



Energy Security and Innovation Observing System for the Subsurface (ESIOS)

Science Plan

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1. Executive Summary

The Energy Security and Innovation Observing System for the Subsurface (ESIOS) capital project will establish new centres for research into the sub-surface environment. The knowledge they generate will contribute to the responsible development of new low-carbon energy technologies both in the UK and internationally. The Natural Environment Research Council (NERC), through its broader science base and with input from industry, regulators and policy-makers, will use ESIOS to provide the UK research community with world-leading facilities. The capital project is NERC's response to the government's announcement in the 2014 Autumn Statement that it would allocate £31m to create world-class sub-surface energy research test centres through NERC. Science conducted using ESIOS facilities will be generated through NERC strategic and discovery research, innovation and training funding processes.

NERC's strategy, *The Business of the Environment*, identified the importance of increasing the understanding of subsurface processes in order to benefit from and protect natural resources. The UK needs secure, affordable, low-carbon energy sources – but it needs to develop them efficiently, safely and sustainably. A range of energy resources that utilise the subsurface, and the infrastructures and technologies around those energy resources, will be key to delivering the UK's transition to a low-carbon energy system. These could include subsurface energy storage, conventional and unconventional oil and gas, renewable geothermal energy, underground radioactive waste disposal and carbon capture and storage. The UK has a complex geological history, compared to many areas of the world where subsurface energy applications are used (e.g. the interior basins of the USA and Canada or the relatively simple passive margin of Australia). This places extra demands on those who wish to understand how the subsurface environment could respond to human-induced perturbations.

ESIOS aims to facilitate critical research that underpins the safe and environmentally sustainable development of subsurface energy systems. This research will target key gaps in our knowledge around human-induced and natural coupled mass and energy transfer in heterogeneous geological systems, and its effects on the subsurface and surface. Given the potential scale and nature of energy system change, there is an urgent need for an improved evidence base to inform decision making by government, industry and civil society. ESIOS will contribute science-based evidence.

Subsurface experimentation puts special requirements on research projects. For effective subsurface research there needs to be careful management of the science experiments, technical execution and data processing - and critically - interactions with industry and international research organisations to ensure feasibility and use of existing knowledge. ESIOS will provide the experimental infrastructure for independent research including commissioning new sub-surface wells, monitoring, sampling and sample curation and data handling.

Geological systems (the rock mass and the fluids and biota that it contains) are inherently heterogeneous and anisotropic. Understanding the multiple processes that can be triggered by anthropogenic disturbances to a rock mass such as drilling, fluid injection and extraction or hydraulic fracturing requires imaging and characterizing a highly heterogeneous system before experiments begin, and then monitoring and understanding of the coupled processes that result. The ESAG defined four Science Challenges that are critical to understanding these processes:

Science Challenges

1. How fluids, often multiple fluid phases, flow through the rock mass, how the chemical interactions between fluids and minerals modify the fluid flow and mechanical properties of the rock mass, and how fluid chemistry can be used to monitor the evolving structure of the rock mass, fluid flow and biological processes and mechanical processes such as cracking.
2. How stress changes either as a consequence of injecting, producing or mobilising fluids, or imposed deliberately, cause mechanical responses.

3. How the nature of the subsurface biosphere responds to perturbations caused by fluid flow and mechanical changes.
4. Whether and how anthropogenic perturbations in the subsurface alter the links and feedbacks between the deep subsurface and the shallow subsurface and surface; for example, whether they affect the near subsurface (e.g. potable aquifers and other groundwater) or surface (e.g. subsidence, emissions).

These four Science Challenges are intrinsically coupled and making the observations necessary to understand the links between them will be central to the science carried out by ESIOS. They lead into five separate but interlinked Research Areas, plus six Experimental Requirements that contribute to the Science Challenges.

Research Areas

- i. Imaging complex, heterogeneous and evolving rock mass.
- ii. Multiphase flow in heterogeneous media.
- iii. Mechanical response to artificial perturbations.
- iv. Biogeochemical response to artificial perturbations
- v. Surface-subsurface interactions and impacts.

Experimental Requirements

- a) Planning based on prior knowledge of the geological structure;
- b) Determination of baseline conditions (both natural and the legacy from human/industrial activities);
- c) Implementation of remote and in-situ monitoring systems;
- d) The drilling phase, which will include monitoring while drilling, sampling of core and fluids, downhole geophysical logging and installation of downhole instrumentation;
- e) Ongoing (legacy) monitoring and sampling
- f) Conduction of downhole experiments and related sampling and monitoring.

The science research programmes associated with ESIOS must be involved in all of these Experimental phases, especially in the likely event that decisions on changes in the experimental programme need to be taken urgently on the basis of new observations or technical requirements.

In addition to the Science Challenges, Research Areas, and Experimental Requirements (Sections 4 and 5), the ESIOS Science Advisory Group (ESAG) offers a set of 20 recommendations (Section 7) to NERC based on the science ideas process and subsequent international review of the proposed science and facility delivery. ESAG would like to highlight the following:

- A key role of ESIOS is to deliver novel and excellent science which can drive innovation and economic growth. Open-access data and results will facilitate the dissemination of excellent science both between the ESIOS operator and facility users, and to end-users.
- The data from initial site characterisation and baseline measurements must be made freely available to the research community to facilitate and constrain effective design of later experiments. These data should be used to develop a “live” and constantly updated 3D geological framework model of the site such that subsequent experimental design builds upon the integrated model.
- ESIOS will be a platform for world-leading international collaboration.
- Site selection should ensure that sites can provide the geological environment and surface facilities to match the objectives of this Science Plan. The first ESIOS site is likely to be close to Thornton in Cheshire. BGS surveys have shown that this geology is suitable for a wide range of research into the coupled fluid-mechanical and geo-microbial effects of Carbon Capture and Storage (CCS), gas storage, geothermal energy and hydrocarbon extraction. This was supported by the input received from the ‘Call for Ideas’ process.
- Science advice must be involved during the baseline, drilling, and ongoing science implementation phases of the projects. As with all drilling projects, on occasion urgent

pragmatic decisions may be needed. A clear process for all science decisions at both sites must be set up at the earliest opportunity.

- The process of selecting and designing strategic research programmes must be managed carefully to ensure that the full scientific opportunities are exploited, and that competing uses of the facility are avoided. Ancillary scientific research programmes related to, but not directly using, the facilities are crucial to maximise the benefits of this facility. These include research which develops data processing, novel monitoring techniques and sample analyses.
- Stakeholder engagement is essential for the success of the project. All stakeholder engagement should be on a fully transparent basis, and open -access publication of results will be required.
- The ESIOS sites will provide excellent opportunities for public engagement, both to inform debate around future energy technologies, but also to enthuse the UK public about NERC science.

2. Background

The Energy Security and Innovation Observing System for the Subsurface (ESIOS) capital project will establish new centres for research into the underground environment. The knowledge they generate will contribute to the responsible development of new low-carbon energy technologies both in the UK and internationally. NERC, through its broader science base and with input from industry, regulators and policy-makers, will use ESIOS to provide the UK research community with world-leading facilities.

The capital project is NERC's response to the government's announcement in the [2014 Autumn Statement](#) that it would allocate £31m to create world-class subsurface energy research test centres through NERC. This allocation is subject to final governmental approval of NERC's business case. ESIOS aims to enable world-leading knowledge that will be applicable to a wide range of energy technologies. Two sites for subsurface research will be commissioned by NERC and operated by the British Geological Survey (BGS).

Strategic science conducted using ESIOS facilities can be generated through the NERC Strategic Research funding process, via the "Ideas" process for Highlight Topics (HTs) and Strategic Programme Areas (SPAs) or through the Joint Strategic Response (JSR) route. A HT focuses strategic research on a defined topic area with the size and duration of projects specified for each topic. SPAs are major activities that address complex science questions in which the research is expected to be large-scale and complex, logistically challenging, and/or there are significant opportunities for partnership development. HTs are usually up to the value of £4m and last four years whereas SPAs are usually longer in duration and might typically range in size from £5m to £20m depending on their scope and partnership funding. JSR is aimed at providing a timely response by NERC to opportunities to partner with research funders such as other research councils and government departments. The ESIOS facilities will provide the research community with opportunities to propose world-leading science through all of these strategic mechanisms. It is expected that discovery science¹ will also use ESIOS as a facility for research, and that the facility will be available for innovation and training activities.

