

Geothermal Energy

A large geyser erupts in a snowy landscape, sending a massive plume of white steam and ash high into a clear blue sky. The surrounding terrain is covered in snow and ice, with other smaller vents visible in the distance. The scene is captured from a low angle, emphasizing the height and power of the eruption.

ARUP

Who we are

Arup is the creative force at the heart of many of the world's most prominent projects in the built environment and across industry. We offer a broad range of professional services that combine to make a real difference to our clients and the communities in which we work.

We are truly global. From 90 offices in 35 countries, our 10,000 planners, designers, engineers and consultants deliver innovative projects across the world with creativity and passion.

Founded in 1946 with an enduring set of values, our unique trust ownership fosters a distinctive culture and an intellectual independence that encourages collaborative working. This is reflected in everything we do, allowing us to develop meaningful ideas, help shape agendas and deliver results that frequently surpass the expectations of our clients.

The people at Arup are driven to find a better way and to deliver better solutions for our clients.



Geothermal energy

Geothermal energy is the energy stored in the form of heat beneath the surface of the earth. This can be a low or high temperature resource.

Exploiting low temperature resources normally requires a ground source heat pump (GSHP). GSHP systems can provide heating or cooling (air conditioning) to a building by harnessing the heat energy stored in the ground. A heat exchanger transfers thermal energy between the surface and the ground, and a heat pump or chiller heats or cools the space.

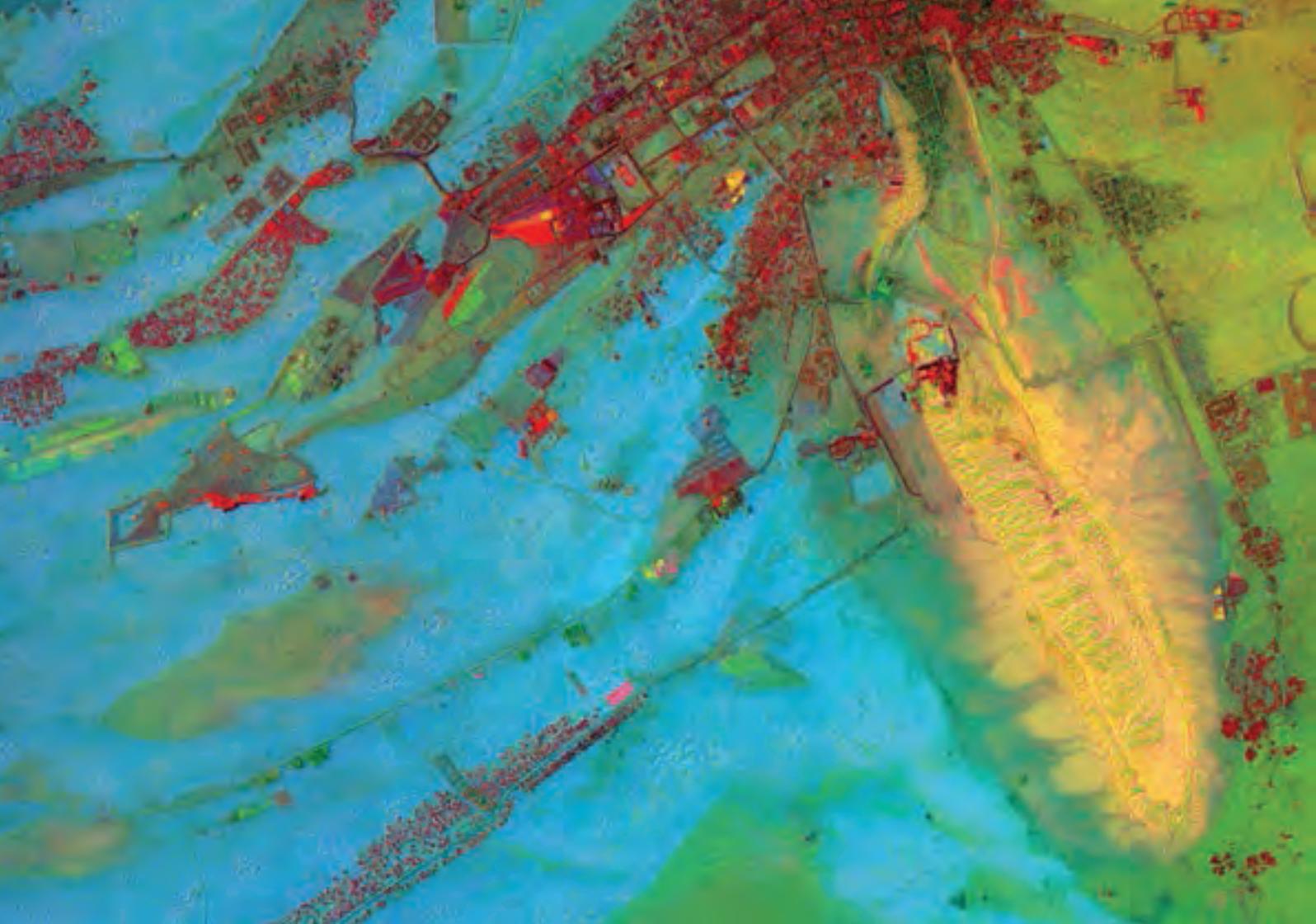
These systems are effective because underground temperatures are stable due to the high thermal capacity of soil and rock. GSHP systems typically operate to depths less than 200m.

