothermie-perspectives.fr/
7 https://map.geo.admin.ch
8 http://www.geothermaleranet.is
9 Described in Trumpy et al., Building a European geothermal information network using a distributed e-Infrastructure, International Journal of Digital Earth, 2015

- Set principles of geological data freely available after a period of time, in national regulations (details in chapter D: Topic 6: Establish Legal and regulatory framework)
- Data preparation, harmonization and publication through national web-services.
- Development of the Geothermal Information Platform, providing services for open-access data harvesting, data mining and data management (e.g. graphs, statistical tools etc.)
- Inclusion of geothermal properties and resource mapping taking the advantage of a common geothermal exploration protocol (see Resource assessment item)

Target

(Link: Declaration of Intent)

Reducing exploration costs, by access to relevant data and derived models

Topic 2: Organization and sharing of geothermal information

Objective

Facilitate the access to geothermal information at the European level via the development of an Information Platform, creation of standard and common data model at EU level and harmonization of national data to facilitate information discovery and data mining, to foster the technical and non-technical knowledge exchange on a European level.

Realize a web-based knowledge transfer system related to technical and non-technical aspects of interest in different European countries, and create a community that fuels this system at the same time.

State of the art

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

One regarded the concept of a European Geothermal Information Platform (EGIP), a Web tool gathering data and knowledge from national and scientific providers following the European INSPIRE directive, i.e. data remain the property of the providers who host them. The state-of-the-art and needs in regarding geothermal data and existing tools to manage them were described, the interest to the various topics was prioritized by mean of a questionnaire, and the concept and its application described in various documents. EGIP is meant to be interoperable with other pan-european data platforms, e.g. EGDI. At the moment it remains unrealized, beside 1) a Pilot Platform for a few underground data and documents sharing and 2) the Search Engine of European project documents realized within the ETIP-DG website.

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

Potential for technological development

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

- Definition and prioritization of technical and non-technical topics and issues to be organized (to finalize the activity already initiated in the Geothermal ERA-NET).
- The coordination of European and national contracts/subsidies on chosen topics, handled nationally by the national ministries/governmental agencies, bringing together national experience.
- Creation of working groups of the national experts and stakeholders (industry, research, public and administration, depending on the topic) to provide a collection and an overview of documents and of technical issues and their applied and potential solutions.
- Definition of standards (e.g. for database format, services which make automatic uses of data) and data models
- Data preparation, harmonization and publication through national web-services.
- Development of the Geothermal Information Platform, providing links to tools (e.g. common wiki-style tools) and services for open-access data harvesting, data mining and data management (e.g. graphs, statistical tools etc.)
- Explore and test new tools (e.g. available energy signposting) and development of innovative ones for sharing information

Target

(Link: Declaration of Intent)

Market uptake and accelerated innovation by reducing the amount of time required to find valuable information and making knowledge more accessible. Transparent and harmonized methods and instruments for technical and financial risk management.

Topic 3: Shared Research Infrastructures

Objective

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

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

State of the art

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

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

Potential for technological development

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

Target

(Link: Declaration of Intent)

Large scale demonstration and deployment to prove innovative concepts and their integration in the energy system

F. Mission

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

1. *Increase reservoir performance* [, including underground heat storage,] *resulting in power demand of reservoir pumps to below 10% of gross energy generation and in sustainable yield predicted for at least 30 years by 2030;*
2. *Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10% in 2030 and 20% in 2050;*
3. *Reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) below10 €ct/kWhe for electricity and 5 €ct/kWhth for heat by 202515;*
4. *Reduce the 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 to commands from a grid operator, at any time, to increase or decrease output ramp up and down from 60% - 110% of nominal power.*

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[10]to 540 TWh in 2050[11], 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 to12,5% of the 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 1.745TWhin 2050[12].According to the

10 EGEC, 2018. 2017 EGEC Geothermal Market Report. Available at: www.egec.com
11 2015 JRC Geothermal Energy Status Report. The JRC-EU-TIMES10 - a system cost optimization model for technology deployment - is used to assess how different exogenous policy-driven decarbonisation pathways affect the power sector's technological deployment until 2050/
12RHC-Platform, 2013. Strategic Research and Innovation Agenda for Renewable Heating & Cooling. Available at: http://www.rhc-platform.org/

Vision of the ETIP-DG 13, geothermal will be a key energy source in the "*City of the Future*": a place where is good to live for everybody with respect for the environment and driven by a combination of renewable energy sources, for local electricity and heating/cooling supply at house level, with or without storage facilities, and 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 that has 100% renewable energy sources 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.
This dream can only be achieved in case it is shared by all stakeholders. As we have learned in the last decades, energy transition is not only a matter of techno-scientific innovation, but even more of cultural habits, social issues and political choices, which are strongly interconnected. To redesign the European energy systems towards a more sustainable future, it is fundamental to put in place an interdisciplinary, open, 360 degrees approach, which cannot exclude the inexhaustible, renewable, and indigenous heat flow running under our feet.

Geothermal is a key technology in this vision. By 2050, large geothermal power plants that tap into ultra-hot, supercritical heat reservoirs supply a large part of Europe's baseload electricity would need to be developed. In places where the geothermal resources are of 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 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 4th generation district heating and cooling (DH&C) networks, including low and high temperature underground thermal storage, tank and pit storage using advanced storage media, as well as storage in the building mass and the piping of the DH&C-network. The 4th generation DH&C networks work in a temperature range of 55 – 25°C or lower. This allows utilization 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 allows efficient utilization of the

13https://www.etip-dg.eu/publication/vision-for-deep-geothermal/

flexibility and ensures an optimal utilisation of all energy sources that are connected to the network. In this way, a hybrid energy infrastructure is created that connects DH&C networks with the electric grid, and other energy vectors through various coupling points.

Figure 3: Hybrid energy infrastructure composed of interconnected energy networks that 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 realization of this hybrid energy infrastructure ask for technology developments and innovations that go far beyond the strategic research agenda for deep geothermal. Though an open dialogue the geothermal sector can assure that their technology developments are in line with the roadmaps for:

- Hybrid power generation;
- Smart networks for energy transition;
- Energy efficient buildings;
- Short and long term energy storage solutions;
- Renewable heating & cooling such as (high-temperature) heat pumps, solar thermal, innovative cooling devices and hybrid systems;
- 4th 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, e.g. oil & gas and (metal) mining. An example is the development of combined heat, power and metal extraction from deep geothermal brines. Exploiting the energy potential that is present in many geothermal brines can increase the energy output and profitability of the geothermal plant, and at the same time can lower Europe's dependency on foreign metal resources. Within the coming decades, securing the supply of critical raw materials, in particular metals, will be a major challenge for the European industry and society. Our dependency on the import of metals is growing every year, despite significant efforts in the development of recycling technologies and in material science [14].

Figure 4: Concept of a combined heat, power and metal extraction geothermal plant (based on Horizon 2020 project CHPM2030: https://www.chpm2030.eu/introduction/).

14Public Consultation on Commission Raw Materials Initiative, Background paper, P1, More information: http://ec.europa.eu/enterprise/policies/raw-materials/public-consultation/index_en.htm

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

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

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, exponentially more geothermal resources can be accessed through next-generation of technologies, such as:

“Open call for presenting next-generation of technologies”

Objective	State of the art	Potential for technological development	Target

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