This Science Plan describes the Science Challenges that the research community seeks to answer through provision of ESIOS facilities. The science ambitions, economic rationale and use of ESIOS capital are linked through the Business Case, which describes the value of ESIOS to the UK in business and economic terms, and the steps needed to implement ESIOS.

The UK is committed to implementing a transition to a low-carbon energy system. This commitment is reflected in the 2008 Climate Change Act, which includes a long-term target for reducing greenhouse gas emissions by 80% between 1990 and 2050. The Act also commits the UK to a series of five-year carbon budgets that are legislated by government following advice from an independent advisory body, the Committee on Climate Change. Alongside this commitment to emissions reduction, the UK government also emphasises a number of other important policy goals – particularly commitments to maintaining energy security and to ensuring that the low-carbon transition is implemented so that it is affordable for consumers and businesses². Britain needs secure, affordable, low-carbon energy sources – but it must also develop them efficiently, safely and sustainably.

¹ NERC's discovery science (formerly responsive mode) funding stream supports excellent environmental research that is driven by curiosity rather than by NERC's wider strategic priorities. Discovery science can support pure, applied, technology-led or policy-driven research, but it must address - or provide the means to address - clearly-defined scientific questions.

² HM Government (2015) *Government response to the Committee on Climate Change*. Summary document. URN 15D/484. London, HMSO.

A range of energy resources, infrastructures and technologies are likely to be required as part of the UK's transition to a low carbon energy system³. Many of these resources are likely have impacts on, or implications for, the subsurface⁴. They include:

- i. Non-renewable resources including conventional and unconventional oil and gas. Whilst the development of low-carbon energy systems will mean a substantial reduction in the use of fossil fuels, such resources are likely to have a significant role in the UK's energy mix for many years to come, particularly for heating and transport.
- ii. Carbon Capture and Storage (CCS) could offset CO₂ emissions from use of fossil fuels during the transition to carbon-free energy sources. The technologies are currently being piloted globally and if successfully commercialised, there is very significant potential for the UK offshore subsurface to be used for carbon dioxide storage.
- iii. Renewable resources, particularly geothermal energy. There have been programmes to explore the potential for geothermal energy in the UK for several decades. In addition to deep geothermal energy, there is also increasing interest in the deployment of smaller-scale ground source heat pumps and the recovery of 'waste heat' from sub surface activities (e.g. minewater).
- iv. Energy storage. The subsurface is already used for the storage of natural gas at several sites in the UK, including the Caythorpe Gasfield in onshore South Yorkshire and the larger Rough offshore gas storage field located offshore in the southern North Sea. Several new sites for gas storage have been granted planning permission in recent years. The subsurface could also be used for energy storage (e.g. in the form of heat or compressed air) to help balance supply and demand for heat and electricity. Energy storage is particularly crucial to a low-carbon electricity system since it is one of a number of sources of flexibility that could help to integrate large-scale generation from intermittent renewable resources such as wind and wave energy.
- v. Plans to develop radioactive waste disposal site(s) in the UK have been debated for many years. Despite a lack of progress in developing a specific site, deep geological disposal is regarded by government as the best long-term option for dealing with this waste.

In addition to these direct implications of low-carbon energy systems, energy supply chains may also have impacts on the subsurface. Examples include mining for rare earth materials that are used in certain low-carbon technologies such as wind turbines and electric vehicles.

Against this background, the purpose of ESIOS is to facilitate research that improves understanding of subsurface energy developments, mass and energy transfer in coupled systems, and their impacts on the subsurface and surface and consequently their interactions with the wider energy system. Given the potential scale and nature of energy-system change, there is a need for an improved evidence base to inform decision-making by government, industry and civil society. ESIOS is designed to facilitate the new research that industry and the research community couldn't otherwise address.

³ Committee on Climate Change (2015) *The fifth carbon budget – The next step towards a low-carbon economy*. London, CCC.

Ekens, P., I. Keppo, et al. (2013) *The UK energy system in 2050: Comparing Low-Carbon, Resilient Scenarios*. UKERC Research Report. London, UKERC.

Energy Technologies Institute (2015) *Options Choices Actions: UK Energy Scenarios for a Low Carbon Energy System*. Insight Report. Birmingham, ETI.

⁴ While the term resources is often used to describe energy sources such as fossil fuels or geothermal energy, the subsurface can provide resources in other senses, such as providing pore space for disposal of CO₂, or storage of gas or energy.

Due to the interconnected political, economic, social, technological, legal and environmental considerations associated with this change, a ‘whole systems’ approach is required⁵. Whilst much of the research ESIOS will enable is rooted in physical and natural sciences and engineering, it is also relevant to research in other fields including psychology, sociology, economics, and policy and regulation.

This ESIOS Science Plan will inform the science specification for commissioning ESIOS. The process for development of the Science Plan was initiated by NERC in September 2015 and concluded in March 2016. Science Plan development was conducted through the ESIOS Science Advisory Group (ESAG) and included an online ideas process call as well as a Town Hall meeting. ESAG incorporated submitted ideas and the outputs of the meeting into the Science Plan.

⁵ Whole systems energy research aims at a better understanding of the energy landscape incorporating environmental, socio-economic, physical, natural and biological systems at all spatial and temporal scales. It addresses complexities, interactions and interdependencies within the landscape and with other systems. Whole-systems energy research necessarily draws upon a wide range of disciplines and methodologies.

3. NERC's Strategy

3.1. Science strategy

The NERC strategy of 2013, [The Business of the Environment](#), identified the importance of increasing understanding of subsurface processes to benefit from, and protect, natural resources. The vision is to enable science that describes how natural processes control resource availability and how natural resources can be used responsibly for present and future generations. ESIOS will facilitate research into efficient and environmentally secure extraction of resources from the subsurface, protection of the subsurface and surface environments and use of the subsurface as part of a wider low-carbon energy system. The feasibility, efficiency and environmental sustainability of these subsurface technologies need to be understood and improved to drive innovation and encourage investment to enable safe and efficient utilisation of the subsurface, and inform debate, policymakers and regulators. NERC science will therefore be critical in helping address the UK's 'energy trilemma' (sustainable, secure, affordable energy).

ESIOS will form part of NERC's long term strategic approach to integrated environmental observation and data science to deliver the NERC Strategy, drive innovation and growth and bring closer a 'full model of the environment', working in partnership with industry and government. Investments in sensor and data transfer technologies will provide environmental data at unprecedented spatial and temporal scales enabling a significant shift in the understanding of the natural environment. This would cement the UK's leading position in Earth and environmental science as well as offering the potential to inform improved, more efficient, monitoring and forecasting of natural phenomena for wider societal and economic impacts for businesses, government and the public. The ESIOS investments will support and inform energy policy decisions and decisions by the research community, private sector, civil society etc.

Strategic research undertaken using ESIOS infrastructure is anticipated to be of interest to NERC's funding partners, especially the Engineering and Physical Sciences Research Council (EPSRC), the Economic and Social Research Council (ESRC), Innovate UK and the Department of Energy and Climate Change (DECC).

3.2. World-class multidisciplinary science and training

The UK's subsurface energy science is world class. Scientists at UK universities and research organisations developed some of the basic physics and chemistry of subsurface fluid flow, geomechanics, geobiology and imaging, which have had global application in subsurface resource management. UK universities and NERC research centres have a long tradition of top-quality applied research of direct relevance to the sector. Joint Industry Projects (JIPs) have covered areas including improved acquisition, processing, analysis, interpretation and quantification of seismic data in offshore waters of the UK continental shelf and onshore areas where acquisition and processing are even more challenging. This science fundamentally underpins extraction technology in the oil and gas and other extractive industries worldwide, and has made Britain's offshore oil and gas industry amongst the most scientifically sophisticated in the world while also acting as exportable knowhow.

The UK has also pioneered science in areas such as CCS and geothermal energy. With the requirement for a deeper understanding of the subsurface to drive development of low-carbon energy applications such as geothermal and subsurface energy storage, as well as to reduce the environmental impacts of subsurface developments, onshore subsurface energy research at ESIOS will provide an environment to develop and enhance subsurface science, training new scientists and technologists, and developing new centres of excellence in partnership with international bodies, universities, and new institutions.