Sometimes a high temperature resource is situated close to the earth's surface and may be easily harnessed. This is the case in Iceland, where, according to the National Energy Authority, over 66% of the country's primary

energy is geothermal. However, in most places, geothermal resources are located several kilometres below the earth's surface, making them difficult to access.

Where groundwater of a high enough temperature occurs naturally it may be pumped to the surface and used for space heating as part of a district heating scheme, or to generate electricity. Where water does not naturally occur, hot dry rock, hot fractured rock and enhanced or engineered geothermal systems are being trialled and developed to exploit the heat resource. The aim of these systems is to manufacture a reservoir at a depth where the temperature is sufficient to generate heat and/or power.

Arup's multidisciplinary approach can help developers through all the stages of a geothermal project from initial feasibility studies and permitting to geophysical testing and GSHP design or power plant design.



Seismic hazard assessment

Induced seismicity is a product of many diverse engineering projects, predominantly major dam and mining projects. More recently, public attention has been focused on seismicity associated with deep geothermal drilling or stimulation and shale gas 'fracking'. The risk of induced seismicity (both real and perceptual) needs to be well managed and predictive tools are key part of this.

We have been involved in regional and site-specific seismic hazard assessments for over 20 years, carrying out studies for projects around the world. We assess ground motion hazards based on geological, tectonic and seismological information. Our aerial photo interpretation and remote sensing group has particular expertise in lineament analysis of satellite imagery for determination of faulting structures.

We routinely undertake seismic hazard assessments, which, when coupled with deep geomechanical modelling, help predict the likelihood and scale of seismic events associated with geothermal fluid abstraction and injection.

Detailed seismic hazard calculations use our in-house program Oasys SISMIC. This incorporates the probabilistic methodology originally proposed by Cornell (1968) and uses uncertainty in the input parameters via the logic tree formulation. The program is able to directly model slip rates, characteristic earthquakes and maximum credible events based on fault geometry using the Youngs and Coppersmith (1985) procedures.

Transactions advice

Arup has developed recommendations to the Indonesian government for appropriate tariff levels for geothermal electricity. As part of this work Arup has developed a bespoke financial model drawing from a range of geothermal conditions and project development plans.

The development of the tariff system for Indonesia involved the assembly of a range of technical assumptions (such as well productivity, drilling requirements, power plant construction and steam field use) in order to appropriately reflect capital investment and operation costs for projects in Indonesia. Arup's experts in geothermal worked together with a range of stakeholders in Indonesia to generate a matrix of cost profiles based on reasonable technical assumptions.

The cost profiles developed by the geothermal engineering team were used as inputs into a financial model which incorporated a full set of financial statements (including profit and loss account, cash flow, and balance sheet). The financial model, developed by Arup's transactions experts, also incorporated Indonesia specific incentives, taxation, and royalty payment requirements.

The output from the financial model was used to generate the recommended fixed tariff system.

With this experience and with the expertise of Arup's engineering and transactions teams, we are uniquely positioned to provide financial planning support at a variety of project levels.



Above – View of Flores Island in Indonesia, where Arup has worked with the Indonesian government to generate a road map for geothermal development on the island.



Left – We are currently assisting Cornwall County Council in developing their deep geothermal resources, advising on planning process and investment strategy

Planning and permitting

We understand the geological, technological, environmental, political, and commercial challenges faced by clients developing geothermal projects. Respected worldwide for excellence in the built environment, we deliver innovative, future-proof, sustainable solutions to these challenges.

At Arup, we apply an integrated planning approach to all projects, large and small. Teams of policy experts, town planners, masterplanners, environment and transport planners work closely together.

This ensures you gain access to specialist knowledge from across our firm to provide intelligent solutions to the challenges of your project. From shaping policy through to implementation, we have established a reputation for adding value.

We provide comprehensive development control and management services, which includes all aspects of the process.

- Advice on development proposals and strategies for obtaining planning permission (consents)
- Pre-application consultation and negotiation
- Producing supporting information for application validation including
- Planning statements, environmental impact assessments, transport assessments, energy statements, health assessments and design and access statements
- Submitting planning applications and reserved matters applications
- Appeal services, including preparing proofs of evidence and presenting expert witness evidence at public inquiries



Resource identification and characterisation

Uniting global expertise to create a unique investigative and interpretive capability

Drilling represents one of the largest expenses for geothermal projects. It also carries a greater risk than any other activity — geohazards have to be mitigated efficiently before they affect the project.

Through its relationship with the University of Auckland's Institute of Earth Sciences and Engineering (IESE), Arup is uniquely placed to offer a suite of shallow and deep site investigation techniques and interpretation. The combined strengths of Arup and IESE enable clients to accurately evaluate the resource's potential and find the best location to drill.

In the area of geothermal exploration, IESE offers a unique joint geophysical imaging (JGI) technology that combines data from seismographs and other geophysical instruments. The technique takes advantage of signal polarisation effects produced by subsurface fractures and is designed to significantly lessen development risks by locating optimum drilling targets. In some geothermal fields, the JGI approach has doubled new well outputs by finding high permeability zones. The JGI method improves resolution of reservoir boundaries, upflow, fault and fracture zones, and fracture density and orientation.

IESE has also co-developed a cableless, downhole seismometer and data acquisition arrays for deep borehole observatories. Since data is recorded within each sonde of the array, data losses due to transmission noise are eliminated. This new tool is especially suited to recording the faintest seismic signals, potentially the smallest ever detected in deep boreholes. In more standard applications, IESE's microearthquake monitoring networks assist in geothermal development and management by tracking the locations of seismicity that relate to fluid production and injection.

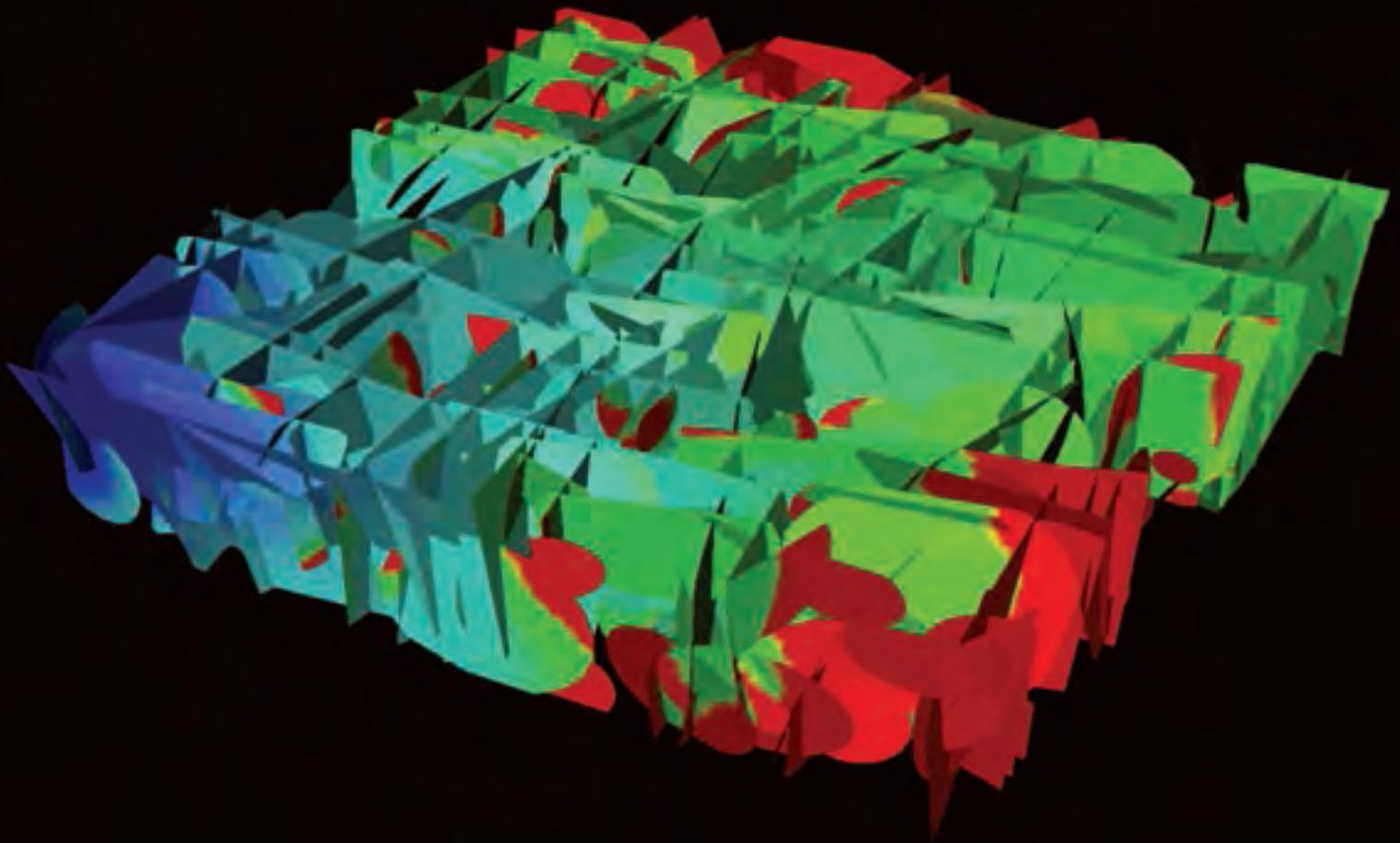
Power plant design and commissioning

For more than thirty years, Arup has provided engineering design and consultancy services to power generation and related infrastructure projects. From development and delivery to decommissioning, our in-house multidisciplinary teams have worked on schemes in more than 20 countries.

We provide strategic programme and project advice to clients and we offer a full range of services. These range from feasibility and site assessment evaluation, including socio-economic, techno-economic and ground evaluation, to the preparation of tender documents, including specification, tender review and procurement. We are also experienced in due diligence contract documentation, permits and approvals, cost estimating and cost control.

Arup brings together technical, commercial and financial expertise, advising clients on complex transactions. This involves technical assessment of cycle efficiencies, capital and operating costs and consideration of the commercial and long-term management strategies for the plant. We also advise on capital investments, condition, economic life, operational efficiencies and revenues. We assess debt sizing and structure based on cash flows, sensitivity and scenario analysis. And we advise on options to enhance the underlying project value. Our approach is particularly useful on greenfield projects, where a significant capital program is planned or where there are key technical issues driving a transaction.