ESIOS will provide an opportunity for existing training bodies, for example the NERC Centre for Doctoral Training in Oil and Gas, Doctoral Training Partnerships (DTPs) funded by NERC and other research councils etc., to provide a highly-skilled workforce with expertise that can be used across the wider energy and environment sectors. ESIOS infrastructure, samples and data will be made

available for PhD students and NERC-supported researchers who apply for funding via discovery science and strategic research programmes. For companies and Small and Medium Enterprises (SMEs), ESIOs will provide opportunities for continuous professional development and cross-disciplinary training for early career scientists and engineers.

4. Science Requirements

4.1. Overview

The following sections outline key outstanding science questions that ESIOS needs to address and the general requirements for planning and delivering the ESIOS facilities, and subsequently for executing and observing the experiments.

Subsurface experimentation puts special requirements on research programmes. For effective subsurface research there needs to be careful management of the science experiments, technical execution and data processing leading to the associated scientific research programmes. It involves critical interactions with industry in order to both use information gained from industry in drilling the wells and generate additional data through the commissioning of downhole instruments and sampling.

ESIOS will provide the experimental infrastructure in collaboration with industry including commissioning new wells, monitoring, sampling and sample curation, data handling, negotiating access to wells funded by industry, as well as overseeing the science management structure. The science management structure will need to select the appropriate experiments, determine that the experimental infrastructure is appropriate, ensure that the full scientific opportunities are exploited and that ancillary scientific research programmes (data processing, sample analyses, data availability, interpretation and publication) are in place.

4.2 Science Challenges

Geological systems (the rock mass and the fluids and biota that it contains) are inherently heterogeneous and anisotropic. Understanding the multiple processes that can be triggered by anthropogenic disturbances to a rock mass such as drilling, fluid injection and extraction or hydraulic fracturing requires imaging and characterizing a highly heterogeneous system before experiments are initiated, and then monitoring and understanding of the coupled processes that result. These processes are best defined as four Science Challenges:

1. How fluids, often multiple fluid phases, flow through the rock mass, how the chemical interactions between fluids and minerals modify the fluid flow and mechanical properties of the rock mass and how fluid chemistry can be used to monitor the evolving structure of the rock mass, fluid flow and biological processes and mechanical processes such as cracking.
2. How stress changes either as a consequence of injecting, producing or mobilising fluids, or imposed deliberately, cause mechanical responses.
3. The nature of the subsurface biosphere and how it responds to perturbations caused by fluid flow and mechanical changes.
4. The effect of anthropogenic perturbations in the subsurface become relevant to wider UK stakeholders when they directly affect the near subsurface (e.g. potable aquifers and other groundwater) or surface (e.g. subsidence, emissions), so the final section addresses research questions concerning the links and feedbacks between the deep subsurface and the shallow subsurface and surface.

The Science Challenges are intrinsically coupled and making the observations necessary to understand the links between them will be central to the science carried out by ESIOS. The sections below outline the five separate but interlinked Research Areas, emphasising that they too are intrinsically coupled, and how ESIOS will provide opportunities to address these questions.

4.2.1 *Research Area i. Imaging a complex, heterogeneous and evolving rock mass*

Extraction of hydrocarbons, heat and water from the subsurface as well as injection of fluids into the subsurface demands an understanding of the three-dimensional architecture of a highly heterogeneous rock mass for efficient and environmentally secure recovery of resources or long-term geological storage. While geological science can predict the first-order controls on the geometry and properties of the rock mass, there are significant uncertainties that can affect commercial viability and environmental impacts. The geology is predicted from surface mapping,

remote observations and the limited sampling and observations in exploration, extraction or injection wells. Being able to understand how to characterise the subsurface in order to reduce the uncertainty in predicting the performance of rock masses is a major issue in geology. The heterogeneity of the rock mass has implications for well stability and well design, is a critical control on the flow of fluids and impacts the rock's mechanical properties. A thorough understanding of rock mass, fluid and biological heterogeneity at a variety of scales will enable much more efficient and environmentally secure use of the subsurface resource and will reduce the environmental impact and increase safety.

In order to accurately image bedrock layers and to understand the geometry and properties of any pathways that may control migration of fluids, it is essential to gain an accurate 3D picture of the subsurface strata and any faults that transect and compartmentalise them. Geophysical remote sensing surveys are improving in fidelity, but have inherent resolution limits. As an example, most seismic datasets are acquired in time and then depth converted using a model of the seismic velocity of the overburden. Without a full understanding of the overburden bedding geometries, lithological variations and unit thicknesses, it will be difficult to build the pre-requisite velocity model, in enough spatial detail, that permits accurate depth conversion to produce maps of geological horizons or faults. Grids of spaced 2D seismic lines or borehole extrapolations have traditionally been used to map areas and build subsurface models. Such subsurface models are particularly difficult to create challenged where the line orientations are dictated by roads and land use. In recent years, closely spaced 3D seismic volumes have become the norm to better characterise and constrain subsurface geology, especially in the offshore realm where access difficulties are minimised. Improved and novel acquisition and processing techniques (e.g. broadband seismometers collect the full bandwidth of seismic frequencies to explore the overburden geometries as well as deep target formations) have now enhanced the capability and fidelity of land 3D seismic to an extent that their use is seen as best-practice in controlling subsurface rock and fracture models.

A significant geological issue is to be able to develop methodologies for interpreting sparse data and delivering robust forecasting algorithms for rock mass performance. This is because the wells drilled to appraise or exploit a resource are effectively widely-spaced one dimensional sample lines of high data density and resolution in complex, heterogeneous volumes of low data density and resolution. Existing modelling of subsurface flow, geochemical and mechanical processes is based primarily on laboratory scale experiments and measurements of rock properties which are used to derive theoretical models that are then applied over scales appropriate to the subsurface industries.

These 'reservoir-scale' models are populated with properties obtained by sampling (coring, logging, fluid sampling), which are then statistically distributed using geological principles constrained by remote imaging with limited resolution. This approach, commonly known as upscaling, is fraught with uncertainty as to the representativeness of the sampling process, the upscaled experiments and the theory.

Due to its position within the shifting continents over geological time the UK has a long and complicated geological history. In contrast to areas where unconventional hydrocarbon exploration and CCS demonstration projects are taking place, such as interior of the USA and Canada, or the relatively simple passive margin of Australia, UK geology is complex and therefore contains an even greater degree of heterogeneity to be sampled and modelled. Future uses of the UK subsurface will therefore rely heavily on our ability to develop models from sparse, limited resolution data, to predict the coupled fluid-mechanical-thermal and geo-microbial consequences of industrial uses of the subsurface.

ESIOS sites will deliver a particularly well-characterised rock mass that will enable models and upscaling methods to be validated by direct observations on downhole experiments. As computational power has increased, our ability to model heterogeneity at short length scales is increasing, yet our ability to image or test models of the heterogeneity in the subsurface is lacking.

ESIOS will enable the validation of established and novel monitoring techniques and the development of new approaches to modelling heterogeneities by downhole experiments in a well-characterised site.

4.2.2 Research Area ii. Multiphase flow in heterogeneous media

Flow of fluids is central to all energy-related use of the subsurface including extraction of energy as hydrocarbons or geothermal heat, injection to boost such extraction, or for disposal of CO₂ or other waste products. Migration of fluids through the geological overburden or up failed well bores is a potential environmental hazard if contaminated fluids reach the near-surface. Prediction of the fluid flows in response to such anthropogenic perturbations is critical for efficient and environmentally sound use of the subsurface. The problem is complex. Rocks, even relatively uniform permeable horizons, are characteristically anisotropic and heterogeneous with, for example order-of-magnitude ranges of permeabilities. This complexity is enhanced by faults and fractures. As discussed above, the structure of the heterogeneities is poorly determined. Many uses of the sub-surface involve multiple fluid phases (e.g. in enhanced oil recovery, geological carbon storage, proppants in hydraulic fracturing operations) and the mutual flows of these fluids are governed by their surface energies which control their relative saturations, relative permeabilities and create critical entry pressures which may, for example, exclude one phase from accessing lower permeability horizons. Fluids may react with minerals in the rock, changing the permeability structure and the rock's mechanical properties.

Laboratory measurements are used to determine rock permeabilities as well as relative permeabilities and saturation characteristics for multi-phase fluid flows. Modelling the multi-phase flow properties is still essentially empirical. It is recognised that the inherent heterogeneities in rock properties make upscaling these measurements to rock mass-scale problematic and the associated uncertainties add major expense to subsurface operations. Further, key processes such as diffusive exchange between fluids (e.g. CO₂ dissolution in brines or oil) are very poorly understood but likely to be strongly impacted by heterogeneities that control fluid-fluid contact areas, mixing and relative transport rates. Conversely, given the sensitivity of multi-phase flows to rock structure and heterogeneities, subsurface experiments capable of sampling multi-phase flows are likely to be informative about the nature and impact of rock mass heterogeneities.