Geomechanics

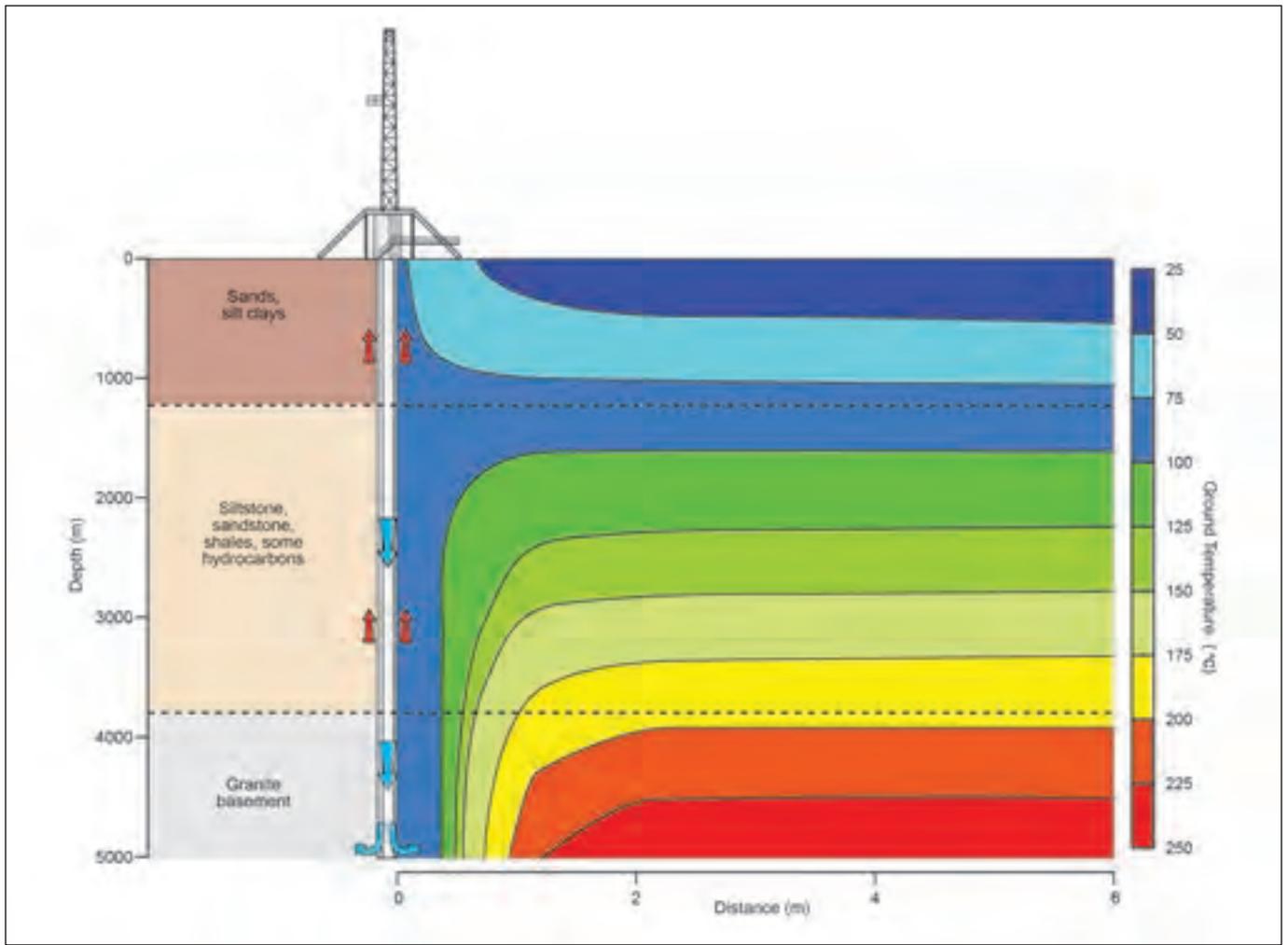
Geomechanics has moved beyond the confines of the oil and gas industry and is becoming an important consideration for carbon capture and sequestration (CCS), deep geothermal reservoir development and management and long term nuclear storage projects. We use all the available data to predict and manage geomechanical behaviour. The sole aim of the geomechanics toolset is to identify, predict, and prevent events that could significantly affect the implementation and long-term economics of a project.

We use a range of in-house and external software to understand and represent the stress regime and rock mechanical properties for a specified zone within a stratigraphic section. The results are optimised and analysed to include time-lapse analysis of the reservoir, caprock integrity monitoring and detailed fractured-reservoir characterisation.

Four dimensional reservoir geomechanics are used to understand how subsurface stress during the life of a reservoir (be it geothermal or CCS) can create severe challenges. The models can simulate formation compaction and subsidence, changes in reservoir permeability, water breakthrough, and fault reactivation or propagation.

The geomechanical changes caused by increased geothermal production, combined with complex geology, can influence wellbore stability and cause casing to collapse. To try and ensure that this does not occur, developers must predict the geomechanical behaviour of the reservoir and surrounding formations throughout the production life of the project. This information can then be used to design the well and plan the management of the reservoir.