One of the important potential sets of experiments to be carried out by ESIOS will involve monitoring multi-phase flows in the subsurface to compare the results of the field-scale experiments with predictions based on laboratory characterisation of rock core, and/or geophysical and geological models of the 3D subsurface geometry. Results from a number of previous multi-phase field injection experiments are available and have led to developments in instrumentation to estimate relative saturations, flow paths, dissolution rates and fluid-mineral reaction rates. The results confirm the significance and difficulty of prior modelling of the impacts of rock heterogeneities. Interpretation of the results of all these experiments, valuable as they are, is hampered by a combination of restricted knowledge of rock properties, restricted remote imaging, and restricted fluid sampling. The development of dedicated subsurface experimental sites for ESIOS will enable more comprehensive multi-phase fluid injection experiments with planned imaging and sampling. The ultimate objective will be to use the observations based on remote monitoring combined with sampled fluid chemistries to understand and predict fluid flows in characteristically heterogeneous rock formations. Given that subsurface observations and sampling are necessarily limited, the evolution of reactive fluid chemistries will provide critical additional information on the nature of the fluid flow processes, and how flow and fluid chemistry evolves in tandem with mechanical and biological change.

4.2.3 Research Area iii. Mechanical response to artificial perturbations

Human activities affect in-situ stresses by changing loads and by changing effective stresses (pore pressure) either by injecting or extracting fluid. The response of a single rock to changes in applied stresses may be described in broad terms by continuum mechanics. However rock masses, with lithological and structural heterogeneities on many scales, and with fluids contained within them, represent a more complex and challenging problem. Rock mass and fluid properties and the resulting interplay of rock and fluid properties, may also change substantially through time. By understanding the coupled mechanical-thermal-hydraulic-chemical behaviour of the subsurface we

will be better able to monitor sites where human (and natural) stress changes are taking place, engineer projects to minimise adverse effects of coupled mechanical changes, design early warning systems, and explore and design remediation strategies. Finding the right balance between monitoring everything possible and more targeted monitoring in response to activities will need to be carefully considered. For subsurface energy industries, key outstanding questions are:

- i. How can we improve the measurement and characterisation of rock mass mechanical properties? Recent technological advances have enhanced our ability to monitor mechanical/stress changes from the surface or within wellbores, e.g. 4D seismic reflection imaging, seismic interferometry, geo-electricity, novel thermal imaging, borehole breakout, etc. Rocks exhibit considerable anisotropy in elastic properties (primary anisotropy from depositional or emplacement processes; anisotropy induced by deformation or fracture populations); and whilst this can be tricky to monitor it offers valuable insights into the state of stress and how it varies spatially and temporally. ESIOS will provide facilities for characterising rock mass heterogeneity and anisotropy and provide a better understanding of the controls on crack properties and fracture and fault network development. Validation of high-resolution techniques for in-situ characterisation will reduce risk associated with upscaling of geomechanical models. This requires good linkage between geomechanical, fluid flow and geophysical properties.
- ii. How can subsurface fluid injection/extraction cause mechanical failures and thereby impact on the resulting biogeochemical-thermal evolution of the rock mass? As an example, induced seismicity is related to the well-understood process of weakening a pre-existing fault by elevating fluid pressure, yet overpressure may inhibit the dynamic instabilities that result in earthquakes. This contradiction poses a serious problem in our understanding of earthquake physics, with implications for seismic hazard assessment and forecasting of human-induced seismicity. Similarly, forecasting the hazard from ground motion (subsidence) at a particular site requires a comprehensive understanding of the mechanics. Monitoring of rock mass deformation during injection/extraction experiments, particularly monitoring of heterogeneous fault and fracture network evolution, will provide key observations to constrain mechanical models. Long term monitoring is required to understand the timescales for recovery of mechanical and hydraulic properties. Equally important is establishing the baseline state-of-stress before any operations commence. This will require micro-seismic monitoring with low magnitude detection thresholds and other in situ tests like mini-fractures, leak-off tests and studies of regional break-out data. Regional structural elements of any proposed field site must be fully characterised before any artificial perturbations, including comprehensive knowledge of fault geometries and likely fault rock properties.
- iii. How can we forecast and manage mechanical failure in utilising subsurface resources, including the deliberate creation of mechanical change? The performance of stimulated (hydraulically fractured) rock volumes to enhance production of hydrocarbon, geothermal and water resources is highly variable. It is not clear if this is a result of variability in the in-situ rock properties, natural fractures, in-situ stress, proximity to more competent basement rocks, or wellbore effects. Observations of micro-seismicity, geo-electrical properties, strain, in-situ pressures and proppant tracking among other techniques can be used to track rock mass evolution on large or small length scales, from using aftershocks to illuminate the geometry of slipping faults, to tracking fracture growth in a stimulated well volume. Microbes can be stimulated to precipitate minerals, thus changing the hydro-mechanical properties of the rock. Validating these technologies against a well characterised rock mass on multiple length and timescales, will increase confidence in their reliability, and the reliability of models that rely on these data. Both statistical and physics based models need to be developed and tested to better forecast the mechanical response (e.g., induced seismicity).

4.2.4 Research Area iv. Biogeochemical response to artificial perturbations

Biological and geochemical processes are very closely linked and therefore there is likely to be strong coupling between the biological processes and the thermal, hydro-mechanical and chemical

processes that will affect multi-phase flow processes, in situ stress fields and rock properties such as porosity and permeability. The key issue for biogeochemists and geo-microbiologists is to quantify and parameterise the coupling of biological processes to mass and energy transfer in the subsurface in response to perturbations caused by the activities of energy industries. Only through a multidisciplinary interconnected approach can the potential changes be fully understood, and their impact on industrial activity, human health or the environment measured.

Building on the crucial baseline data outlined above, specific challenges in the area of biogeochemical responses to artificial perturbation to these natural systems can be divided into three themes:

- i. Understanding potentially negative impacts on industrial activity, e.g. economic losses through the activity of sulphate-reducing organisms (corrosion and souring) or reduced fluid flow caused by biological activity.
- ii. Understanding the response of ecosystems to pollution by gases or liquids migrating through geological formations from depth or through deficient wells. In addition to microorganisms, the larger fungi and metazoans may be ecologically important at shallower depths.
- iii. Understanding the potential for beneficial impacts. Not all impacts on microbial activity will be negative and practices that encourage beneficial activity leading to, for example enhanced gas/water/heat recovery, should be investigated. Characterising the ecosystem response is crucial to investigate the potential for bioremediation of near-surface groundwaters affected by pollution.

The subsurface biosphere remains largely unexplored and fully describing the microbial communities in the subsurface and their repertoire of activities would be a considerable advance in the field. Key questions include elucidating the controls on microbial growth and metabolic rates, the nature of biogeochemical processes in subsurface environments, and how these respond to perturbations such as fluid inputs. This information may be obtained from manipulations applied to the subsurface in situ (linked to a long-term sampling campaign at ESIOS), augmented by laboratory experimentation designed to mimic and extend field conditions in *ex situ* experiments. Recent developments in sampling, culturing under in situ conditions and biological characterisation (including high throughput genomic sequencing, bioinformatics, and 'meta-omics'⁶ techniques including transcriptomics and proteomics) are all now available to support ESIOS research.

The UK has played a leading role in identifying the rich biodiversity of the deep subsurface, and has strong research infrastructure that already provides international leadership in this key area.

4.2.5 Research Area v. Surface-subsurface interactions and impacts

The interface between subsurface and surface environments is a critical zone for the science and management of geological resources. Almost all of the potential health and environmental impacts that concern the public relate to aspects that arise at relatively shallow depths (< a few 100 m) where pathways transmitting subsurface pollutants interact with shallow groundwater and surface flows of water and air. There are also deeper groundwaters that need protection e.g. important deep spring sources and brackish waters that could provide a future resource, as well as current legal requirements to protect 'all groundwater' irrespective of depth or quality. The issues with surface interactions include determining the nature of possible releases (that could be potentially far from any wellbore), the pathways by which releases might occur (which may be manifold and diffuse), how the subsurface and surface environments should be monitored to detect potential releases and how any unwanted release may be managed or mitigated.