We are also investing in new modelling techniques, with our collaborative doctoral research programme at the University of Cambridge studying geomechanics and hydraulic fracture.



Modelling

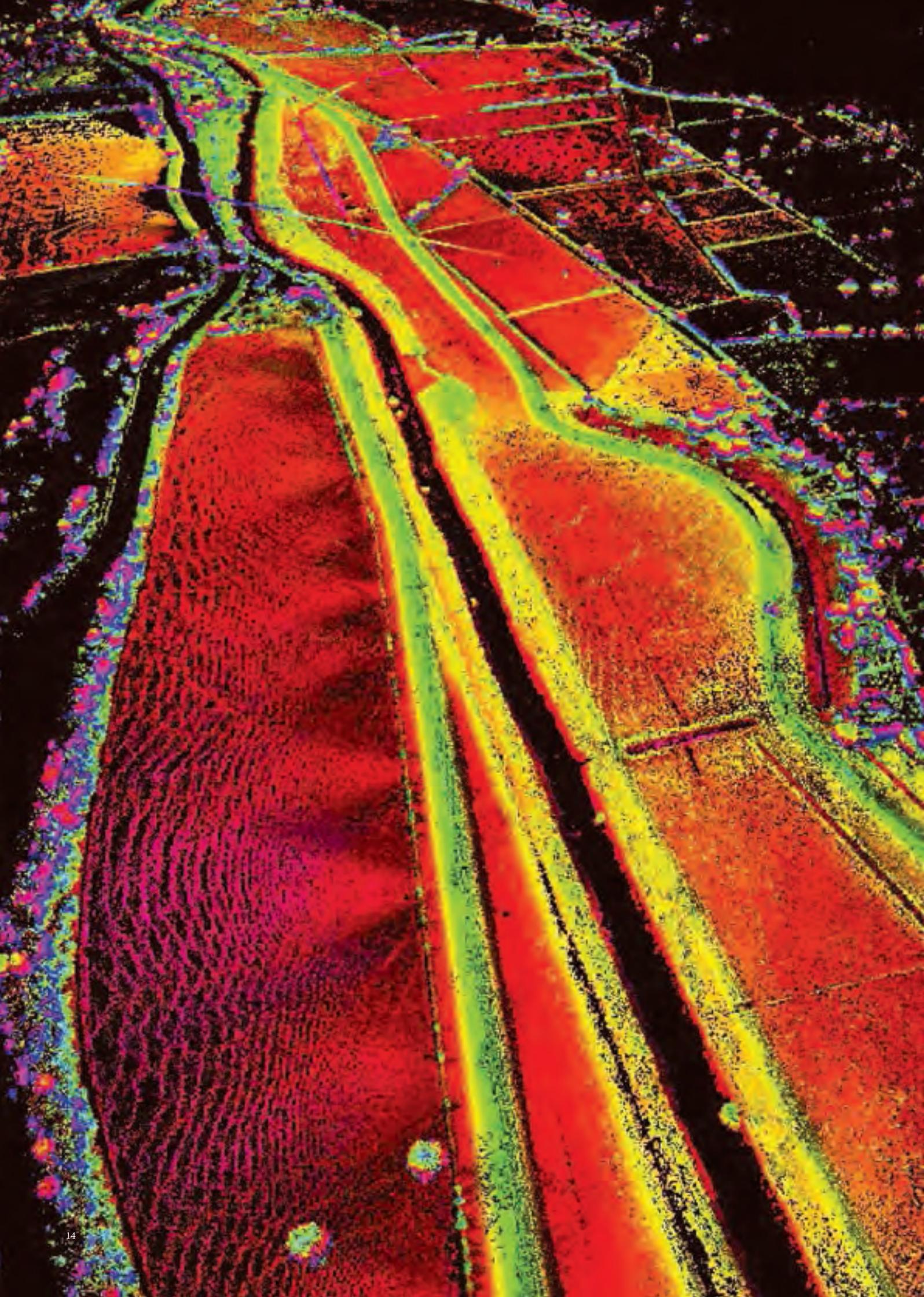
We are at the forefront of numerical modelling, using it for structural engineering for advanced building design, geotechnical engineering and soil mechanics, and complex fluid dynamics. To support this we invest in in-house research and development as well as partnering with the University of Cambridge, Manchester University, Leeds University, Imperial College London and others to ensure we remain at the leading edge of model design and interpretation.

The temperature, pressure and fluid interaction within any geothermal system is complex. This is particularly true for deeper systems that rely principally on fracture networks. Arup works with both in-house and established numerical models to understand geothermal reservoirs prior to drilling and during operation.

We also have the capability to link established sub-surface models such as TOUGH-2 and SUTRA 3D to surface models that simulate power plant operation. This combined modelling approach enables project developers to understand the key factors that influence the geological and economic performance of geothermal power plants. Developers use our sensitivity analysis results to explore the likely economic returns on a project and understand the best power plant configuration.

We also use numerical models to understand heat transfer to and from wells during drilling and mud circulation. The results have been used to predict how long a well will remain suitable for logging tools after mud circulation has finished.