⁶ High-throughput, global analysis of DNA, RNA, proteins, or metabolites isolated directly from a community of organisms living in a particular environment. (from Human Genome Project Information Archive Glossary (2012) by U.S. Department of Energy)

- i. The compositions of potential pollutants in fluids and gases (e.g. methane, naturally occurring radioactive materials (NORM), non-methane hydrocarbons (NMHC), H₂S, metals) and natural and potential anthropogenic controls on those compositions (e.g. oxidation state, microbiology) needs to be determined in all geological horizons likely to be accessed by energy-related activities.
- ii. The potential for fluid- and gas-flow pathways through the geology or industrial infrastructure (e.g. wellbores, reactivated faults) needs to be assessed. The flow rates and fluxes along these pathways will be modified by biological, chemical and mechanical effects.
- iii. Effective monitoring and sampling strategies for potential fluid and gas migration to the surface need to be assessed and refined to take account of rapidly evolving technology and quantitative mass flux derivation methods throughout the lifetime of the facility. The efficacy of such technologies and strategies for specific key experiments such as proxy tracer analyses and transport labelling will also be assessed and tailored as necessary. A key issue in energy applications is the payoff between more expensive monitoring at depth, which may enable timely remediation before surface impacts occur, versus more comprehensive surface monitoring such as surface networks of sensors and shallow boreholes.
- iv. Remediation strategies to mitigate unwanted fluid migration and pollutant release need to be designed based on both best informed prior site characterisation and new scientific understanding and measurement.
- v. As well as interactions in the shallow subsurface, there is a need to consider the effect of introducing wells and associated fluids into the deep subsurface. For instance, the introduction of oxygenated water and/or microbial populations into wells at depth can result in enhanced corrosion of well casings. ESIOS should provide opportunities for long-term monitoring of well integrity and near-wellbore interactions with introduced fluids.

The fundamental science required to constrain subsurface-surface interactions is that common to other scientific research questions, i.e. obtaining a proper understanding of the controls on fluid-flow, fluid-chemistries and their interactions with the mechanical and biological processes within a rock mass. More immediately, monitoring techniques need to be employed and tested so that the UK can acquire a robust evidence base on various subsurface energy-related activities to enable effective and environmentally safe management.

5 Experimental Requirements

The timelines for the development of ESIOS will include:

- i. Planning based on prior knowledge of the geological structure;
- ii. Determination of baseline conditions (both natural and the legacy from human/industrial activities);
- iii. Implementation of remote and in-situ monitoring systems;
- iv. The drilling phase, which will include monitoring while drilling, sampling of core and fluids, downhole geophysical logging and installation of downhole instrumentation;
- v. Ongoing (legacy) monitoring and sampling; and
- vi. Conduction of downhole experiments and related sampling and monitoring.

The associated science research programmes must be involved in all of these phases, especially in the likely event that decisions on changes in the experimental program need to be taken urgently on the basis of new observations or technical requirements.

Careful planning is needed to maximise the scope and scientific return from the downhole experiments. It is essential that the planned observations will test appropriate hypotheses. Potential conflicts between mutually exclusive downhole monitoring techniques and experiments will need to be carefully managed.

For the purposes of this Science Plan, distinction is made between relative shallow, and probably uncased observation boreholes and deep, largely cased, wells used for injection, production or hydraulic fracturing experiments. Of course monitoring tools may be deployed in a deep well, and experiments may be conducted in shallow wells. It may be possible to develop ESIOS sites around existing deep wells, and existing shallow boreholes can be re-occupied to supplement the array of monitoring boreholes. The latter was done very successfully at the Soultz Hot Dry Rock site.

An over-arching priority common to virtually all Science Challenges would be to provide a facility with at least one deep (>1000 m) well that can be used for a range of experimental research purposes over a period of several years. This should be complemented by an array of relatively shallow boreholes to characterize the rock volume within and around the experimental research facility, to facilitate high-definition (downhole) monitoring and imaging, and to monitor impacts on shallow groundwater systems resulting from the deeper borehole experiments. These arrays are required to look at spatial variability (heterogeneity) at different scales. The testing of these wells and boreholes will allow collection of a wide range of information on physical, chemical, hydrogeological and biological properties. Multiple boreholes will also allow interference and tracer tests to be carried to examine hydraulic properties at different scales and characterization of pathways. Repeat testing at different times will allow changes to be identified.

The following sub-sections summarise the various infrastructure and technology requirements proposed to meet the Science Challenges and the five separate but interlinked Research Areas outlined in Section 4.

5.1 Project Management

The experiments will need careful management at all stages, in particular the interaction between those responsible for developing the infrastructure and those executing the scientific experiments. Real-time scientific input will be needed for decisions that will arise during development (i.e. during drilling and completion) where operations and requirements change that have implications for the feasibility of subsequent experiments and/or where there are financial implications. Data management and archiving must be planned in advance: data acquisition and handling will be needed on site, including the real time transmission of broadband data. Protocols concerning access to data and cored rock samples and publication of results must be established in advance.

Appropriate modelling of the subsurface processes, potential impacts of near surface and atmospheric releases and their dispersal must be initiated prior to operations to permit the design of the well to be optimised. Baseline measurements at the surface and near-surface should be taken at least one year before drilling starts, because of potential seasonal variation.

A working group (with an evolving membership representative of the user community) in the model of e.g. the NERC Facility for Airborne Atmospheric Measurements (FAAM) working group, should be established to monitor the use of - and the evolving infrastructure of - the facility in order to meet the needs of the user community throughout ESIOS' lifetime.

5.2 Baseline experimental studies and remote monitoring

Before initiating drilling, the sites must be characterised in terms of geological, geophysical and geotechnical properties and environmental baseline. This will include a synthesis of the geology, 3D seismic reflection surveys, geo-electric studies, gravity, magnetic mapping, passive micro-seismic and ground deformation, air quality and perhaps development of novel experiments (e.g., imaging using neutrinos). A permanent set of survey stations should be installed so that repeat surveys are accurately co-located, improving the precision of remote monitoring during and after the downhole experiments, and facilitating joint inversion of multiple (sequential) datasets. Comprehensive geological, hydrological and geomechanical models will need to be developed to inform well design. This could include reprocessing of legacy seismic data and re-analysis of core and other existing borehole measurements. These models should be updated as the results of future experiments become available.

The baseline chemistry and microbiology of deep and shallow ground water systems and air quality local to experimental sites will need to be established (especially levels of impurities including methane levels, heavy metals, and NORM, Volatile Organic Carbon (VOC) and air quality markers, and noting any perturbation of these by prior or ongoing industrial activities). Existing fluid composition data should be collated and supplemented by sampling during the drilling phase. Surface fluid sampling, atmospheric sampling, airborne surveys and possibly satellite measurements will be required; this work needs to be conducted for at least a year before drilling starts to obtain representative statistics. Baseline seismicity levels should be monitored with a detection threshold of ML-1.0. Baseline in-situ stress data should be collated from focal mechanisms, and available prior data such as borehole breakouts. New techniques and instruments are likely to be developed and tested during the lifetime of ESIOS and adequate baseline data will be critical to validate these new techniques. Finally, studies of the interdependencies of these measurables are required. For example, is there any correlation between seismicity, groundwater, biological activity, and gas emissions?

The data from initial site characterisation and baseline measurements must be made freely available to the research community to facilitate and constrain effective design of later experiments. These data, and resulting models built with those data should be updated as further data are acquired during drilling and subsequent experiments.

5.3 Borehole experiments

Drilling experiments need to consider well design, casing and well completion because these processes impact contamination (e.g. drilling muds), coring, instrumentation, sampling, monitoring, tracer injection, fluid injection and subsequent sampling. Drilling of multiple wells needs to be carefully planned. Consideration will need to be made for planning junctions in the wells to allow lateral wells to be drilled and sleeves that allow access to the rock outwith the casing, or if appropriate, to leave an uncased section at the base of the well(s) to allow access to the rock. Access to the rock mass can also be accomplished by having uncased section beyond the cased section, i.e. by having a casing that does not extend to TD (total drilling depth).

Logging while drilling and/or wireline logging may include: azimuth/declination, casing joints and calliper measurements to characterise the bore hole. Gamma ray density, formation resistivity, acoustic velocity, self-potential, temperature (DTPS) and pressure, formation micro-imagers (FMI),

neutron cross-section capture (Reservoir Saturation Tool), and nuclear magnetic resonance scanners (NMR) among others will define the geology and measure petrophysical properties. *In situ* stress measurements will be required (e.g., mini-fractures, polyaxial stress measurements). *In situ* permeability measurements will be required. Drilling, logging, fracturing and coring wells would be conducted by service companies. ESIOs will provide sites for testing of novel logging tools, but this should be carefully planned prior to deployment.

Core must be logged before being scanned (e.g. a state-of-the-art micro CAT scanner dedicated to characterizing the 3D structure of the core at a sub μm resolution), and sampled for petrology, petro-fabrics, fluid content and composition, and comprehensive petrophysical analyses (e.g. permeabilities, geomechanical strength). It is important the core extends, as much as possible, from surface to total depth. Minimising and monitoring contamination will be critical for chemical, biological and geo-microbiological analyses of core and fluids. This will require careful analysis of injected and produced fluids, including the drilling mud. Gasses evolved from core (e.g. methane at *in situ* conditions) will need to be sampled at surface where preservation of sections of pressurised core will take place.

Consideration will need to be made for instrumentation deployed within the borehole. Examples include: fibre optic cable outside the casing for measuring temperature, strain and seismicity; probes for measuring *in-situ* chemistry of fluids, gases, and pH; sondes clamped to the inside of the casing for measuring seismic signals, both artificial (e.g., for Vertical Seismic Profiles [VSPs]) and naturally occurring (micro-seismicity). Fluid sampling methods (e.g. U-tube with isolation packers, sidewall or downhole pressure samplers) must be planned based on hydrology predicted from the site characterisation phase (and updated during data acquisition) and the competing requirements of likely experiments. Consideration of the competing requirements of these technologies must be taken early in the well design phase. For instance permanent installation of certain sensors or sampling equipment might preclude access to lower sections of a well.

5.4 Experiments during stimulation, injection, or extraction

Time lapse monitoring of experiments will be required to detect changes in physical, chemical and biological properties at all depths, including above ground. These, first carried out during the pre-drilling baseline surveys, will include repeat geo-electric, seismic reflection, and gravity surveys as well as continuous monitoring of ground deformation by seismic networks (both surface and downhole), tiltmeters, and geodetic observations (Global Positioning Systems [GPS], Interferometric Synthetic Aperture Radar [InSAR]). Continuous or periodic sampling of deeper fluids at formation pressures may be required coupled with continuous sampling of near-surface groundwaters and atmospheric emissions. The on-site infrastructure required will need to be planned carefully (e.g. for power, managing communications and data, handling core and fluid samples as well as real time analyses of the core, fluids and biological samples).

5.5 Ongoing monitoring experiments

A range of experiments will need to be designed to assess the long-term impact of any borehole activity (e.g., shale gas, geothermal, waste disposal, etc.). This will include water sampling at a range of depths, long-term gas monitoring, careful analyses of impacts on the biospheres, and legacy geomechanical issues such as seismicity and ground subsidence. How long to record for and over what spatial area are important questions which, while forecast at the planning stage, are likely to need revision given ongoing observations. Real-time monitoring would be an important component of the long-term activity, but also repeat surveys or site visits.

5.6 Well design and operational design

- i. Regulation. Planning permission and the environmental permit will require full information concerning the design and operation of the facility regarding matters that lie within the planning remit. There needs to be an environmental impact assessment, and details of plans for decommissioning at the end of the facility's operation. As part of this process, the ownership of the facility and associated responsibilities needs to be clearly defined.

- ii. Prior to procurement, the design of well(s) needs to include consideration for casing and down-hole cement to enable the optional future use of CO₂ as an experimental fluid. H₂S resistance may be necessary; whether or not this is needed may be identified from experience gained in other deep boreholes near the proposed facility.
- iii. Provided the conditions listed in paragraph (ii) above are satisfied, the simplest approach will be to case well(s) using a conventional steel casing specified for a life of (say) 30 years, but this material will limit future research use. It is very unlikely that an open hole will be stable through some stratigraphic intervals, fault zones and other loose formations. Consideration therefore needs to be given to a completion that allows access for experimental purposes. Care needs to be taken to identify intervals ahead of procurement that require any of the following: composite casing material, perforated casing, formation isolation using packers.
- iv. A range of hydraulic testing and sampling should be carried out during drilling and after well completion (for instance via packed off intervals through casing perforations) to provide detailed hydrogeological data and information to characterize all geological formations and fault and fracture networks. This should include:
 - Environmental (head) pressure monitoring – interval testing to determine initial head and hydraulic conductivity/permeability distribution;
 - Full Sector Testing to identify flow horizons and zones of enhance permeability; and
 - Packer Testing to allow collection of groundwater samples (pressurised/unpressurised) for groundwater chemistry/microbiology and additional head measurement at specific horizons or fault zones.
- v. Drilling should consider the needs of the microbiologists, drawing on International Continental Scientific Drilling Programme (ICDP), International Ocean Discovery Program (IODP) experience, so that samples suitable for microbiological work can be taken during drilling and appropriately preserved (see 5.7.2, bullet five).
- vi. The installation of permanent monitoring equipment, such as optical fibre sensor systems and multi-level fluid sampling systems, should be designed prior to defining the specification for the casing.
- vii. Wells should be cored as much as possible. Pressurised sidewall cores should be taken at specific intervals, in response to early research needs. The borehole should be image-logged to total depth.
- viii. During the research phase, it is assumed that downhole logging tools will be determined as required for experiments using the facility as necessary, and that they will be hired by research teams as and when needed at cost to be charged to separate successful project proposals.
- ix. All operational details, geophysical logs carried out during drilling and daily drilling logs need to be recorded and collated in a form that allows use by researchers. The specifications of oilfield chemicals used to make up the drilling fluids needs to be recorded, and the amounts used during drilling.
- x. As part of the capital spend, routine/basic wireline logging (azimuth/declination, casing joints, gamma, temperature, conductivity, caliper etc.) and formation imaging should be carried out during the drilling exercise and as appropriate on completion of well(s), so that scientists know as much as possible about the geometry and construction of the well, the character of the formations, temperature gradient etc. to inform design of future experiments to be deployed at ESIOS.
- xi. On completion of well(s), they should be purged/developed/stimulated to remove as much contamination related to the drilling process/fluids as possible. While this is challenging, great care needs to be taken that this process has the most minimal effect possible on the rock formations, formation chemistry and/or biota within them. Some of this work can be carried out as part of the essential hydraulic testing (bullet iv).
- xii. Once completed, well(s) should be allowed to fill with formation fluids. Pressurised fluid samples should be taken at specified depth and time intervals for chemical and microbiological analysis, bearing in mind that muds will have perturbed the system. At

least some of the wells and/or boreholes must have permanent installations to allow multi-level (pressurised) fluid sampling and head measurement.

5.7 Monitoring requirements

Key facility monitoring needs, including those identified in submitted science ideas and in Town Hall discussions, concern both subsurface and surface parameters. The following list presents contextual datasets that may be considered useful long-term baselines that underpin many of the emergent science themes.

5.7.1 Surface-subsurface Interactions and Impacts

- i. Interrogation of existing environmental monitoring data relating to the location of the facility, including soil, groundwater, surface water, ground gas (e.g. associated with external monitoring of nearby landfills) and air quality.
- ii. Seismic monitoring: a network of seismometers to detect background seismicity and events associated with deep experiments.
- iii. Survey points for long-term monitoring ground motion (including InSAR)
- iv. Gas monitoring: shallow boreholes in unsaturated zone to measure ground gases in real time (CO₂, CH₄, O₂, N₂, plus other contaminants)
- v. Soil gas monitoring: monitoring CO₂ and CH₄ emissions from the soil surface. Isotopic fractionation of soil gas flux could help to differentiate biogenic and thermogenic sources of gas
- vi. Surface water monitoring: sampling and analysis of surface waters in accordance with standard procedure.
- vii. Atmospheric emissions and air quality baseline monitored by installation of a dedicated eddy covariance tower and a meteorological station.

5.7.2 Subsurface

- i. Groundwater monitoring (shallow and deep groundwater systems): installation of network of monitoring boreholes, measurement of water levels, sampling and analysis of groundwater in accordance with BS:ISO Standards.
- ii. Repeat 3D seismic, and other geophysical or levelling surveys at intervals once experimental work has started.
- iii. *In situ* stress monitoring.
- iv. Facilities required for additional geophysical survey work (e.g. Electrical Resistivity Tomography) and long-term 3D monitoring.
- v. Biological sampling protocols informed by current work on ICDP and IODP wells. Contamination will need to be assessed at site by injection of appropriate tracers. Fluid and core samples will need appropriate handling facilities at surface (e.g. temperature and pressure (if pressurised cores available) control, anaerobic handling) and equipment to support baseline characterisation (e.g. assessment of contamination, microscopic cell counts and microcosm/culturing experiments), with arrangements in place for rapid dispatch to research laboratories where advanced complementary e.g. 'meta-omics' techniques will be available.