Above – Section showing ground condition and predicted temperature at the end of the cooling stage of a deep geothermal well in Australia. The section relates to the Cooper Basin borehole modelling project



Left – GIS model indicating the areas at risk from flooding from a river

Geographical information systems for site location

We use geographic information systems (GIS) technology to visualise, manage, analyse and collate data based on any location.

Our GIS solutions make it simpler and quicker for you to manage your assets geographically, identify opportunities, reduce risk and adapt to better face the future.

Arup combines IT and communications expertise with specialist market knowledge to tailor innovative GIS solutions. These range from web-based mapping tools to 3D models, often incorporating building information modelling (BIM). They always focus on practical outcomes such as predicting floods or planning business logistics.

For geothermal projects, we have evaluated the criteria to meet planning requirements for exploration and production boreholes and power plants. We have used GIS technology to assist in site suitability assessment and planning to aid stakeholder consultation and prevent project delays. This demonstrated how useful GIS visualisations can be in illustrating technical issues for stakeholder and societal engagement.

Data is collected for each site in relation to its location, geography, local infrastructure and socio-economic characteristics. This involves compiling GIS data, GIS modelling, assessing site characteristics, and preparing 3D imagery and fly-through digital film sequences.

Arup has developed GIS solutions that combine real-time reporting with pinpoint accuracy. They make it possible to react instantly to data changes, and predict risks more accurately. We have used this to mitigate potential ground movement on major infrastructure projects such as London's Crossrail and the Transbay Terminal project in earthquake-prone San Francisco.

Select Arup Geothermal and Related Projects October 2017

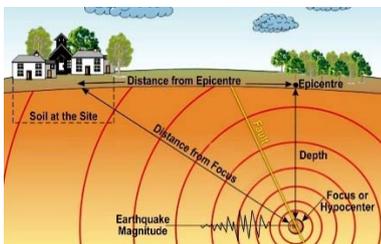


Technical Due Diligence of 1.2 GW of Geothermal Power, Philippines.

Client: Macquarie Infrastructure Asia Real Assets

Status: Completed 2017

Arup provided a technical due diligence evaluation of EDC power generation assets in the Philippines. The evaluation was in support of the successful acquisition of a 30% stake in EDC and provided inputs to the valuation process. The work included review of resources, power plants, environmental, health & safety, as well as review of 300 MW of wind power, hydroelectric, and solar power assets.



Seismic Hazard Assessment.

Client: Geothermal Engineering Limited

Status: Ongoing

Arup performed an assessment of seismic hazards related to proposed operation of geothermal electricity project in Cornwall, UK. The work included evaluation of the natural seismic regime and the potential impact due to geothermal operations.

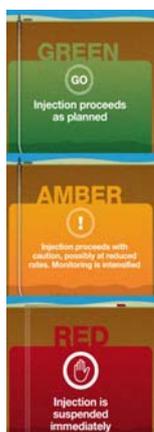


Development of a Fixed Tariff System for Geothermal Electricity in Indonesia.

Client: UK Foreign Commonwealth Office

Status: Completed 2017

Arup has developed recommendations to the Indonesian government for appropriate tariff levels for geothermal electricity. As part of this work Arup has developed a bespoke financial model drawing from a range of geothermal conditions and project development plans. The output from the financial model was used to generate the recommended fixed tariff system.



Traffic Light System for Geothermal Stimulation, Finland

Client: st1 Deep Heat

Status: Ongoing

Arup is working with a developer, local regulatory authority, and institute of seismology to develop a traffic light system (TLS) to be used during stimulation of 6+km deep geothermal wells in Espoo near Helsinki. Arup is developing the TLS based on the natural seismic regime and potential for induced events during stimulation.

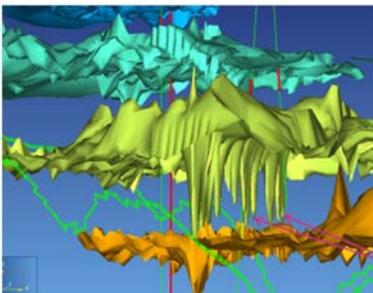


Road Map for Geothermal Development, Flores, Indonesia.

Client: UK Foreign Commonwealth Office
Status: Completed 2017

At the request of the Indonesian government, Arup is putting together a road map for geothermal development on Flores island. The road map considers the range of technical, economic, and social factors which influence the production of geothermal electricity. Work has included engagement with local communities and governments; electricity grid operator, PLN; and other relevant stakeholders.

The road map will include a strategy to increase geothermal electricity on Flores while empowering local communities and minimising the impact of transitioning from diesel based electricity to geothermal.



Client Expert Role: Geothermal Well Project, Belgium

Client: Johnson & Johnson / Janssen Pharmaceutica
Status: Ongoing

Arup acts as a client representative for the design of a deep geothermal well (including a technical and economic due diligence of the available geothermal resource and well drilling costs as an independent review of work performed by others). Work consisted of detailed evaluation of numerical modelling and model assumptions (including well production rates), review of costs, and review of well design.

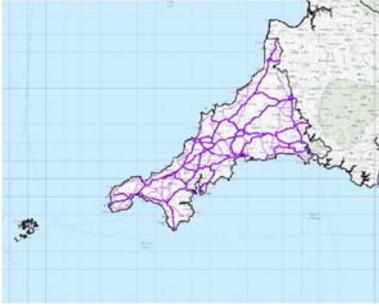
The value of our work was to provide an independent and third party assessment of project risks. Our assessment aided the client's project team in decision making and understanding of risk associated with geothermal resource development.