5.7.3 What's needed on or alongside each site

- i. Appropriate safety restrictions, such as fencing etc., and health and safety protocols.
- ii. Utility connections, access roads, auxiliary power.
- iii. Data repository, including curation, accessible to the public domain within NERC guidelines.
- iv. Water supply/power sufficient to meet drillers' and researchers' needs.
- v. Core and fluid handling space during drilling, away from rig and with facilities necessary for microbiological sampling, including anaerobic chambers.
- vi. Cold store and freezer storage for sample holding. Freezers down to - 80°C to stabilise sensitive biological material e.g. RNA.

- vii. Well head design: Christmas tree capable of managing the well/produced fluids and simultaneously permitting monitoring and access for experimental work. This will be a long lead time item and the requirements need to be identified early.
- viii. Well-head facilities, including winch sufficient to handle downhole equipment to be used in the research. Must be mobile and capable of being withdrawn to permit access to the well by drillers in future. If there is a need to pull the production string then a rig may be needed as well as a wire-line system for intervention.
- ix. Access for heavy vehicles (including mobile cranes) and equipment, during drilling and then during use of the site; access for mobile plant required for fracturing or other manipulations.
- x. Staff facilities, including working/office space at surface in accordance with health and safety regulations.
- xi. Enclosure/building for core continuous instrumentation.
- xii. Communications/internet access/broadband telemetry data transfer capability.
- xiii. Visitor centre, including café, space for school/student workshops, local authority workshops
- xiv. Test facilities for new downhole and/or monitoring equipment, including an electrical/mechanical workshop
- xv. Agreed sampling/testing/monitoring and publication protocols.

5.8 ESIOS enablers

Investment will be needed to establish the infrastructure to deliver ESIOS in the long-term, including informatics, core and sample storage and analysis, equipment for pre ESIOS baseline study and software and computing to construct an ESIOS online portal that delivers the stated aims of ESIOS in transparency and openness.

5.8.1 Informatics

ESIOS will require computer infrastructure and software for ingestion and real-time ‘on the fly’ analytics of subsurface geological and biological data, as well as storage of data and models. ESIOS will require highly automated telemetry using standard low cost Global System for Mobile communications (GSM) networks, but also will use mechanical, hydraulic and optical telemetry methods. Rapid ingestion and real time analysis and display of subsurface big data will be required, as will telemetry of sensed data in high temperature, high pressure saline environments.

5.8.2 Core and sample storage and analysis

Non-pressurised core rock and other samples will be recovered and there will be a need to measure changes in rock as well as static and fixed character of rocks by non-invasive imaging. Thus core scanners and mass spectrometers will be required for analysis and imaging, associated with an upgrade in the storage space and analytical facilities provided by the BGS national core store (National Geoscience Data Centre [NGDC]).

5.8.3 Pre-ESIOS baseline study

Monitors and sensors will be placed at the surface and in the subsurface to determine the conditions of the subsurface and atmosphere before any activities at ESIOS. A suite of sensors at the surface and in boreholes will monitor, among other variables, air quality, groundwater, seismicity, pressure, temperature, heat flow, tilting, strain accumulation, fluid chemistry, and physical and biological properties with the aim of gaining a subtle understanding of baseline conditions and the range of natural variation.

5.8.4 ESIOS online portal

Transparency and upfront disclosure of monitoring methodologies, measurements and data, as far as possible in real time, is an essential theme of ESIOS and dedicated software and computing facilities may be required to develop a complex high-traffic online portal.

6 Knowledge/technology transfer, innovation and wider benefit

Innovation is at the heart of ESIOS. Capital investment by the Department for Business, Innovation and Skills (BIS) in sensors and monitoring equipment to enable world-class science and understanding of subsurface processes and interactions opens the possibility for: i. proactive knowledge transfer from underpinning science (translation of existing science to industry); and, ii. science-led demand for innovative devices (science as a technology consumer). ESIOS will invest in equipment capable of developing real-time, independent data that can be used to provide evidence to better inform decisions relating to emerging and innovative energy technologies.

Whilst this Science Plan is primarily aimed at outlining the potential Science Challenges to be answered and the possibilities of the ESIOS investment, ultimately it is important to recognise that ESIOS aims to be the most detailed monitoring and observing system of its kind in the world. The comprehensive nature of the measurements will mean the ability to monitor and understand subsurface processes at a level rarely achieved before.

The benefits will be felt across the country as the UK will be better equipped to:

- facilitate real-time, open-access observations of subsurface processes and interactions;
- inform better management, regulations and environmental security assurance to realise and de-risk new technologies;
- provide a platform for the development and commercialisation of a range of new low carbon technologies; and
- export new UK-created technology and expertise.

Particularly important in achieving the above benefits will be the approaches taken to exploiting the scientific outputs as part of the project.

Proactive knowledge transfer. The ESIOS investment will ultimately develop data, expertise and insight that will be valuable to the UK's energy technology community. ESIOS science will therefore consistently be cognisant of its future application potential in designing the approaches to gathering data and topics to be considered. This will be done with a view to proactively transferring this knowledge to industry and policymakers responsible for the development of new low-carbon energy technologies for the future of the UK economy.

Science-led demand for innovative devices and technologies. Related to the above, this Science Plan includes areas where the technology does not currently exist to meet the needs of the Science Challenges. In this context, as well as major players in the emerging energy and energy technology space, ESIOS will be cognisant of the opportunity to work with the value chain of small to medium-sized enterprises with the technological capacity to develop innovative sensors and monitoring technology. In doing so, NERC will need to work closely with other organisations to develop opportunities to provide the capital infrastructure that will meet the developing needs of the science around ESIOS. Where the technology or technological capacity does not yet exist there is a real opportunity for innovation across the UK research base.

The ESIOS programme, dedicated to observing, and modelling subsurface geology and petrophysical, subsurface fluid flow, mechanical and biological processes will provide the opportunity to train researchers, provide Continuing Professional Development (CPD) for industry personnel and provide a forum for engagement with the public. Equally, the UK science community can learn from industry and the public. Such three-way interactions should provide an opportunity to improve the way in which science is viewed by the public, help align both public and researchers with the needs of the nation and ensure industry is responsive to the capabilities offered by academia as well as the sensitivities expressed by the public. Done properly, the experimental research programme will deliver excellent science, and help to inform government policies, public engagement and industry decision-making. A key outcome must be the practical transfer of this

information to technology design/application and policy development for new subsurface uses and to inform discussion, engagement and debate about what kind of low-carbon transition people would like to see. In particular ESIOS has a role to play in guiding environmental regulators, so that appropriate evidence-based regulatory controls can be developed.

UK researchers are involved in many relevant initiatives both within UK and international consortia. ESIOS will link to and benefit from the infrastructure and knowledge gained from existing research programmes worldwide, including activities supported by the Deep Carbon Observatory, IODP cruises, ICDP, US Department of Energy Subsurface Biogeochemical Research (SBR), and international underground research laboratories (URLs) including Grimsel, Mont Terri, Aspo and Bure (and World Meteorological Organisation [WMO] / Implementing Geological Disposal Technology Platform [IGDTP] research focused on these facilities). It is anticipated that there will be opportunities for collaboration between these sites. ESIOS should aim to engage much of the relevant UK research community on world-leading initiatives – by using ESIOS facilities and by collaborating with those using other facilities. In this way it will naturally provide the focus/hub for science and industry, and will also be able to encourage and support co-ordination of research activities.

7. Recommendations

The aim of ESIOS is to provide facilities for research that investigates the use of the subsurface for energy resources. ESIOS should aim to provide one or more facilities that consist of *at least* one deep (>1000 m) well complemented by an array of relatively shallow boreholes. High-definition monitoring and imaging from the surface, the deep wells and shallow boreholes will result in a rock volume characterised to an almost uniquely high resolution. The wells, borehole arrays, and surface facilities can then be used to deploy experiments to capture the effects of induced changes within the rock mass; to validate new monitoring techniques; to validate new modelling and upscaling methods; and to quantify any impacts on the near-surface and surface from subsurface experiments. If the sites are well-designed and maintained to take account of the requirements of the Science Challenges, they should be able to be used for a range of experimental research purposes over a period of decades.

In addition to the Science Challenges and Experimental Requirements detailed in Sections 4 and 5 above, ESAG also makes the following recommendations to NERC:

Open-access data and evolving models

1. One of the key roles of ESIOS is to facilitate genuinely interdisciplinary science. Open-access data and results will facilitate the dissemination of excellent science both between the ESIOS operator and facility users, and to end-users. ESIOS science should be conducted under the Code of Practice for Research produced by the UK Research Integrity Office.
2. The data from initial site characterisation and baseline measurements must be made freely available to the research community to facilitate and constrain effective design of later experiments. These data, and the resulting models built with them should be updated and made available as further data are acquired during drilling and subsequent experiments. These data should be used to develop a 'live' and constantly updated 3D geological framework model of the site such that subsequent experimental design builds upon the integrated model. Consideration should be given to how best to archive and maintain access to these evolving datasets and models through the lifetime of ESIOS.
3. To facilitate collaboration, protocols concerning data, embargo periods, management and archiving of data and samples, as well as the joint publication of results must be established as soon as possible.
4. It is possible that some of the experiments could be undertaken jointly between ESIOS and overseas sites. There is scope to develop a network of UK and international sites to ensure that all key subsurface environments are covered. ESIOS will be a platform for world-leading international collaboration.

Site selection

5. A number of academic research programmes and individual subsurface experiments are underway globally. A survey of the science programmes at these sites should be used to define specific research gaps that could be filled with either or both ESIOS sites. In addition there are key lessons to be learnt from overseas subsurface research sites. Early engagement with key players will help to maximise the potential for excellent science from the sites.
6. The first ESIOS site is likely to be close to Thornton in Cheshire. BGS has already started compiling data at the locality and has set up a baseline sampling programme. In the Call for Ideas, out of 71 ideas, 48 were suited to the stratigraphy, structural geology and rock properties of the site, and 9 specifically mentioned the site as suitable. The site has a typical and representative subsurface sequence of UK Carboniferous to Triassic siliciclastic and carbonate rocks, two major regional unconformities, and the older rocks have been complexly folded and faulted. As such the site has a complex geology that is representative of the UK, and appropriate to test the science questions around many geo-energy applications. The Carboniferous Limestone Supergroup and overlying Craven Group contain shale-related hydrocarbons; while the Millstone Grit Group

contains deep reservoirs that allow consideration of geothermal resources. The Pennine Coal Measures Group contains deep reservoirs suitable for geothermal research, as well as deep 'unmineable' coal seams that allow research into coal bed methane and associated CCS technology. The Sherwood Sandstone Formation overlying the regional Variscan unconformity at Thornton is an important regional reservoir unit. The Morecambe Bay gas field, the second largest in the UK, is within the Sherwood Sandstone; in other areas across the north of England, the UK's second most important groundwater aquifer is contained within the Sherwood Sandstone. This unit is therefore suitable for a wide range of research into the coupled fluid-mechanical and geo-microbial effects in reservoir units of CCS, gas storage, geothermal energy and hydrocarbon extraction.

7. If for some reason the Thornton site cannot be delivered, site selection should ensure that an alternative site can provide the geological environment and surface facilities to match the objectives of this Science Plan.
8. The second ESIOS site should be defined by identifying subsurface experiments that cannot be conducted at site 1.

Key monitoring requirements and science priorities

9. Key monitoring requirements for each site depend on the existing or leveraged infrastructure at the site, the nature of the site (i.e. urban vs rural will determine what emissions monitoring should take place) and the nature and complexity of the geology under those sites. The sections above provide a longlist of monitoring technologies. Monitoring that is considered additional to ESIOS requirements could be provided by other providers.
10. Drilling a relatively shallow borehole would be within the budget of a NERC discovery science Standard grant, so the array of surface observation systems may well evolve as experiments are implemented at ESIOS sites. However the capital cost of the deep wells means that it is highly advantageous to leverage existing or soon-to be delivered infrastructure in partnership with private companies. There are certain technologies identified in this Science Plan which cannot be retrofitted once a well is completed. If ESIOS experiments use a deep well provided by an operator, detailed and transparent discussions will need to take place to develop a well design that maximises the scientific opportunities from that well, while not compromising the use of the well by the operator.
11. Through baseline data collection, drilling at the ESIOS sites and the post-drill phase there will be opportunities for new data collection, novel monitoring and experiments. This was emphasised by the spread of science ideas collected during the ideas process. The research and end-user communities are encouraged to submit ideas for strategic science using ESIOS, via the NERC ideas process for HTs and SPAs. In addition applicants are encouraged to submit discovery science proposals which would use ESIOS as a facility for research. In particular there are opportunities early in this timeline, for time-critical steps such as baseline monitoring before drilling, deploying semi-permanent sensors behind the well casing, or for ideas that will add to the planning permission process.
12. The longlist of Experimental Requirements in section 5 above will not be able to be delivered at any one site. ESIOS will deliver comprehensive samples and datasets, over and above what is routinely collected by industry in accordance with regulatory guidelines. However these samples and datasets represent enormous value for money scientifically. Priority needs to facilitate world-leading science therefore include the requirement to take downhole rock and water samples at pressure for geo-microbiology, rock mechanics testing and geochemistry; as complete a set of core through the 'overburden' as possible; and as complete a suite of baseline data as possible over and above that routinely collected for environmental permitting (including passive seismic data, down-hole stress measurements).

Maximising delivery of excellent science

13. ESAG recommend that the ESIOS project will need a management structure for the development and operational phase of the subsurface research centres that the ESIOS project will deliver. ESAG suggest that the management structure would need to consider topics related to site development such as liabilities associated with the development of deep boreholes, and decision structure in relation to installation of scientific instruments during borehole completion. The management structure would also need to consider operational issues such as health and safety and liability issues related to site work at the research sites, alongside requirements and funding for decommissioning of the boreholes at the sites. ESAG noted the similarities with IODP and suggest that it might be sensible to consider the IODP approach when developing a management structure for ESIOS.
14. A Science Advisory Group should be established to advise on the procurement and use of the ESIOS facilities. The Group should also offer science advice on future infrastructure upgrades throughout ESIOS' lifetime. The group should have an evolving membership including representatives from academia and end-users in order to meet the needs of the user communities. There will need to be a very clear management structure with clarity on who is responsible for what and for how and when the science advisory group is called upon.
15. Drilling through the heterogeneous subsurface is inherently hard to predict. At all drilling sites, geoscientists are required to be present to take quick decisions that may be required during drilling. The steering group may need to be consulted at short notice during the drilling phase if any of these decisions look like compromising a particular sub-set of future experiments.
16. The process of selecting and designing strategic research programmes must be managed carefully to ensure that the full scientific opportunities are exploited, and that competing uses of the facility are avoided. Ancillary scientific research programmes related to, but not directly using the facilities, are crucial to maximise the benefits of this facility. These include research which develops data processing, novel monitoring techniques and sample analyses.

Stakeholder engagement

17. Local communities around ESIOS sites should be engaged with at the earliest possible stage. Transparency about the purpose of the site, and ongoing engagement with local communities and NGOs, will be vital for local buy-in.
18. The use of ESIOS facilities to drive innovation (e.g. by providing a test bed for prototype technologies) requires a strong engagement with relevant public and private sector stakeholders.
19. There is much expertise within industry that will need to be drawn upon to design the sites themselves and the experiments that will be deployed there. Private sector involvement might take the form of in-kind contributions of data or equipment, secondment of staff into projects or funding for projects of research staff. Experts within the energy sector (including the regulators of the sector) should be consulted where necessary to ensure that all ESIOS science is aligned to producing the most relevant science for ensuring safe, efficient and secure use of the UK's subsurface. All industry engagement should be on a fully transparent basis, and open-access publication of results should be required.
20. ESIOS will provide robust scientific evidence to underpin debates around the future of energy in the UK and beyond. The end-users of ESIOS science include industry, regulators, policymakers and the general public. These stakeholders should have the opportunity to engage fully with ESIOS and the results of ESIOS science. Proposals for individual science experiments at the sites should require a clear plan of engagement with stakeholders. ESIOS will also provide the opportunity to enthuse the UK public about the excitement of NERC Earth and environmental science.