Review of Geothermal Regulatory Regime, Indonesia

Client: Green Energy Geothermal
Status: Complete

Arup performed a review of the Indonesian geothermal regulatory system which has resulted in the development of a new tariff system. The work was performed for the Indonesian government on behalf of the UK government with funds provided by a geothermal developer. The outcome of this report led to a variety of recommendations to the Indonesian government to accelerate geothermal development.



Deep Geothermal Investment Options Appraisal, Cornwall, UK

Client: Cornwall Council
Status: Completed 2015

Arup performed an appraisal of investment options into geothermal resources for Cornwall Council. The work included development of an economic model, review of the subsidy regime and state aid rules, assessment of Cornwall's low carbon heat zones, and development of a risk matrix.

The value of this work was to facilitate decision making within the council on how best to procure geothermal resource development services (including well drilling) while maintaining state aid compliance its procurement.



Planning and Permitting, Deep Geothermal Heat Well, Crewe, UK

Client: Geothermal Engineering Ltd
Status: Completed 2015

Arup provided the documentation required to achieve planning permission and all other relevant permitting for a 2km vertical heat well in an urban area. Work included a full noise assessment, transport, environmental and hydrogeological impact assessments. We also worked with the client on liaising with the public (consultation events) and with the Environment Agency/ on shore Health and Safety. The client achieved Planning Permission in September 2015.



EIA for Shale Gas Exploration, Lancashire, UK

Client: Cuadrilla Resources, Ltd.
Status: Completed 2014

Arup provided the first of its kind Environmental Impact Assessments (EIAs) and Environmental Risk Assessments (ERAs) in the UK for shale gas exploration operations by Cuadrilla in Lancashire. In addition, Arup has assisted Cuadrilla to obtain planning consent from local authorities for the exploration activities. Public consultation has played a critical role in this project to achieve effective communication with stakeholders. Both the planning consent and public consultation processes required close communication with regulators, local authorities, and the surrounding community. The EIA process was comprehensive and included evaluations of traffic, visual, noise, ecology, climate change, health, hydrogeologic and contamination impacts as well as potential impacts due to well construction and integrity, hydraulic fracturing and induced seismicity.



Technical and financial due diligence, Aduas, Turkey

Client: Financial investor, UK

Status: Completed 2008

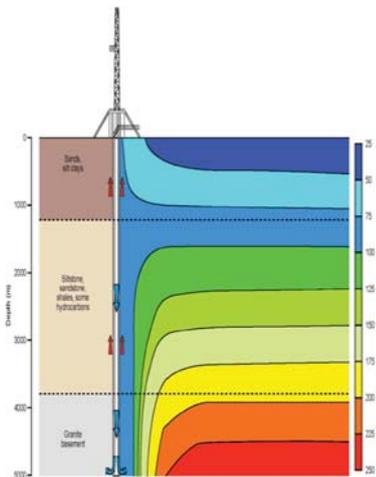
Arup was commissioned to undertake a technical and financial due diligence review of renewable energy projects in Turkey, on behalf of a potential infrastructure investor based in the UK. We reviewed a total of nine existing power plants; seven hydro-electric plants, one geothermal and one diesel generation plant, which are being privatised by the Turkish Government. Output ranged from 5-21MW each and the assets were built between 1961 and 2003.

Our report focused on the need for future capital investment to maintain the sites, plus the potential for increasing output from the plants. In addition, we provided a review of a number of new opportunities, which were being developed by a co-investor as part of a larger portfolio.

Reservoir modelling, Cooper Basin, Australia

Client: Geodynamics

Status: Completed 2010



Geodynamics Limited is developing the Cooper Basin geothermal reservoir for electricity production in Australia. The geothermal wells are 5,000m deep and uncased in the granite below 3800m. At the bottom of the borehole the temperature is 280°C.

In order to undertake fracture logging and packer tests in the open section of the well, the borehole temperature in the granite needed to be cooled to a low enough temperature so that geophysical logging could be undertaken in the well.

Arup was asked to carry out modelling work to simulate the cooling effect of injecting mud at a temperature of $100^{\circ}\text{C} \pm 25^{\circ}\text{C}$ and flow rate of 400 ± 200 gal per minute. A 2D model of the geothermal system was developed using SUTRA (a modelling program developed by the USGS). For each of the nine scenarios, the cooling process was run for 48 hours followed by a 48 hour period when the circulation had stopped. The section shown above shows the predicted temperature in the granite at the end of the cooling stage.

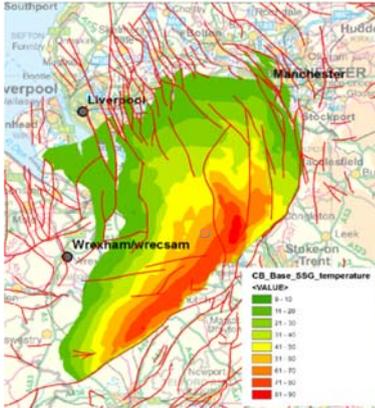


Geothermal Single Well Design, United Kingdom

Client: Geothermal Engineering Ltd

Status: To be completed 2015

Arup's is part of a design and testing team for an innovative geothermal single well system. The project is located in Cornwall, UK. The overall goal is to develop a design solution for heat generation and supply for district heating or other similar types of end users while reducing capital costs and investment risk. Work additionally included the design and construction of bespoke thermal response test equipment.

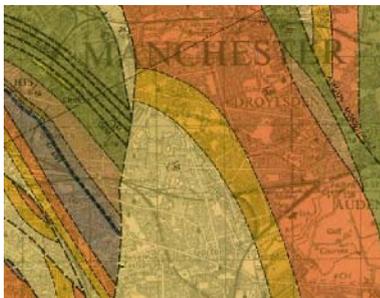


Geothermal resource planning, Cheshire, UK

Client: Cheshire East C

Status: Completed 2013

Arup carried out an expert review on the development of a deep geothermal exploratory well system. The geology, fracturing and temperature regime of the geothermal resource in the Sherwood Sandstone was examined. This helped inform the council on the potential energy resource available and target the site location to best maximise the resource. The review also assessed the economics of the deep geothermal well program and justified the need for government investment in the development.



Deep geothermal EIA, Manchester, UK

Client: Manchester City Council

Status: Completed 2013

Arup, in collaboration with the Auckland University Institute of Earth Sciences and Engineering performed an external assessment of an Environmental Impact Assessment submitted by the developers of a deep geothermal heating scheme in central Manchester. The assessment focussed on whether sufficient detail and information had been provided by the developer, particularly with respect to the geology, hydrogeology and induced seismicity. Arup recommended what additional information should be supplied by the developer to reassure the local Council that the scheme does not represent an Environmental hazard.



Geothermal financial analysis, Manisa, Turkey

Client: Enerjisa

Status: Completed 2013

Arup was appointed to carry out an energy consultancy project for a geothermal power plant. We carried out the analysis for CAPEX and OPEX estimates for the 50MW power plant. The work provided valuable information with which the client based its investment decisions.



Deep geothermal options study, UK

Client: Cornwall Council

Status: Completed 2012

Arup was commissioned to undertake a detailed study into the barriers to the development of deep geothermal power projects in Cornwall and potential strategies to stimulate the sector. The study covered technical, geological, financial and policy barriers.

Financial models of deep geothermal power plants were developed and extensive interviews were undertaken with developers, stakeholders, the Department of Energy and Climate Change and the Environment Agency. An investment and risk mitigation strategy was developed for the Council to follow. The report has been used as a reference document for the ongoing funding (National and Local level) of deep geothermal technology in Cornwall.



Deep geothermal risk assessment, UK

Client: Cornwall Council/ DECC (now BEIS)

Status: Completed 2012

Arup completed a financial and technical risk assessment of the two deep geothermal projects currently being developed in Cornwall, UK. The study focused on the strategic and technical risks of the two projects and has been used as a basis for high level local and National funding decisions.



Deep geothermal heating scheme, Manchester, UK

Client: Manchester City Council

Status: Completed 2012

Arup was appointed by Manchester City Council to evaluate a private development proposal to drill and install deep geothermal wells in the city centre to provide heat for a district heating scheme. The study focused on the geological and hydrogeological assumptions made in the proposal. The study effectively acted as a technical due diligence exercise to enable the Council to make a decision as to whether the proposed scheme was technically feasible.



GIS study, deep geothermal power, UK

Client: Geothermal Engineering Ltd

Status: Completed 2010

Arup evaluated the criteria needed to meet the planning requirements for the deepest on-shore exploration/production wells to be drilled in the UK, along with the design of the subsequent air cooled power plant. Data was collected for each site in relation to site location and geography, local infrastructure and socio-economic characteristics. This required a compilation of key GIS data, some GIS modelling and site characteristic assessment, and preparation of the 3D imagery and fly-through digital movie sequences.

Arup deliverables included reports which summarised the findings of the study, as well as the publication of a series of GIS thematic maps which are accessible via free software presented to the client.

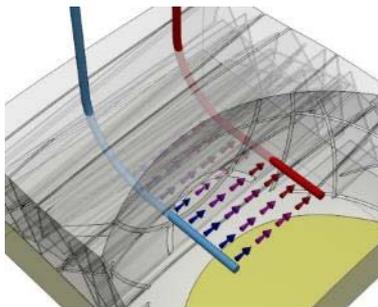


Geothermal district heating system, Belfast, Northern Ireland, UK

Client: Confidential

Status: Completed 2010

Arup were asked to undertake a study on the potential to develop a deep geothermal heating scheme for a hospital in Belfast, Northern Ireland. The study focused on the geological potential, the space requirements for drilling and installation and the economics of the scheme. Technical as well as financial risks and early stage well design work was also undertaken for the client.



Feasibility study, Rabigh, Saudi Arabia

Client: KAUST University

Status: Completed 2009

Arup were asked to complete a feasibility study on the potential to install a deep geothermal system to provide absorption cooling to a new University planned in Saudi Arabia. The study involved the collection of geothermal and geophysical data to evaluate the potential and costs of drilling wells to tap into a resource with temperatures above 100°C.

The study highlighted that there was significant potential to supply substantial quantities of cooling to the building from the deep geothermal resource.

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